Technology, Knowledge and Learning
https://doi.org/10.1007/s10758-024-09764-z

ORIGINAL RESEARCH

Understanding Learning and Learning Experience in Immersive Virtual Reality

Panagiotis Antonopoulos[1] · **Emmanuel Fokides**[1] · **George Koutromanos**[2]

Accepted: 1 July 2024

Abstract
There is a pervasive belief that immersive virtual reality (imVR) holds transformative implications for almost all technology-mediated human activities, including the sphere of education. Given this context, it becomes essential to comprehend the impact it exerts on learning, in addition to ascertaining whether it positively affects factors that enhance the learning experience of users. Consequently, a research study was conducted to compare learning outcomes resulting from the use of an imVR application vis-à-vis outcomes procured from web pages and a desktop virtual reality (dVR) application. Additionally, contributory factors to the learning experience were juxtaposed. The research set comprised 103 university students interacting with tailor-made applications presenting ancient Greek inventions, facilitated via head-mounted displays (the imVR condition) and personal computers (for dVR and web pages conditions). Evidence suggested that learning in the imVR environment outperformed only web pages. However, in several factors that were theorized to have an impact on one's learning experience, imVR surpassed both the other two media. The broader implications of these findings also form a part of the subsequent discourse.

Keywords Desktop virtual reality · Immersive virtual reality · Learning · Learning experience

✉ Emmanuel Fokides
fokides@aegean.gr

Panagiotis Antonopoulos
pred19003@rhodes.aegean.gr

George Koutromanos
koutro@primedu.uoa.gr

[1] Department of Primary Education, University of the Aegean, Rhodes, Greece

[2] Department of Primary Education, National and Kapodistrian University of Athens, Rhodes, Greece

Published online: 05 August 2024

1 Introduction

Virtual Reality (VR) represents a technology that encompasses computer-generated simulations of 3D, interactive environments, that either resemble real ones or are fictional, enabling users to immerse in them. The principal aim of this technology is to create to users the feeling of "being" in a digital world even though they are physically present in the real one. Within an educational milieu, VR applications are employed as a tool to enhance students' learning experiences, thus offering a more engaging and dynamic platform for students to understand complex concepts, theories, or systems, and also for skill practicing (Fokides, 2023).

Advanced VR applications are predominantly based on immersive VR (imVR) technology. ImVR represents a sophisticated form of VR, with its principal goal being to provide augmented levels of immersion. This is achieved by simulating experiences closely mirroring the physical world, consequently cultivating an illusion that persuades the human brain into accepting artificially created realms as reality (Atsikpasi & Fokides, 2022). This is typically accomplished through the use of head-mounted displays (HMDs). HMDs can be conceptualized as wearable devices that isolate the user from their real-world surroundings. They provide stereoscopic vision, thereby facilitating a 3D perception of the virtual world and provide spatial sound, enhancing the user's overall immersive experience. A crucial feature of HMDs is the incorporation of motion-tracking sensors, designed to mirror and react to users' head movements and body actions in real-time. As a consequence, the image within the users' line of sight is perpetually adaptive, with continuous alterations in harmony with the changes in their viewing angle. Additionally, hand tracking, facilitated either by the use of controllers or external cameras and sensors mounted to the HMDs, permit users to interact with the virtual environment and receive haptic feedback. These elements together contribute towards formulating an enhanced sense of realism, thus embodying the concept of "immersion."

In the sphere of education, imVR serves as a significant advancement, marking a considerable evolution in pedagogical methodologies. This transformation signifies a departure from traditional educational approaches that are dependent on analog or conventional digital media, establishing a new pathway for more experience-based, interactive, and effective learning and teaching (Fokides, 2023). Indeed, the prospect of integrating imVR into education has gathered significant enthusiasm among scholars, practitioners, and policymakers alike. Current research aims to comprehend the impact of this technology on teaching and learning, to assess its efficacy across different learning domains, and to evaluate potential opportunities and challenges tied to its comprehensive application in the educational sphere. For instance, evidence supports the notion that imVR can revolutionize the established teacher-student dynamics and help transcend spatial and temporal restrictions (Lin et al., 2022). Several studies have reported that educational imVR applications provided a rewarding learning experience and positively influenced factors identified as facilitators of learning, including autonomy, interest and engagement in the learning process (Kye et al., 2021; Radianti et al., 2020), enjoyment and positive emotions (e.g., Abichandani et al., 2019; Allcoat & von Mühlenen, 2018; Butt et al., 2018; Caro et al., 2018), motivation (e.g., Rupp et al., 2019), self-confidence (e.g., Tzanavari et al., 2015), creativity and active learning (e.g., Caro et al., 2018; Erturk & Reynolds, 2020). Concerning knowledge acquisition and skill development, the discussion remains continuous and inconclusive, given that the results are mixed, as it will be further elaborated in the coming section. Notwithstanding the aforementioned point, the scarcity of comparative studies pertinent to this matter is notable. Limited research has rigorously explored the learning outcomes produced by imVR applications in comparison with other digital or analog media. Consequently, there is a prevailing uncertainty about the extent to which learning in imVR environments surpasses or lags behind other educational tools.

In response to the above issues, in mid-2021, the authors embarked on a multifaced research project, the objectives of which were to develop a series of imVR applications, examine their impact on learning, and scrutinize the factors that could potentially hold pivotal significance in the process of learning. The study at hand presents the results stemming from the third phase of the said project, in which a comparison was made among the learning outcomes produced by an imVR application, desktop VR (dVR) application, due to the close relationship of this technology with imVR, as well as web pages, that can be considered as a more conventional digital media. The subsequent sections elucidate the rationale underpinning this research; they detail the specific methodology implemented, elaborate on the data collection process, and present how the data was subsequently analyzed. This is then coupled with a comprehensive discussion of the derived results.

2 Related Work

2.1 ImVR and Learning

In the sphere of education, imVR has consistently demonstrated its affirmative influence on learning processes, a notion reinforced by an abundance of empirical data (e.g., Abichandani et al., 2019; Andreoli et al., 2017; Fanini et al., 2018; Fokides, 2023; Fokides et al., 2021; Luigini et al., 2020; Pappa et al., 2018). This data, in conjunction with literary reviews and metanalyses (e.g., Atsikpasi & Fokides, 2022; Villena-Taranilla et al., 2022), underline the positive direction of imVR's impact on learning.

Nevertheless, a valid consideration that consequently arises is the comparative advantage of imVR against other media or technologies used for educational purposes. The Cognitive Affective Model of Immersive Learning (CAMIL), as proposed by Makransky and Petersen in 2021, offers a robust theoretical framework for understanding the dynamics of learning within imVR environments. CAMIL synthesizes and expands upon the foundational research and theoretical underpinnings from an array of disciplines, including virtual reality, multimedia, educational psychology, and educational technology. This model elucidates the process by which imVR facilitates learning by pinpointing the critical roles played by presence and agency, which it identifies as the core psychological affordances for learning within imVR settings. The model posits that immersion, alongside control factors and representational fidelity, significantly bolsters these key affordances. Furthermore, CAMIL articulates the vital influence of both affective and cognitive factors, namely interest, motivation, self-efficacy, embodiment, cognitive load, and self-regulation, on the learning outcomes achievable through imVR. These outcomes encompass the acquisition of factual, conceptual, and procedural knowledge, as well as the capability for knowledge transfer. According to CAMIL, the level of interaction and immersion attainable through conventional, non-immersive, or less immersive media, such as videos or PowerPoint presentations, is inherently constrained. Conversely, imVR, as well as emerging immersive technologies, substantially enhances these dimensions. As a consequence, presence and agency, which are psychological constructs emanating from both immersion and interaction, are inherently elevated in immersive mediums. In light of these findings, it is unequivocal that instructional methodologies that effectively amplify presence or agency can substantially augment learning via immersive technology. The implications of CAMIL are profound, suggesting that educators and technology designers should prioritize these elements to optimize instructional outcomes through the utilization of imVR and related technologies.

In the realm of research, there have been instances where imVR and dVR have demonstrated equivalent learning outcomes (e.g., Buttussi & Chittaro, 2018: aircraft evacuation training; Cheng et al., 2017: Japanese language learning; Zhao et al., 2018: museum education). Conversely, a multitude of studies have unveiled the superior performance of imVR over other media/technologies (e.g., Checa & Bustillo, 2020: history, Checa et al., 2016: history, Ogbuanya & Onele, 2018: electrotechnics). In addition, an array of studies indicated imVR's possible inferiority in comparison to other technologies across a spectrum of learning subjects (e.g., Makransky et al., 2019: natural sciences, Parong & Mayer, 2021a: biology, Parong & Mayer, 2021b: history). That is probably because imVR may overload and distract learners (Makransky et al., 2019).

The paradox embraced within these findings underlines the lack of a definitive stance on imVR's superiority compared to other instructional technologies. The different learning subjects examined in past research, as well as the different capabilities and specific characteristics of the media/technologies with which imVR was compared (e.g., educational videos, dVR, real world), renders the drawing of concrete conclusions foggy. This issue appears to stem from the fact that the research mostly focused on application development and on examining usability issues, rather than focusing on learning, on learning theories that give support to the use of imVR, and in the use of imVR applications on a regular basis, as indicated in the systematic review of the literature conducted by Radianti et al. (2020). To further substantiate this argument, there are meta-analyses and literature reviews underscoring the benefits of imVR, whereas others exhibit a comparatively minor effect size. For instance, Di Natale et al.'s (2020) examination of 18 studies concluded that imVR has the capacity to facilitate a diverse array of activities and experiences, which, in turn, enhance learning and bolster student motivation. Furthermore, they noted that the primary advantage of imVR is its ability to provide users with first-hand experiences that are unattainable within the constraints of the physical world. This offers unparalleled opportunities for learners to engage in experiential and situated learning scenarios. Similarly, Villena-Taranilla et al. (2022) in their meta-analysis of 21 studies concluded that the effect sizes in imVR were larger compared to semi- or non-immersive VR. In their analysis of 29 articles, Hamilton et al. (2021) discovered that the majority of research underscored a considerable benefit associated with the deployment of imVR within educational contexts, while a minority of the studies did not report any discernible differences in educational outcomes when comparing the effects of immersive and non-immersive instructional strategies.

Yet, Coban et al. (2022), who analyzed 48 studies, concluded that despite the positive impact, the effect size was small, varying based on the education level, academic discipline, and the instructional resources utilized. Similarly, Wu et al. (2020), based on the meta-analytical review of 35 studies, noted that imVR indeed had an upper hand over non-immersive instruction and learning methods, but the effect size was modest. To complicate things even more, in their review, Jensen and Konradsen (2018) supported that imVR's advantages are confined only to certain skills acquisition scenarios. They continued by saying that when contrasted with less immersive technologies or traditional instructional methods, imVR offers no additional benefits and even results in being counterproductive. The causes for this counterproductivity included simulator sickness, technological complications, and instances where the immersive experience distracted users from the primary learning task.

2.2 Factors Related to the Learning Outcomes in imVR

As noted in the "Introduction," several studies have discussed the capacity of imVR to promote more immersive and authentic learning experiences. For example, Jensen and Konradsen (2018) explored the use of imVR in simulating real-life scenarios in engineering education, finding that immersion and engagement levels were significantly enhanced with the use of HMDs. Radianti et al. (2020) concluded that in the context of higher education, the immersive and interactive characteristics of virtual environments foster deep learning, engagement, and collaboration among learners. Allcoat and von Mühlenen (2018) compared text, videos, and imVR. They found increased positive emotions and engagement in the imVR condition. The authors concluded that imVR offers a better learning experience. Enjoyment, positive emotions, interest engagement, and motivation emerged as contributing factors to users' positive learning experience in several other studies and meta-analyses (e.g., Abichandani et al., 2019; Bertrand et al., 2017; Butt et al., 2018; Caro et al., 2018; Huifen et al., 2021; Rupp et al., 2019).

Whilst numerous researchers have scrutinized and deliberated the concept of the learning experience within imVR, the lack of a universally agreed-upon definition of the term "learning experience" creates a degree of ambiguity. Generally, a positive learning experience can be perceived as the process in which an individual acquires knowledge, enhances skills, and experiences personal development, through methods that are both enjoyable and effective. The ultimate goal of a positive learning experience is to instill a passion for continued learning. This occurs when individuals feel a sense of motivation and confidence in their capacity to persist in their learning trajectory and apply newly-acquired knowledge. However, it should be noted that this is entirely subjective, demonstrating considerable variation based on a learner's individual preferences and objectives.

The subjectivity of the term, as well as the subjectivity of the factors defining this term, propelled researchers to investigate a plethora of factors that may have a bearing on an individual's learning experience, hypothesizing that these determinants exert an influence on learning outcomes. Indeed, in a study in which 128 scholarly articles were analyzed, the data revealed that researchers examined more than 200 such factors (Fokides, 2023). Given the impractical nature of incorporating all these factors into a single study, it nonetheless remains feasible to classify them into more comprehensive constructs and/or scrutinize those that were frequently studied. Proceeding along this trajectory, the aforementioned factors may be delineated into three principal constructs that past research considered influential in shaping one's learning experience: (i) the technical affordances of imVR, (ii) factors inherently associated with the learning content, and (iii) the emotional responses of the users.

In examining the first construct, it appears that three primary factors emerge as commonly considered aspects. The first factor pertains to the perceived quality of the graphics of the virtual environment. In the context of imVR, it is rational to presuppose that users would anticipate realistic depictions of these digital spaces. Representational fidelity holds the potential to diminish, if not eradicate entirely, the users' disbelief regarding how "real" the virtual environment is (Mystakidis, 2022). Empirical findings corroborate the presence of a positive relationship between the realism of the virtual environment and an array of factors, including learning outcomes (Kim & Ahn, 2021). The second factor is the users' perceived ease of use and control over the virtual environment. Complicated systems can lead to user disinterest and a tendency to avoid the system's utilization (Fokides, 2023). It is, therefore, suggested that in order for VR to augment learning experiences and exert a significant effect on learning outcomes it must be considered user-friendly (Lee et al., 2010). This is because user-friendliness subsequently facilitates the implementation process, thereby bolstering experiential learning (Asad et al., 2022). The third factor to consider is interaction, as imVR applications are innately interactive. Heightened levels of interactivity present arguably a more holistic experience. This facilitates users' transformation into active learners (Mystakidis, 2022), resulting in a favorable influence on the efficacy of VR/AR applications (Potkonjak et al., 2016).

Examining the second construct, it is evident that not only the visualization of content, but the content per se, notably contributes to shaping an individual's learning experience. As posited by the cognitive load theory, educational material bolsters learning when it exerts minimal stress on working memory. In contrast, if the burden becomes excessive, it could render learning challenging (Sweller, 2020). In the study conducted by Cecotti et al. (2020), it was determined that the cognitive load of imVR applications was considerably low. Furthermore, Armougum et al. (2019) deduced that there was no significant disparity in the cognitive load presented by a virtual environment and its corresponding real counterpart. Mirroring this sentiment, Wenk et al. (2023) inferred that the cognitive load remained consistent across varying visualization technologies. Contrarily, some scholars have proposed that imVR applications could potentially augment cognitive load (Breves & Stein, 2022; Juliano et al., 2022; Makransky et al., 2019; Parong & Mayer, 2021a). Of equal importance to the presentation of information and learning content is the feedback users receive in the form of help screens, text, images, and audio. Feedback aids in guiding users, circumventing confusion surrounding tasks, locating information, and conceptualizing learning objectives. Studies have underscored the importance of feedback in determining the effectiveness of VR and AR applications (Portman et al., 2015; Potkonjak et al., 2016).

Coming to the third construct, it appears to be the most comprehensive. This view is substantiated by the fact that researchers have scrutinized multiple factors connected to emotional responses. Within these factors, immersion is particularly noteworthy as it characterizes imVR. Immersion is related to the affordances of a system to deliver a virtual environment that gives users a sense of reality (Atsikpasi & Fokides, 2022). Closely related to immersion is the feeling of presence which refers to the illusion of "being" in the virtual environment. Both trigger mental and emotional engagement within the virtual environment (Lindgren et al., 2016), resulting in a better understanding of the learning content (e.g., Fokides & Atsikpasi, 2022; Maas & Hughes, 2020). Simulator sickness is the second common factor closely scrutinized pertaining to user experiences in imVR. This condition is characterized by symptoms such as disorientation, nausea, and in more severe cases, vomiting. Understandably, the manifestation of such symptoms is capable of exerting a severe adverse effect on the learning experience, although studies have indicated that the symptoms decrease with visual fidelity (de Winkel et al., 2022). Indeed, the detrimental effect extends not only to the learning outcomes but also to the user's presence and engagement (Atsikpasi & Fokides, 2022; Maraj et al., 2017). This outcome persists even in cases where the symptoms are classified as mild (Hsin et al., 2022). Regardless of whether a learning environment is analog or digital, motivation remains a pivotal contributing factor to a user's learning and overall learning experience. In the context of imVR, it has been noted in several studies that learners exhibit higher levels of motivation (Huifen et al., 2021; Makransky & Lilleholt, 2018; Olmos-Raya et al., 2018; Villena-Taranilla et al., 2019). This might be attributed to the immersive, interactive, and engaging nature of imVR applications, which serve to enhance and reinforce motivation (Barry et al., 2015; Díaz et al., 2020; Erturk & Reynolds, 2020). Finally, enjoyment in imVR for gauging learning experiences has been prevalently employed. The findings suggested that imVR applications are often deemed enjoyable by users (e.g., Büssing et al., 2022; Makransky & Lilleholt, 2018; Makransky & Mayer, 2022; Pallavicini & Pepe, 2019; Parong & Mayer, 2021a). This, in turn, facilitated more efficient learning processes (e.g., Lehikko, 2021; Parong & Mayer, 2021a). Nonetheless, fun and enjoyment are just one aspect of the learning experience; a host of additional facets encapsulated by the notion of positive emotions significantly impact the learning experience in imVR. Among these factors, satisfaction (Kim & Ahn, 2021) and happiness (Ramírez-Correa et al., 2019) were also considered.

In summary, it can be concluded that imVR is utilized across various learning domains, demonstrating an interesting educational potential. Nevertheless, the current studies have shown heterogeneous -if not contradictory- findings regarding its impact on learning compared to other media or technologies. Additionally, it is worth acknowledging that previous literature reviews have consistently identified methodological shortcomings within numerous studies. These deficiencies, including the use of non-randomized trials, limited participant numbers, unbalanced demographic samples, the brevity of study periods, a restricted scope limited to scientific subjects, and the employment of non-validated instruments, have notably impeded the extrapolation of their results to wider contexts (Di Natale et al., 2020; Hamilton et al., 2021). These research gaps create significant opportunities for further investigation in this field. Additionally, as previously noted, the learning outcomes associated with imVR are influenced by a multitude of factors. These include graphics quality, cognitive load, ease of use, immersion, feedback and content quality, degree of interaction, motivation, and the enjoyment and positive emotions induced by the technology, as well as symptoms of simulator sickness. The extensive array of factors contributing to learning outcomes introduces a certain level of uncertainty regarding the relative impact of each factor. This complexity is further compounded by the tendency of researchers to focus on a select few factors based on their individual preferences, making it challenging to draw definitive conclusions about their specific impacts (Atsikpasi & Fokides, 2023).

3 Method

In light of the findings presented in the previous sections, a decision was made to examine more systematically whether imVR has a measurable impact on learning outcomes, and if these results supersede (or fall below) those achieved using conventional digital media, such as web pages. Furthermore, due to its close association with imVR (yet, considerably less immersive), dVR was included as a third media/technology. The inclusion of dVR was anticipated to enhance the discernment of tangible benefits associated with imVR. Moreover, to further this objective, it was deemed crucial to analyze user perspectives concerning their learning satisfaction and subsequent levels of learning experiences. As mentioned earlier, though past research examined factors that shape the learning outcomes in imVR, the simultaneous examination of several of them was not that common. For that matter, it was decided to examine ten factors that were theorized to shape learning satisfaction and learning experience, discussed in the previous section. This led to the formation of the following research questions:

- RQ1. Are the learning outcomes using imVR superior compared to those achieved through dVR and web pages?
- RQ2-11. Do the participants perceive that imVR offers enhanced graphics quality (RQ2), reduced cognitive load (RQ3), improved ease of use and control of the application (RQ4), increased immersion (RQ5), better feedback and content quality (RQ6), better interaction (RQ7), increased motivation (RQ8), causes less simulator sickness symptoms (RQ9), and more positive emotions (RQ10), compared to dVR and web pages?
- RQ11. Which of the aforementioned factors influence the learning outcomes in imVR, dVR, and web pages?

The chosen research design was that of within-subjects with three treatments/conditions, as the participants interacted with three media/technologies, specifically an imVR application, a dVR application, and web pages. The rationale for selecting this particular design was as follows: (i) it requires smaller sample sizes without compromising the validity of the results, (ii) it evades the confounding effects of individual differences since each treatment involves the same subjects, and (iii) the participants act as their own controls, eliminating the concern of variance among groups (Keren, 2014). To counterbalance the disadvantages of the within-subjects design, various preventative measures were implemented. To safeguard against the fatigue effect (participants' loss of interest due to their previous activities), all sessions for each participant were scheduled at the same time and day. The carryover and context effects were mitigated by randomizing media usage and preventing participants from knowing which medium they would engage with in each session. The significant drawback of this research design, namely the practice effect, was also addressed. As the repetition of learning material across all conditions could positively impact subsequent outcomes since participants have potentially learned previously, the learning material for each condition was different but equitable. This issue will be discussed more comprehensively in the section "Materials and apparatus."

3.1 Participants and Sample Size

The sample size and the target group warranted significant consideration in this study. An a priori power analysis was executed to address the former issue. G*power was utilized to detect small effect sizes with ample power. Following Cohen's (2013) guidelines, for a within-subjects design with three conditions, a f_{Cohen} of 0.14 (corresponding to η^2=0.02-representing a small effect size), a power of 0.90, and a probability error of 0.05, an estimated sample size between the range of 67 to 153 participants was projected, depending on the correlation among the repeated measures (values from 0.3 to 0.7 were employed, with the default value of 0.5 implying a sample size of 110 participants).

Concerning the target group, there exists no comprehensive demographic data related to the characteristics of users of imVR educational applications. Nonetheless, it was hypothesized that the majority would be educators or students circa twenty years of age. This assumption is drawn from the fact that most applications of relevance are targeted at adolescents or young adults, while the majority of studies are centered on university or college students, as highlighted by recent literature reviews on the educational applications of imVR and Metaverse in general (Alfaisal et al., 2022; Atsikpasi & Fokides, 2022; Tlili et al., 2022). Given these assumptions, it was deemed rational to target students studying at a Department of Primary Education, who not only fall into the aforementioned age group but also represent future educators. A call for participation directed at students from the Department of Primary Education at the University of (name has been omitted for the review) was disseminated on social media, enumerating the study's objectives and procedures. There was no prerequisite experience in using HMDs or imVR applications required for enrollment. A total of 103 participants enrolled, nearing the desired sample size. The university's ethical committee approved the project, and informed consent was obtained from all participants.

3.2 Materials and Apparatus

The selection of educational material and appropriate applications for the study was a topic necessitating thoughtful deliberation. The primary concern revolved around the suitable applications to be employed for the imVR and dVR conditions. Though a multitude of applications exist, few are available in Greek and an even smaller subset are not excessively complex, highly specialized -particularly in the context of their learning subject- or demand considerable time to complete. This issue was addressed in the pilot study by crafting a custom-made application focused on ancient Greek inventions as the subject of learning. Given the positive feedback and constructive experience gained, it was decided to further augment the application by adding more inventions. Concurrently, web pages were crafted to present the inventions in the relevant condition. As an outcome, twelve inventions were included across all three conditions, as presented in Table 1; Figs. 1 and 2.

For the imVR and dVR conditions, the development process was essentially as follows. Given the absence of available 3D models of the inventions, they were developed from scratch. With input from relevant ancient texts, published work, and museum exhibits, considerable effort was invested to ensure accurate reconstruction. The resultant models were fully interactive, allowing users to experience their functionality. For instance, in Heron's automatic holy water server, users could insert a coin, observe water filling the disk, and simultaneously witness the mechanism as it became transparent, enhancing their understanding of its functioning. The application also included a selection area where users could choose the invention they wished to view. All inventions were situated in a virtual outdoor environment. Information buttons were incorporated which when activated, displayed explanatory text, images, and audio narratives elucidating the functioning of the invention along with contextual facts regarding its inventor and historical relevance. Close to each invention, its parts were displayed to afford users a detailed view.

For the utilization of the application in the imVR condition, the Meta Quest 2 HMD was the chosen device. Its affordability coupled with its commendable technical specifica-

Table 1 The learning material/ inventions per medium

Type of invention	Immersive VR	Desktop VR	Web pages
For demonstration/ amazement	Heron's aeolosphere	Heron's hovering sphere	Archytas's flying pigeon
Weapons	The flamethrower of the Boeotians	Archimedes's steam cannon	Dionysius's of Alexandria repeating catapult
Communication	Kleoxenos's and Dimokleitos's phryctoria (a telecommunication system using fire signals)	Aeneas's hydraulic telegraph	Aeneas's cryptographic disk
Automation	Heron's automatic opening of the temple gates after a sacrifice had taken place on its altar	Heron's automatic holy water server with coin-collector	Heron's sound alarm

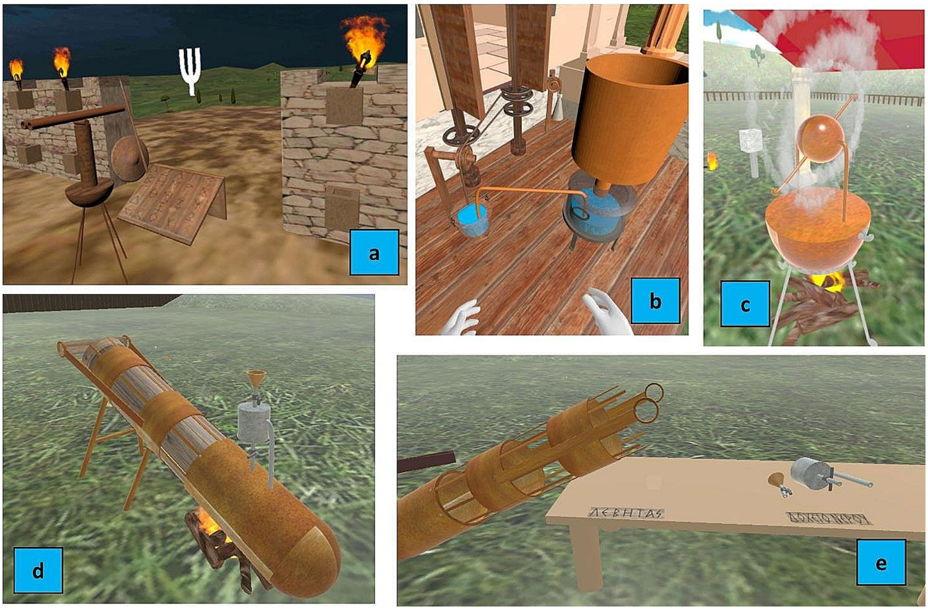

Fig. 1 Screenshots from the dVR and imVR applications. a: the phryctoria, b: the automatic opening of the temple gates, c: the aeolosphere, e: Archimedes's steam cannon, d: the steam cannon, and e: a disassembled invention

Fig. 2 Screenshots from the web pages

tions makes it an attractive option for the average consumer aiming to experience imVR. Unfortunately, it is untethered (i.e., not linked to a computer). Although this ensures fewer cables and enhanced freedom of movement, the graphic quality suffers due to the limited processing power of the headset, which must house numerous electronics in a constrained space. The experiment was conducted in a spacious office with an area of approximately $40m^2$. This precaution was taken to avoid potential injuries from participants bumping into furniture or walls and to allow for actual walking as opposed to relying on the headset's controllers for emulating movement; it was hypothesized that this approach would offer a more immersive experience and potentially mitigate simulator sickness symptoms.

Regarding the dVR and web conditions, participants utilized computers equipped with 27-inch monitors.

To further enhance data validity and address issues associated with within-subjects research design, certain measures were implemented in addition to those outlined under the "Method" section. Of paramount importance was ensuring the equipotency of the learning material across all inventions. Despite differences in information for each invention, equivalent attributes existed in terms of quantity and quality of information (e.g., in all the inventions there was the same number of dates, names, and places, the word count was approximately the same, and the same number of images was included). To increase the data validity, each participant selected and examined two inventions per medium and was subsequently tested twice on the acquired knowledge using the evaluation tests detailed in the subsequent section. Furthermore, the inventions were organized into four categories. When a participant chose to view a particular invention in imVR, they were obligated to view inventions from the same category in the remaining two mediums. This method was chosen to ensure consistent contextual information across all media.

3.3 Instruments

In order to collect data pertinent to the learning outcomes, twelve evaluation tests were specifically designed, mirroring the number of inventions that were available for viewing. The test given to a participant was contingent upon the invention viewed by them. As with the learning material, measures were taken so that the difficulty level to be the same in all tests. Specifically, they followed the same logic and structure and all had ten multiple-choice questions of escalating difficulty. Half of them corresponded directly with the information presented within images, texts, and audio narrations. For example, there were questions regarding the historical period in which the inventor lived, the purpose the invention served, and details related to the inventor's life. The remaining questions were related to information that a participant could infer indirectly by interacting with the inventions and their parts, or by looking at the images (depending on the medium used). For instance, in the latter scenario, participants were asked to identify the materials utilized in the inventions or their components, approximate their dimensions, arrange the operational steps in the correct sequence, and make estimates about their range and/or velocity (e.g., in the situations involving the flamethrower of Boeotians and the Heron's aeolosphere).

A questionnaire was deployed to gather data concerning the participants' learning experiences and levels of learning satisfaction. It included the items present in the (name has been omitted for review) scale. This scale was expressly conceived to capture users' learning experiences across diversified Metaverse applications, inclusive of imVR (Fokides, 2023). Having 40 items in total, it scrutinizes the ten factors incorporated in this particular study: simulator sickness (six items), perceived cognitive load (three items), motivation (six items), perceived ease of use/control of the virtual environment (three items), immersion/presence (six items), perceived quality of graphics (six items), perceived feedback and content quality (three items), perceived degree of interaction (three items), and positive emotions (four items). The scale is presented in the Appendix. In addition, a further two items were added with the intent of recording additional demographic details of the participants, namely their gender and age. Both the evaluation tests and the questionnaire were made accessible online via Google Forms.

3.4 Procedures

The experiments were executed as part of an extracurricular activity, deliberately devoid of any formal teaching. This strategic approach was adopted to ensure an unobstructed analysis of the media's intrinsic effects. Had any instructional activities been intertwined with the applications or website usage, it would have significantly complicated the task of isolating the media's influence from that of the pedagogical strategies employed. Consequently, the decision to exclude teaching was both deliberate and critical, allowing for a clear attribution of the observed outcomes solely to the media in question.

As stated in the "Method" section, measures were put in place to counteract the potential fatigue effect, that is, the diminution of participants' interest attributable to their previous activities. To this end, all sessions for each participant were scheduled to occur at a uniform time and day. Furthermore, to minimize the carryover and context effects the media usage was randomized and the participants were not aware with which media they would interact in any given session. The above were accomplished by generating a randomized sequence for each participant to engage with the three distinct media types under investigation. Following this randomization, an appointment schedule was crafted, tailored to each participant. Given that the study design necessitated each participant's interaction with three media, three sessions were arranged, each to take place at an identical time and day across three successive weeks. For example, if a participant's initial appointment was for Monday at 11:00 AM, the subsequent appointments were also set for the following two Mondays at the same hour.

In the imVR condition, each participant was welcomed and subsequently provided with oral instructions detailing what to expect and how to navigate and interact within the application. The HMDs were then distributed to them. After making necessary adjustments to the straps and interpupillary distance to optimize image quality, the participants were granted a period of fifteen to twenty minutes to familiarize themselves with the welcoming space and available menus after activating the headsets. They also received guidance on handling potential encounters with the "play" area boundaries (the operating system of the HMDs informs users when they leave this area, in order to avoid accidents). This initial procedure was important, considering the participants had no prior exposure to imVR and VR devices.

The ensuing step involved the participants launching the application and choosing from the landing space the invention they wished to observe. An estimated timeframe of twenty to twenty-five minutes was provided for this, a duration deemed sufficient for a comprehensive experience and review of pertinent learning materials. Additional instructions were given to participants facing significant difficulties with navigation and interaction. Following that, an evaluation quiz was administered. The entire procedure was then repeated for a second invention.

After this, the questionnaire was administered, a task requiring approximately fifteen minutes to complete. As already mentioned, the scale and tests were accessible online. For that matter, the participants used laptops, available in a nearby office. The whole procedure demanded slightly less than two hours per participant. Forecasting instances of severe simulator sickness, participants were instructed to discontinue application usage, remove their headsets, and rest. However, those with minor or mild symptoms were given the liberty to continue or terminate the experiment. Regardless of their decision, all participants were subjected to both the quizzes and questionnaire, based on the hypothesis that simulator sickness significantly impinges on the learning experience and learning outcomes.

A comparable procedure was employed for the dVR and the web pages conditions, with the omission of the familiarization period. Some instructions for navigating and interacting with the dVR application were provided, given that just the mouse was used for navigating and interacting with it. In contrast, no directions were necessary for the web pages as participants were already conversant with their operation.

4 Results

Out of the 103 participants, 78 (72.8%) were females, while the vast majority of them belonged to the 18–24 years-old age group ($n=87$, 84.5%). Their evaluation tests were graded on a 10-point scale and three new variables were calculated representing participants' average score in the evaluation tests in each medium. The resulting data together with the data from the scale questionnaires were inserted into SPSS 29 for all the analyses presented in the coming paragraphs. The questionnaires' internal consistency was checked using Cronbach's alpha. Given that α was in all cases (either for the questionnaires as a whole or for the factors comprising them) above the widely used threshold of 0.70 (Taber, 2018), it was concluded that there were no issues regarding the questionnaires' internal consistency. Following that, thirty new variables were calculated (ten for each medium), representing the average score per factor per participant. Table 2 presents the descriptive statistics for the study's variables.

To examine the differences in the results each medium produced and for answering RQ1 to RQ10, a series of within-subjects Analysis of Variance (ANOVA) tests were deemed appropriate. Then again, as there were issues related to the normal distribution of the data, it was decided to proceed using Friedman's Two-Way Analysis of Variance by Ranks test, which is the non-parametric equivalent of the within-subjects ANOVA, followed by Wilcoxon's Signed Ranks Tests (using the Bonferroni correction, which controls for Type I errors) for post-hoc pairwise comparisons (Table 3).

For answering RQ11, three multiple regression analyses were run (one for each medium), using the results in the evaluation tests as dependent variables and the questionnaires' factors as independent ones (Table 4).

- RQ1. The learning outcomes produced by the imVR application were better only when compared to the ones produced by the web pages, while the effect size was small ($\chi^2=2.47$, $p_{Adj.}=0.040$, $\eta^2=0.021$-small). There were no differences neither between the imVR and dVR applications ($\chi^2=1.29$, $p_{Adj.}=0.592$), nor between the dVR application and web pages ($\chi^2=1.18$, $p_{Adj.}=0.709$).
- RQ2. The graphics in the imVR application were considered better compared to both the dVR application ($\chi^2=3.52$, $p_{Adj.}=0.001$, $\eta^2=0.078$-medium) and web pages ($\chi^2=7.46$, $p_{Adj.}<0.001$, $\eta^2=0.154$-large). Moreover, the graphics in the dVR application were considered better than the ones in web pages ($\chi^2=3.94$, $p_{Adj.}<0.001$, $\eta^2=0.088$-medium).
- RQ3. The participants' perceived cognitive load in the imVR application was the same as the one in both the dVR application ($\chi^2=-0.94$, $p_{Adj.}=0.999$) and web pages ($\chi^2=1.88$, $p_{Adj.}=0.180$). On the other hand, the cognitive load in the dVR application was statistically significantly less than that in web pages ($\chi^2=2.82$, $p_{Adj.}=0.014$, $\eta^2=0.027$-small).

Table 2 Descriptive statistics for the study's variables

Variable (N=103)	Immersive VR		Desktop VR		Web pages	
	M	SD	M	SD	M	SD
Evaluation tests	5.99	1.59	5.78	2.04	5.39	1.84
Graphics	4.51	0.62	4.11	0.80	3.55	1.00
Cognitive load*	4.30	0.81	4.34	0.94	4.04	0.93
Control	3.92	0.88	3.58	0.92	3.40	1.19
Immersion	3.78	0.94	2.45	1.06	1.92	1.12
Feedback/Content	4.28	0.66	4.11	0.76	3.90	0.84
Interaction	4.27	0.66	3.45	0.95	2.86	1.03
Motivation	4.34	0.80	3.76	0.91	3.31	1.13
Simulator sickness	1.36	0.56	1.11	0.34	1.07	0.32
Positive emotions	4.12	0.97	3.36	1.19	2.86	1.32

Note. * = As the responses in the factor's items were reverse-coded, higher values indicate less cognitive load

Table 3 The results of the related-samples Friedman's two-way analysis of Variance by ranks tests and Wilcoxon's pairwise comparisons

Variable	Friedman's test (N=103, df=2)		Pairwise comparisons								
			Web-dVR			Web-imVR			dVR-ImVR		
	χr^2	p	Std.χ^2	$p_{Adj.}$	η^2	Std.χ^2	$p_{Adj.}$	η^2	Std.χ^2	$p_{Adj.}$	η^2
Evaluation tests	6.89	0.032	1.18	0.709	0.009	2.47	0.040	0.021	1.29	0.592	0.002
Graphics	72.54	<0.001	3.94	<0.001	0.088	7.46	<0.001	0.154	3.52	0.001	0.078
Cognitive load	11.69	0.003	2.82	0.014	0.027	1.88	0.180	0.019	-0.94	0.999	0.004
Control	13.33	0.001	1.25	0.629	0.010	3.34	0.002	0.042	2.09	0.110	0.036
Immersion	104.71	<0.001	3.94	<0.001	0.093	9.75	<0.001	0.212	5.82	<0.001	0.192
Feed/Content	19.00	<0.001	2.02	0.130	0.023	3.73	0.001	0.61	1.71	0.263	0.017
Interaction	89.13	<0.001	4.01	<0.001	0.076	8.85	<0.001	0.202	4.84	<0.001	0.137
Motivation	62.90	<0.001	2.33	0.059	0.051	6.86	<0.001	0.144	4.53	<0.001	0.101
Sim. sickness	63.855	<0.001	0.84	0.999	0.006	5.44	<0.001	0.116	4.60	<0.001	0.102
Pos. emotions	72.22	<0.001	3.24	0.004	0.061	7.84	<0.001	0.168	4.60	<0.001	0.112

Notes. Web=Web pages; dVR=desktop VR; imVR=Immersive VR; χr^2=Friedman's test statistic; *Std.* χ^2=Std. test statistic; $p_{Adj.}$ = p value adjusted by the Bonferroni correction for multiple tests; η^2=eta squared effect size

- RQ4. The imVR application was considered easier to use/control compared to web pages (χ^2=3.34, $p_{Adj.}$ = 0.002, η^2=0.010-small), but there were no differences between the imVR and dVR applications (χ^2=2.09, $p_{Adj.}$ = 0.110). Moreover, there were no differences regarding the ease of use/control, between the dVR application and web pages (χ^2=1.25, $p_{Adj.}$ = 0.629).
- RQ5. The imVR application offered a more immersive experience compared to both the dVR application (χ^2=5.82, $p_{Adj.}$ < 0.001, η^2=0.192-large) and web pages (χ^2=9.75, $p_{Adj.}$ < 0.001, η^2=0.212-very large). In addition, the dVR application was more immersive than web pages (χ^2=3.94, $p_{Adj.}$ < 0.001, η^2=0.093-medium).
- RQ6. The quality of the feedback and content of the imVR application were considered better when compared to web pages (χ^2=3.73, $p_{Adj.}$ < 0.001, η^2=0.061-medium), but not when compared to dVR application (χ^2=1.71, $p_{Adj.}$ = 0.263). There were also no differences between the dVR application and web pages concerning this factor (χ^2=2.02, $p_{Adj.}$ = 0.130).
- RQ7. The imVR application was considered more interactive compared to both the dVR application (χ^2=4.84, $p_{Adj.}$ < 0.001, η^2=0.137-large) and web pages (χ^2=8.85, $p_{Adj.}$ < 0.001, η^2=0.202-very large). Also, the dVR application was considered more interactive compared to web pages (χ^2=4.01, $p_{Adj.}$ < 0.001, η^2=0.076-medium).
- RQ8. The imVR application was considered more motivating compared to both the dVR application (χ^2=4.53, $p_{Adj.}$ < 0.001, η^2=0.101-medium to large) and web pages (χ^2=6.89, $p_{Adj.}$ < 0.001, η^2=0.144-large). Also, there were no differences between the dVR application and web pages (χ^2=2.33, $p_{Adj.}$ = 0.059).
- RQ9. The imVR application proved to cause more simulator sickness symptoms compared to both the dVR application (χ^2=4.60, $p_{Adj.}$ < 0.001, η^2=0.102-medium to large) and web pages (χ^2=5.44, $p_{Adj.}$ < 0.001, η^2=0.116-medium to large). There were no differences between the dVR application and web pages (χ^2=0.84, $p_{Adj.}$ = 0.999).
- RQ10. The participants in the imVR application had more positive emotions compared to both the dVR application (χ^2=4.60, $p_{Adj.}$ < 0.001, η^2=0.112-medium to large) and

Table 4 Results of the regression analyses

	Model summary	$F(10, 92)=6.96, p<.001, R=.656, R^2=0.431$				
	Factors	***B***	***SE B***	***β***	***t***	***p***
Immersive VR	Graphics	-0.63	0.28	−0.25	-2.27	0.026
	Cognitive load	0.05	0.17	0.02	0.28	0.777
	Control	0.15	0.17	0.08	0.87	0.387
	Immersion	1.01	0.18	0.59	5.73	<0.001
	Feedback/Content	0.36	0.26	0.15	1.35	0.180
	Interaction	0.01	0.29	0.004	0.04	0.971
	Motivation	-0.24	0.21	−0.12	-1.19	0.239
	Sim. sickness	-0.60	0.24	−0.21	-2.56	0.012
	Pos. emotions	0.36	0.15	0.22	2.45	0.016
Desktop VR	Model summary	$F(10, 92)=2.06, p=.036, R=.428, R^2=0.183$				
	Factors	***B***	***SE B***	***β***	***t***	***p***
	Graphics	0.02	0.31	0.01	0.05	0.957
	Cognitive load	0.41	0.22	0.19	1.87	0.064
	Control	-0.33	0.25	−0.15	-1.30	0.196
	Immersion	-0.45	0.27	−0.23	-1.69	0.094
	Feedback/Content	0.58	0.44	0.22	1.34	0.185
	Interaction	0.39	0.35	0.18	1.12	0.267
	Motivation	-0.03	0.31	−0.01	-0.10	0.919
	Sim. sickness	-0.40	0.63	−0.07	-0.63	0.530
	Pos. emotions	-0.34	0.21	−0.20	-1.67	0.098
Web pages	Model summary	$F(10, 92)=1.58, p=.126, R=.382, R^2=0.146$				
	Factors	***B***	***SE B***	***β***	***t***	***p***
	Graphics	-0.14	0.28	−0.077	-0.51	0.614
	Cognitive load	0.16	0.20	0.079	0.77	0.445
	Control	-0.004	0.21	−0.003	-0.02	0.984
	Immersion	-0.49	0.26	−0.299	-1.88	0.063
	Feedback/Content	-0.56	0.34	−0.257	-1.68	0.096
	Interaction	0.11	0.31	0.060	0.34	0.733
	Motivation	-0.22	0.28	−0.133	-0.76	0.450
	Sim. sickness	0.37	0.59	0.064	0.63	0.532
	Pos. emotions	0.05	0.22	0.035	0.22	0.825

Notes. B=unstandardized beta coefficient, *SE B*=standard errors for *B*, *β*=standardized error coefficient

From the above tables it can be inferred that [please note that for the interpretation of the effect sizes, the following cutoff values were used: 0.010-small effect size, 0.059-medium effect size, 0.138 or higher-large effect size (Cohen, 2013)]:

web pages (χ^2=7.84, $p_{Adj.}$ < 0.001, η^2=0.168-large). The same applied for the dVR application compared to web pages (χ^2=3.24, $p_{Adj.}$ = 0.004, η^2=0.061-medium).

- RQ11. The factors that had a positive impact on the learning outcomes of the imVR application were immersion (t=5.73, p<.001) and positive emotions (t=2.45, p=.016). Then again, the graphics' quality (t = -2.27, p=.026) and simulator sickness (t = -2.56, p=.012) had a negative impact. There were no factors affecting the learning outcomes in the dVR application. As for the web pages, the learning outcomes were positively affected only by the perceived learning effectiveness (t=3.18, p=.002).

5 Discussion

The analyses of data procured from evaluation tests and questionnaires revealed insights necessitating deeper discussion. To facilitate this, this section is structured in three parts beginning with a discourse on the learning outcomes, followed by the discussion of the questionnaire's factors, and, finally, the impact of the factors on learning is examined.

5.1 Comments on the Learning Outcomes

In relation to the learning outcomes examined in this study, the findings suggest that across all media, participants were able to answer correctly between 5.5 and 6 out of ten questions (see Table 2). Although this may appear unimpressive, it is important to note that this should not be seen as disappointing. The assumption was that it was highly unlikely for participants to have had any prior knowledge of the inventions due to the lack of relevant information being included in the curricula across all educational levels. What is more, the results demonstrated that imVR yielded superior outcomes when juxtaposed with web pages ($\chi^2=2.47$, $p_{Adj.}$ = 0.040, $\eta^2=0.021$), albeit not when compared with dVR ($\chi^2=1.29$, $p_{Adj.}$ = 0.592). In the context of imVR, the information presentation can be described as compelling due to the users' experiencing severance from reality and immersion into a highly interactive virtual environment, facilitated by HMDs (Dolezal et al., 2020; Fokides & Atsikpasi, 2022; Tacgin & Dalgarno, 2022). Conversely, dVR offers a less engrossing presentation of information due to its users not experiencing immersion to the same degree as with imVR, that the environment is presented through a monitor and interactions are implemented using keyboard and mouse commands. On web pages, information delivery typically includes the use of text, images, audio, and videos via a conventional website interface. Given the above observations, the hypothesis that learning outcomes would be superior in imVR may appear plausible. However, the current study results do not entirely corroborate this suggestion, showing the impact of the three media on learning to be roughly equivalent. Despite a statistical significance supporting imVR's superiority over web pages, it holds marginal character ($p=.040$), while the effect size was small ($\eta^2=0.021$). The difference between imVR and dVR was not statistically significant, as was the case between dVR and web pages. Given the above, the study's results find congruity with meta-analyses which have acknowledged a positive influence yet minimal effect size on learning as compared to other media (Coban et al., 2022; Wu et al., 2020).

Consequently, it is crucial to consider the reasons leading to this outcome. It must be recalled that certain learning content, including facts about the invention, its inventor, and the historical context, was conveyed across the three media through images, texts, and audio (in the cases of imVR and dVR). Therefore, there were essentially no disparities in the presentation of this part of the learning content in the three media. In this regard, it is entirely rational not to anticipate a significant fluctuation in the scores of the related questions in the evaluation tests. The primary difference, however, was that in imVR and to a lesser degree in dVR, the participants had the opportunity to interact with the inventions and observe their function. By engaging in this manner, participants could potentially have gained indirect knowledge not easily sourced from the web pages. Consequently, this could have resulted in superior performances in related question sections of the evaluation tests, thereby giving imVR a slight edge over web pages. In fact, several pieces of scholarly literature suggest that when it comes to experiential learning, behaviors, and skills, imVR proves to be substantially more effective than other media or technologies (Çakiroğlu & Gökoğlu, 2019; John et al., 2017; Lohre et al., 2020; Koutitas et al., 2019). It is also possible that immersion played a role, as it will be elaborated in a coming paragraph.

5.2 Comments on the Factors Examined in the Questionnaires

The results from the analysis of the questionnaires revealed a predominance of imVR in the perceived graphics' quality factor, compared to dVR (χ^2=3.52, $p_{Adj.}$ = 0.001, η^2=0.078-medium) and web pages (χ^2=7.46, $p_{Adj.} < 0.001$, η^2=0.154-large). This outcome affirms the results from similar studies (e.g., Casu et al., 2015; Mohamed & Örmecioğlu, 2022). Although anticipated based on prior literature, the finding is intriguing considering that both the imVR and dVR applications utilized the same graphics, sound effects, and levels of detail. However, the participants perceived the imVR application graphics to be superior. The paradoxical finding could be attributed to the impact of immersion that prompted users to perceive the 3D graphics differently, leading to the misconception that they were superior in imVR. The impact of immersion will be further elaborated in a coming paragraph.

Turning the attention to the perceived cognitive load, the study found no statistically significant differences when imVR was juxtaposed with dVR (χ^2 = -0.94, $p_{Adj.}$ = 0.999 and web pages (χ^2=1.88, $p_{Adj.}$ = 0.180). Interestingly, it was found that the cognitive load was less in dVR when compared to that of web pages (χ^2=2.82, $p_{Adj.}$ = 0.014, η^2=0.027-small). The finding concerning imVR aligns with similar research conducted in the field of VR (e.g., Wenk et al., 2023). The same concurrence applies to the finding concerning dVR (e.g., Huang et al., 2020). However, a body of research, such as that of Breves and Stein (2022), Juliano et al. (2022), and Parong and Mayer (2021), reported a higher cognitive load in imVR. The current literature on this matter is insufficient. A majority of the studies examined the cognitive load in imVR, but did not compare it with other media (e.g., Albus et al., 2022; Bueno-Vesga et al., 2021; Collins et al., 2019). This lack of comparison, while making the research simpler to handle, less time-intensive, and cost-effective, creates a gap in our understanding. The difference between dVR and web pages might be due to the different presentation formats. While audio, text, and images were used in dVR, only the latter two were featured on web pages. On the basis of the Cognitive Theory of Multimedia Learning, as well as principles deriving from it (Mayer, 2006), this could possibly explain the lesser cognitive load in dVR when compared to web pages. However, these reasons do not account for the lack of differences between imVR and web pages. Hence, it is plausible that other factors influenced these results, or perhaps it was a circumstantial finding.

Interestingly, the imVR application was deemed easier to use compared to web pages (χ^2=3.34, $p_{Adj.}$ = 0.002, η^2=0.010-small), and considered on par with the dVR application (χ^2=2.09, $p_{Adj.}$ = 0.110). This observation aligns with previous research findings (e.g., Miura et al., 2018; Butt et al., 2018; Fokides, 2023). The latter finding is also in agreement with the study by Pallavicini et al. (2019). Although comparative studies between imVR and other media are limited, it is noteworthy that these observations came as a positive surprise. This is because web page navigation and usage are generally believed to be substantially easier than those in imVR, especially for inexperienced users like those who participated in this study. The instructions and assistance provided to the users, combined with the familiarization time they were allowed to have, could have greatly contributed to these results. Additionally, careful measures were taken to ensure the imVR application was as user-friendly as possible. For instance, users were able to physically walk instead of using the controller joysticks.

As anticipated, users experienced greater immersion with the imVR application, compared to both the dVR application (χ^2=5.82, $p_{Adj.}$ < 0.001, η^2=0.192-large) and web pages (χ^2=9.75, $p_{Adj.}$ < 0.001, η^2=0.212-very large). It was also predicted and subsequently confirmed that the dVR application was more immersive than web pages (χ^2=3.94, $p_{Adj.}$ < 0.001, η^2=0.093-medium). These findings coincide with similar research in the field of VR (e.g., Fokides, 2023; Makransky, & Mayer, 2022; Nicolaidou et al., 2023; Zhao et al., 2018). It follows that users would achieve higher immersion levels in imVR, given that it completely isolates them from the physical environment and immerses them in a 3D virtual world. It is not inconsistent for imVR to surpass web pages in terms of immersion, as they lack immersive features, such as 3D graphics and heightened user interaction. One could argue that, in comparison to other media, imVR likely provides a first-person experience (Fokides & Atsikpasi, 2022). Immersion and presence can trigger mental and emotional engagement within the virtual environment (Lindgren et al., 2016). This engagement can foster self-directed learning experiences (Jeon & Jung, 2021), and coupled with the option for repeating an application on demand, assist users in better comprehending the learning content (Maas & Hughes, 2020), leading to improved learning outcomes (e.g., Atsikpasi & Fokides, 2022; Jeon & Jung, 2021; Maas & Hughes, 2020).

The feedback and content quality of the imVR application were perceived to be superior when compared with web pages (χ^2=3.73, $p_{Adj.}$ < 0.001, η^2=0.061-medium); however, this superiority was not apparent when a comparison was made with the dVR application (χ^2=1.71, $p_{Adj.}$ = 0.263). Differences were not observed between the dVR application and web pages with regard to this factor (χ^2=2.02, $p_{Adj.}$ = 0.130). As with other factors, there is a scarcity of research addressing feedback and content quality within the realm of imVR. Nevertheless, feedback has been highlighted as a crucial factor for the efficacy of VR and AR applications in various studies, such as those by Portman et al. (2015) and Potkonjak et al. (2016). It should be noted that the results of this particular study cannot be construed as paradoxical, as both imVR and dVR applications exhibited considerable similarity in the feedback aspect. Given the aforementioned fact, an absence of statistically significant differentiation was an anticipated outcome. Concerning the disparity between imVR and webpages, factors such as the level of immersion may have contributed. It is plausible to argue that the immersive experience offered by the virtual world enhances the perception of feedback quality as participants are more engaged in the experience.

When examining perceived interaction, it was discerned that the imVR application outperformed both the dVR application (χ^2=4.84, $p_{Adj.}$ < 0.001, η^2=0.137-large) and web pages (χ^2=8.85, $p_{Adj.}$ < 0.001, η^2=0.202-very large). Conversely, the dVR application was deemed more interactive than web pages (χ^2=4.01, $p_{Adj.}$ < 0.001, η^2=0.076-medium). Regrettably, there were no comparable studies found to comment on this specific factor. The pertinent search yielded studies that either did not compare media or explored different interface systems within the framework of imVR. Despite the absence of comparative studies, interaction is emerging as a critical factor in imVR. Modern systems indeed offer numerous interaction possibilities with the virtual environment, such as free movement in space, the ability to touch and grasp objects, and tactile feedback as highlighted in previous research (Atsikpasi & Fokides, 2022; Maereg et al., 2017). Such interactions arguably offer a more holistic experience, as showcased by others (Mystakidis, 2022; Portman et al., 2015; Potkonjak et al., 2016). In contrast, interaction on web pages is limited to clicking on hyperlinks. Consequently, the findings of this study align more or less with expectations.

In accordance with other studies (e.g., Di Natale et al., 2020; Huifen et al., 2021; Makransky, & Lilleholt, 2018; Olmos-Raya et al., 2018; Villena-Taranilla et al., 2019), it was observed that participant motivation was higher while using the imVR application rather than when utilizing the dVR application ($\chi^2=4.53$, $p_{Adj.} < 0.001$, $\eta^2=0.101$-medium to large) or web pages ($\chi^2=6.89$, $p_{Adj.} < 0.001$, $\eta^2=0.144$-large), with no discernible differences in motivation found between the usage of the latter two media ($\chi^2=2.33$, $p_{Adj.} = 0.059$). This finding can be potentially attributed to the immersive, engaging, and dynamic learning environment that the imVR application offers, facilitating experiences that reinforce user motivation (Erturk & Reynolds, 2020). Research indicated that qualities such as immersion, interaction, and enjoyment, which are generated by the usage of imVR applications, serve to enhance motivation by promoting active learning (Barry et al., 2015; Díaz et al., 2020) and by offering first-hand experiences and situated learning (Huifen et al., 2021). A notable point, albeit not encompassed in the results as it was not recorded by the instruments used, was the participants' heightened motivation as displayed by their willingness to re-engage with the imVR application and their recommendations on its usage across various other disciplines. This interest could potentially be attributed to the excitement drawn from the imVR application usage. However, the dVR application and web pages, classified as more "conventional" media, were not as successful in stirring enthusiasm.

It was anticipated participants to experience simulator sickness in imVR but not in the other media. Indeed, the obtained results affirmed this hypothesis ($\chi^2=4.60$, $p_{Adj.} < 0.001$, $\eta^2=0.102$-medium to large when comparing imVR and dVR; $\chi^2=5.44$, $p_{Adj.} < 0.001$, $\eta^2=0.116$-medium to large when comparing imVR and web pages), corroborating the findings of similar empirical studies in the field of imVR (e.g., Cao et al., 2020; Porter et al., 2018; Selzer et al., 2019, Zhao et al., 2020). However, as denoted by the mean in this factor (refer to Table 2), the severity of the symptoms appeared to be comparatively mild. The plausible explanation for this outcome is that during the development of the imVR application, particular provisions were implemented to substantially minimize the manifestation of simulator sickness. As noted in a preceding paragraph, users were given the option to walk, instead of using the controller joysticks. Therefore, it could be asserted that the primary cause of simulator sickness, namely the conflicting signals registered in participants' brains from their motor, visual, and vestibular systems, might have been effectively mitigated. Furthermore, it is conjectured that the minimum symptoms could have reduced the negative impact on users' motivation, immersion, and learning performance, which are the main negative effects of simulator sickness (e.g., Atsikpasi & Fokides, 2022; Hsin et al., 2022; Maraj et al., 2017).

Finally, the imVR application engendered more positive emotions among users in comparison to the other two media ($\chi^2=4.60$, $p_{Adj.} < 0.001$, $\eta^2=0.112$-medium to large when comparing imVR and dVR; $\chi^2=7.84$, $p_{Adj.} < 0.001$, $\eta^2=0.168$-large when comparing imVR and web pages). This outcome is not unprecedented, as it aligns seamlessly with the conclusions drawn from similar research in the field of imVR (e.g., Büssing et al., 2022; Makransky & Lilleholt, 2018; Makransky & Mayer, 2022; Pallavicini & Pepe, 2019; Parong & Mayer, 2021a).

From the foregoing discussion, despite the occurrence of simulator sickness, imVR demonstrated superiority in multiple factors compared to dVR and web pages, endorsing the view that imVR provides a positive learning experience compared to the other two media. Yet, although learning experience and learning satisfaction are considered strong predictors of learning outcomes (Li & Tsai, 2020), this notion was not fully confirmed by the study's results, as it will be further elaborated in the coming section.

5.3 Comments on the Factors Influencing Learning Outcomes

From the previous discussion, one may infer that imVR excels in learning outcomes compared to web pages. Furthermore, it surpasses both dVR and web pages in most of the factors that were theorized to have an impact on one's learning experience. The question, however, is which of these factors significantly contribute to the shaping of one's learning in imVR. The ensuing data analysis yielded perplexing results. Only two factors, namely immersion and positive emotions, had a positive impact on learning outcomes (t=5.73, p<.001 and t=2.45, p=.016 respectively). Contrary to expectations, the perceived quality of graphics had a negative effect (t = -2.27, p=.026), as did simulator sickness (t = -2.56, p=.012). No other factors were found to play either a positive or negative role. Another surprising finding was the lack of factors influencing learning outcomes in the dVR application. As for web pages, the learning results were positively swayed solely by the participants' perceived learning effectiveness.

Concerning the positive impact of immersion and positive emotions as well as the negative effect of simulator sickness on learning, these points have been addressed in the preceding section. Regarding the negative influence of the perceived quality of graphics, there is room only for speculation. This occurred despite existing literature that champions the positive impact of graphics' quality on numerous factors such as immersion, motivation, and learning (e.g., Harrington, 2012; Kim & Ahn, 2021; Lee et al., 2010; Mystakidis, 2022; Parong & Mayer, 2018). One plausible explanation could be that distraction contributed to this outcome as others noted (Makransky et al., 2019). Participants might have directed most of their attention toward the graphics of the virtual environment and not to the learning content, resulting in a reduced ability to respond accurately to evaluation test questions.

The limited array of factors identified as influencing learning outcomes stands in contrast to the findings of multiple studies that have developed and tested diverse models for elucidating learning dynamics within imVR and VR in general. For instance, Makransky and Petersen (2021) have proposed a theoretical model that designates self-efficacy, interest, motivation, cognitive load, embodiment, and self-regulation as facilitators for knowledge acquisition within an imVR context. Moreover, in their empirical investigation, Fokides and Atsikpasi (2018) discovered that the key predictors for learning outcomes were perceived ease of use, motivation, perceived usefulness, and enjoyment. Makransky and Petersen (2019) posited that control and representational fidelity, as well as specific VR features such as usability, cognitive benefits, and self-efficacy exercise influence over learning. Summarily, the evidence suggests there is no universal answer regarding which factors affect learning in an imVR setting; the context in which imVR is applied, the learning content, individual learner characteristics, and the nature of the specific applications deployed, all contribute to significant variations to the factors instrumental in shaping learning outcomes.

5.4 Implications for Research and Education

The findings of this study bear implications for individuals engaged in the software/hardware industry, researchers, and education stakeholders. The analysis demonstrated that imVR produced superior learning outcomes only when juxtaposed with web pages, albeit with a marginally small effect size. In the section entitled “Comments on the learning outcomes”, it was proposed that this variance was derived from two key factors. Primarily, the learning content’s presentation across all conditions was predominantly reliant on images, audio, and texts. With no substantial disparity in the mode of delivery, the minuscule to negligible statistical differences among the three media are plausible. It was also hypothesized that only in the dVR and imVR conditions did participants have the opportunity to interact with the innovations. Through hands-on experiences, learners managed to gain indirect knowledge, resulting in a discernable contrast between imVR and web pages. Accordingly, it can be posited that the application of imVR may not be beneficial when the primary basis of learning content is text, audio, or images. These formats can be more aptly, effectively, and efficiently presented using conventional media. Conversely, the recommendation of imVR can be justified where substantial interaction with the learning material is quintessential for comprehension. In short, the paradigms of learning-by-doing, hands-on experiences, and active learning are the educational territories where imVR can realize its full potential. Educators, consequently, should consider the suitability of learning domains and pedagogical scenarios for the utilization of imVR. Furthermore, software developers bear the responsibility of devising applications that induce elevated levels of interaction with the learning content.

The study also found that immersion positively moderated the learning outcomes. The most distinctive advantage of imVR over other educational technologies is arguably immersion. Therefore, it is logically sound to assert that elevated levels of immersion could potentially yield even better learning outcomes and experiences. Yet, the journey towards achieving fully immersive VR is interspersed with technological challenges that await our attention. Researchers and hardware engineers should aspire to create devices embodying enhanced technical specifications and affordability for the average consumer, augmenting the accessibility of imVR to a wider learner population.

Positive user emotions (such as enjoyment, satisfaction, and enthusiasm) significantly influenced learning outcomes. Therefore, software engineers can develop applications that, whilst maintaining their educational essence, provide an even more enjoyable experience to users. However, such implementations must be approached cautiously, to prevent users from distraction and consequently losing their focus on the learning materials. This was potentially demonstrated in this study, where the perceived quality of graphics -which may enhance user positive emotions- negatively impacted learning outcomes. In consideration of simulator sickness, whilst it was not a pronounced issue, it still had a considerable negative impact on learning outcomes. This is regarded as an undesired outcome of the utilized technology. A range of methods to mitigate simulator sickness can be applied. For example, in this study, users had the option to walk instead of using their controllers. It is therefore suggested that researchers and software developers experiment and evaluate alternative methods.

Amid the execution of the project, it was noted that none of the participants had previous experience with HMDs, and only a handful had an understanding of imVR. This is noteworthy given that the sample consisted of students from an education department. Educational stakeholders can implement several measures to rectify this concern. At the academic level, a curriculum relating to the educational applications of technology and imVR-based applications should be incorporated. Further, in-service training programs may prove beneficial. It is also crucial to conduct research focused on identifying effective teaching methodologies that harness the potential of IVR.

5.5 Limitations and Future Work

The study bears several limitations, the elucidation of which is critical for future exploration. The sample size is one such limiting factor; a larger one would have provided a higher degree of confidence in the results as well as the reliability of the conclusions. As the participants' prior knowledge was not examined, it is uncertain whether it influenced the learning outcomes. Responders' trustworthiness remains a perennial concern. It had to be further noted that the questionnaire was based on a newly developed scale yet to be established. The examination of ten factors (excluding learning outcomes) can be considered satisfactory. However, the omission of other factors risks rendering the conclusions incomplete. The study focused on university students and a specific learning subject. This niche focus calls into question the generalizability of the findings. Another critique could be that the interaction time allotted to each participant for interaction with the application may have been insufficient. On the other hand, the management of over one hundred participants who used three media/tools proved to be a formidable challenge, hence extending the duration of interaction time or sessions was deemed untenable.

For future studies, these limitations must be duly noted and accounted for. Diversified target populations, differing in age and educational backgrounds, can yield insights into the similarities or differences when compared to the findings of this study. The same rings true for various learning domains and types of applications. Collaboration emerges as a key consideration in the context of multiuser applications. The examination of self-efficacy becomes pertinent when the sample includes groups with varying levels of IVR device-related skills. Finally, longitudinal studies provide a viable path toward gaining an in-depth understanding of IVR's educational potential. Studies with a restricted number of sessions pose vulnerability to the "wow effect," whereby users display an amplified enthusiasm in response to novel technological artifacts (Kamstrupp, 2016), consequently affecting the study results.

6 Conclusion

ImVR and its educational applications possess the potential to evolve as a significant tool for educators. However, comprehensive research is indispensable to fully comprehend this potential. It is also imperative to scrutinize whether ImVR holds an advantage in comparison to other technologies or media forms with respect to learning and the learning experience. This constituted the primary objective of the study. The preceding sections delineated the various stages of the study's implementation. All in all, it can be posited that although the learning outcomes were not evidently in favor of ImVR, it provides an enhanced learning experience for users. In conclusion, it is anticipated that the study will facilitate the scientific community in reaching a better understanding of the impact of imVR's educational applications.

Appendix

The name has been omitted for the review scale used in this study.

Factor	Item
Perceived quality of the virtual environment's graphics	The app was aesthetically pleasing
	I enjoyed the app's graphics
	The app was visually appealing
	I enjoyed the virtual environment
	The graphics of the app were attractive
	I was satisfied with the app's graphics
Perceived cognitive load	The cognitive load of the application was reasonable
	The presentation of too much information prevented the memorization of what was important*
	The effort to study the information that the application presented to me, was mentally tiring*
Perceived ease of use/control of the virtual environment	I used/controlled the app with ease
	I had full control over what I did
	When using the app, I had no problems doing whatever I wanted
Immersion/Presence	I immersed myself in the app
	I forgot/ignored everything around me
	I lost the sense of where I am
	I felt like I was inside the virtual world
	I lost the sense of time
	I felt like I was living in another place and time
Perceived feedback and content quality	Overall, the learning content was well presented
	The app gave me useful feedback regarding what I had to do
	The information provided by the app (e.g., objectives, help messages, images, texts, and audio) was clear and understandable
Perceived degree of interaction	I could interact a lot with the virtual world
	The virtual world responded well to my actions
	The interactions with the virtual objects were similar to the interactions with real objects
Motivation to learn and use the virtual environment	I want to know more about what I saw in the app
	I enjoyed the content so much that I would like to know more about this topic
	The content had things that triggered my curiosity
	I feel motivated to keep using the app
	I was intrigued to see what was in the app
	I wanted to explore the app more

Factor	Item
Simulator sickness (To what degree you felt…)	Dizziness?
	Your head being "heavy"?
	Vertigo?
	A general discomfort?
	Nausea?
	Headache?
Positive feelings (To what degree you felt…)	Joy?
	Satisfaction?
	Enthusiasm?
	Excitement?

Notes. * = the scoring of these items was reversed; all items were presented using a five-point Likert-type scale

Funding The study received no funding.

Data Availability The data can be provided upon request by contacting the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical Approval The study's participants volunteered, understood that they could withdraw from the experiment at any time, and provided their informed consent. They were protected by hiding their personal information in this study. The study is part of an ongoing research project for which approval from the Department's Ethical Committee has been granted.

Ethical statement We hereby declare that this manuscript is the result of our independent creation under the reviewers' comments. Except for the quoted contents, this manuscript does not contain any research achievements that have been published or written by other individuals or groups, or by AI tools; we are the only authors of the manuscript. The legal responsibility of this statement shall be borne by us.

References

Abichandani, P., Mcintyre, W., Fligor, W., & Lobo, D. (2019). Solar energy education through a cloud-based desktop virtual reality system. *Ieee Access : Practical Innovations, Open Solutions*, *7*, 147081–147093. https://doi.org/10.1109/ACCESS.2019.2945700.

Albus, P., Vogt, A., & Seufert, T. (2022). Signaling in virtual reality influences learning outcome and cognitive load. *Computers & Education*, *166*, 104154. https://doi.org/10.1186/s12984-022-01084-6.

Alfaisal, R., Hashim, H., & Azizan, U. H. (2022). Metaverse system adoption in education: A systematic literature review. *Journal of Computers in Education*, *2022*, 1–45. https://doi.org/10.1007/s40692-022-00256-6.

Allcoat, D., & von Mühlenen, A. (2018). Learning in virtual reality: Effects on performance, emotion, and engagement. *Research in Learning Technology*, *26*, 1–13. https://doi.org/10.25304/rlt.v26.2140.

Andreoli, R., Corolla, A., Faggiano, A., Malandrino, D., Pirozzi, D., Ranaldi, M., Santangelo, D., & Scarano, V. (2017). A framework to design, develop, and evaluate immersive and collaborative serious games in cultural heritage. *Journal on Computing and Cultural Heritage (JOCCH)*, *11*(1), 1–22. https://doi.org/10.1145/3064644.

Armougum, A., Orriols, E., Gaston-Bellegarde, A., Joie-La Marle, C., & Piolino, P. (2019). Virtual reality: A new method to investigate cognitive load during navigation. *Journal of Environmental Psychology*, *65*, 101338. https://doi.org/10.1016/j.jenvp.2019.101338.

Asad, M. M., Naz, A., Churi, P., Guerrero, A. J. M., & Salameh, A. A. (2022). Mix method approach of measuring VR as a pedagogical tool to enhance experimental learning: motivation from literature survey of previous study. *Education Research International, 2022*. https://doi.org/10.1155/2022/8262304.

Atsikpasi, P., & Fokides, E. (2022). A scoping review of the educational uses of 6DoF HMDs. *Virtual Reality*, *26*(1), 205–222. https://doi.org/10.1007/s10055-021-00556-9.

Barry, D. M., Ogawa, N., Dharmawansa, A., Kanematsu, H., Fukumura, Y., Shirai, T., Yajima, K., & Kobayashi, T. (2015). Evaluation for students' learning manner using eye blinking system in Metaverse. *Procedia Computer Science*, *60*, 1195–1204. https://doi.org/10.1016/j.procs.2015.08.181.

Bertrand, J., Bhargava, A., Madathil, K. C., Gramopadhye, A., & Babu, S. V. (2017). The effects of presentation method and simulation fidelity on psychomotor education in a bimanual metrology training simulation. *Proceedings of the 2017 IEEE Symposium on 3D User Interfaces 3DUI 2017*, *59-68*. https://doi.org/10.1109/3DUI.2017.7893318.

Breves, P., & Stein, J. (2022). Cognitive load in immersive media settings: The role of spatial presence and cybersickness. *Virtual Reality*, *2022*, 1–13. https://doi.org/10.1007/s10055-022-00697-5.

Bueno-Vesga, J. A., Xu, X., & He, H. (2021). The effects of cognitive load on engagement in a virtual reality learning environment. *Proceedings of the 2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, 645–652. IEEE. https://doi.org/10.1016/j.compedu.2019.103603.

Büssing, A. G., Thomsen, D., & Braun, N. (2022). Linking technology usage to instructional quality: Immersive virtual reality increases presence, positive emotions, and cognitive activation. *OsfPreprintsn 2022*, 1–27. https://doi.org/10.31219/osf.io/p9esz.

Butt, A. L., Kardong-Edgren, S., & Ellertson, A. (2018). Using game-based virtual reality with haptics for skill acquisition. *Clinical Simulation in Nursing*, *16*, 25–32. https://doi.org/10.1016/j.ecns.2017.09.010.

Buttussi, F., & Chittaro, L. (2018). Effects of different types of virtual reality display on presence and learning in a safety training scenario. *IEEE Transactions on Visualization and Computer Graphics*, *24*(2), 1063–1076. https://doi.org/10.1109/TVCG.2017.2653117.

Çakiroğlu, Ü., & Gökoğlu, S. (2019). Development of fire safety behavioral skills via virtual reality. *Computers & Education*, *133*, 56–68. https://doi.org/10.1016/j.compedu.2019.01.014.

Cao, S., Nandakumar, K., Babu, R., & Thompson, B. (2020). Game play in virtual reality driving simulation involving head-mounted display and comparison to desktop display. *Virtual Reality*, *24*, 503–513. https://doi.org/10.1007/s10055-019-00412-x.

Caro, V., Carter, B., Dagli, S., Schissler, M., & Millunchick, J. (2018). Can virtual reality enhance learning: A case study in materials science. *Proceedings of the 2018 IEEE Frontiers in Education Conference (FIE)*, 1–4. IEEE. https://doi.org/10.1109/fie.2018.8659267.

Casu, A., Spano, L. D., Sorrentino, F., & Scateni, R. (2015). RiftArt: Bringing masterpieces in the classroom through immersive virtual reality. In A. Giachetti, S. Biasotti, & M. Tarini (Eds.), *Proceedings of Smart Tools and Apps for Graphics-Eurographics* (pp. 77–84). Eurographics https://doi.org/10.2312/stag.20151294.

Cecotti, H., Day-Scott, Z., Huisinga, L., & Gordo-Pelaez, L. (2020). Virtual reality for immersive learning in art history. *Proceedings of the 2020 6th International Conference of the Immersive Learning Research Network (iLRN)*, 16–23. IEEE. https://doi.org/10.23919/iLRN47897.2020.9155108.

Checa, D., & Bustillo, A. (2020). Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century. *Virtual Reality*, *24*(1), 151–161. https://doi.org/10.1007/s10055-019-00389-7.

Checa, D., Alaguero, M., Arnaiz, M. A., & Bustillo, A. (2016). Briviesca in the 15 th c.: a virtual reality environment for teaching purposes. *Proceedings of the International Conference on Augmented Reality, Virtual Reality and Computer Graphics*, 126–138. Springer. https://doi.org/10.1007/978-3-319-40651-0_11.

Cheng, A., Yang, L., & Andersen, E. (2017). Teaching language and culture with a virtual reality game. *Proceedings of the 2017 CHI conference on Human Factors in Computing Systems*, 541–549. CHI. https://doi.org/10.1145/3025453.3025857.

Coban, M., Bolat, Y. I., & Goksu, I. (2022). The potential of immersive virtual reality to enhance learning: A meta-analysis. *Educational Research Review*, *36*, 100452. https://doi.org/10.1016/j.edurev.2022.100452.

Cohen, J. (2013). Statistical power analysis for the behavioral sciences. *Academic Press*. https://doi.org/10.4324/9780203771587.

Collins, J., Regenbrecht, H., Langlotz, T., Can, Y. S., Ersoy, C., & Butson, R. (2019). Measuring cognitive load and insight: A methodology exemplified in a virtual reality learning context. *Proceedings of the 2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 351–362. IEEE. https://doi.org/10.1109/ISMAR.2019.00033.

de Winkel, K. N., Talsma, T. M. W., & Happee, R. (2022). A meta-analysis of simulator sickness as a function of simulator fidelity. *Experimental Brain Research*, *240*, 3089–3105. https://doi.org/10.1007/s00221-022-06485-6.

Di Natale, A. F., Repetto, C., Riva, G., & Villani, D. (2020). Immersive virtual reality in K-12 and higher education: A 10-year systematic review of empirical research. *British Journal of Educational Technology*, *51*(6), 2006–2033. https://doi.org/10.1111/bjet.13030.

Díaz, J., Saldaña, C., & Avila, C. (2020). Virtual world as a resource for hybrid education. *International Journal of Emerging Technologies in Learning (iJET)*, *15*(15), 94–109. https://doi.org/10.3991/ijet.v15i22.14393.

Dolezal, M., Chmelik, J., & Liarokapis, F. (2020). An immersive virtual environment for collaborative geovisualization. *arXiv:2010.06279*.

Erturk, E., & Reynolds, G. B. (2020). The expanding role of immersive media in education. *Proceedings of the International Conference on E-Learning*, 191–194. International Association for Development of the Information Society.

Fanini, B., Pagano, A., & Ferdani, D. (2018). A novel immersive vr game model for recontextualization in virtual environments: The μvrmodel. *Multimodal Technologies and Interaction*, *2*(2), 20. https://doi.org/10.3390/mti2020020.

Fokides, E. (2023). Development and testing of a scale for examining factors affecting the learning experience in the Metaverse. *Computers & Education: X Reality*, *2023*(2), 100025. https://doi.org/10.1016/j.cexr.2023.100025.

Fokides, E., & Atsikpasi, P. (2018). Development of a model for explaining the learning outcomes when using 3D virtual environments in informal learning settings. *Education and Information Technologies*, *25*(3), 2265–2287. https://doi.org/10.1007/s10639-018-9719-1.

Fokides, E., & Atsikpasi, P. (2022). *(Πλήρως Εμβυθισμένη) Εικονική Πραγματικότητα, μάθηση και εκπαίδευση [(fully immersive) virtual reality, learning, and education]*. Zygos.

Fokides, E., Atsikpasi, P., & Arvaniti, P. A. (2021). Lessons learned from a project examining the learning outcomes and experiences in 360° videos. *Journal of Educational Studies and Multidisciplinary Approaches*, *1*(1), 50–70. https://doi.org/10.51383/jesma.2021.8.

Hamilton, D., McKechnie, J., Edgerton, E., & Wilson, C. (2021). Immersive virtual reality as a pedagogical tool in education: A systematic literature review of quantitative learning outcomes and experimental design. *Journal of Computers in Education*, *8*(1), 1–32. https://doi.org/10.1007/s40692-020-00169-2.

Harrington, M. C. (2012). The virtual trillium trail and the empirical effects of freedom and fidelity on discovery-based learning. *Virtual Reality*, *16*(2), 105–120. https://doi.org/10.1007/s10055-011-0189-7.

Hsin, L. J., Chao, Y. P., Chuang, H. H., Kyo, T. B. J., Yang, C. C. H., Huang, C. G., Kang, C. J., Lin, W. N., Fang, T. J., Li, H. Y., & Lee, L. A. (2022). Mild simulator sickness can alter heart rate variability, mental workload, and learning outcomes in a 360° virtual reality application for medical education: a post hoc analysis of a randomized controlled trial. *Virtual Reality, 2022*, 1–17. https://doi.org/10.1007/s10055-022-00688-6.

Huang, C. L., Luo, Y. F., Yang, S. C., Lu, C. M., & Chen, A. S. (2020). Influence of students' learning style, sense of presence, and cognitive load on learning outcomes in an immersive virtual reality learning environment. *Journal of Educational Computing Research*, *58*(3), 596–615. https://doi.org/10.1177/0735633119867422.

Huifen, G., Yan, M., Aizhu, W., Zhu, X., Lijiao, D., & Wenxiang, F. (2021). Who can benefit from immersive virtual reality in education? Effectiveness of IVR in teaching using meta-analysis. *Proceedings of the 2021 Tenth International Conference of Educational Innovation through Technology (EITT)*, 320–325. IEEE. https://doi.org/10.1109/EITT53287.2021.00069.

Jensen, L., & Konradsen, F. (2018). A review of the use of virtual reality head-mounted displays in education and training. *Education and Information Technologies*, *23*(4), 1515–1529. https://doi.org/10.1007/s10639-017-9676-0.

Jeon, J., & Jung, S. K. (2021). Exploring the educational applicability of Metaverse-based platforms. 한국정보교육학회: 학술대회논문집 [Korean Society for Information Education: Conference Proceedings], 361–368. https://koreascience.kr/article/CFKO202130548299122.page.

John, N. W., Pop, S. R., Day, T. W., Ritsos, P. D., & Headleand, C. J. (2017). The implementation and validation of a virtual environment for training powered wheelchair manoeuvres. *IEEE Transactions on Visualization and Computer Graphics*, *24*(5), 1867–1878. https://doi.org/10.1109/TVCG.2017.2700273.

Juliano, J. M., Schweighofer, N., & Liew, S. L. (2022). Increased cognitive load in immersive virtual reality during visuomotor adaptation is associated with decreased long-term retention and context transfer. *Journal of NeuroEngineering and Rehabilitation*, *19*(1), 1–14. https://doi.org/10.1111/jcal.12688.

Kamstrupp, A. K. (2016). The wow-effect in science teacher education. *Cultural Studies of Science Education*, *11*, 879–897. https://doi.org/10.1007/s11422-015-9684-6.

Keren, G. (2014). Between-or within-subjects design: A methodological dilemma. In G. Keren & C. Lewis (Eds.), *A handbook for data analysis in the behaviorial sciences* (pp. 257–272). Psychology Press. https://doi.org/10.4324/9781315799582.

Kim, Y. J., & Ahn, S. Y. (2021). Factors influencing nursing students' immersive virtual reality media technology-based learning. *Sensors (Basel, Switzerland)*, *21*(23), 8088. https://doi.org/10.3390/s21238088.

Koutitas, G., Smith, K. S., Lawrence, G., Metsis, V., Stamper, C., Trahan, M., & Lehr, T. (2019). A virtual and augmented reality platform for the training of first responders of the ambulance bus. *Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments-PETRA '19*, *ACM*. https://doi.org/10.1145/3316782.3321542.

Kye, B., Han, N., Kim, E., Park, Y., & Jo, S. (2021). Educational applications of Metaverse: Possibilities and limitations. *Journal of Educational Evaluation for Health Professions*, *18*, 1–13. https://doi.org/10.3352/jeehp.2021.18.32.

Lee, E. A. L., Wong, K. W., & Fung, C. C. (2010). How does desktop virtual reality enhance learning outcomes? A structural equation modeling approach. *Computers & Education*, *55*(4), 1424–1442. https://doi.org/10.1016/j.compedu.2010.06.006.

Lehikko, A. (2021). Measuring self-efficacy in immersive virtual learning environments: A systematic literature review. *Journal of Interactive Learning Research*, *32*(2), 125–146.

Li, D. C., & Tsai, C. Y. (2020). An empirical study on the learning outcomes of e-learning measures in Taiwanese small and medium-sized enterprises (SMEs) based on the perspective of goal orientation theory. *Sustainability*, *12*(12), 5054. https://doi.org/10.3390/su12125054.

Lin, H., Wan, S., Gan, W., Chen, J., & Chao, H. C. (2022). Metaverse in education: Vision, opportunities, and challenges. *arXiv preprint arXiv*:2211.14951. https://doi.org/10.1109/BigData55660.2022.10021004.

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers & Education*, *95*, 174–187. https://doi.org/10.1016/j.compedu.2016.01.001.

Lohre, R., Bois, A. J., Athwal, G. S., & Goel, D. P. (2020). Improved complex skill acquisition by immersive virtual reality training: A randomized controlled trial. *The Journal of Bone and Joint Surgery*, *102*(6), e26. https://doi.org/10.2106/JBJS.19.00982.

Luigini, A., Parricchi, M. A., Basso, A., & Basso, D. (2020). Immersive and participatory serious games for heritage education, applied to the cultural heritage of South Tyrol. *Interaction Design and Architecture(s)*, *43*, 42–67. https://hdl.handle.net/10863/14619.

Maas, M. J., & Hughes, J. M. (2020). Virtual, augmented and mixed reality in K-12 education: A review of the literature. *Technology Pedagogy and Education*, *29*(2), 231–249. https://doi.org/10.1080/1475939X.2020.1737210.

Maereg, A. T., Nagar, A., Reid, D., & Secco, E. L. (2017). Wearable vibrotactile haptic device for stiffness discrimination during virtual interactions. *Frontiers in Robotics and AI*, *4*, 1–9. https://doi.org/10.3389/frobt.2017.00042.

Makransky, G., & Lilleholt, L. (2018). A structural equation modeling investigation of the emotional value of immersive virtual reality in education. *Educational Technology Research and Development*, *66*(5), 1141–1164. https://doi.org/10.1007/s11423-018-9581-2.

Makransky, G., & Mayer, R. E. (2022). Benefits of taking a virtual field trip in immersive virtual reality: Evidence for the immersion principle in multimedia learning. *Educational Psychology Review*, *34*(3), 1771–1798. https://doi.org/10.1007/s10648-022-09675-4.

Makransky, G., & Petersen, G. B. (2019). Investigating the process of learning with desktop virtual reality: A structural equation modeling approach. *Computers & Education*, *134*, 15–30. https://doi.org/10.1016/j.compedu.2019.02.002.

Makransky, G., & Petersen, G. B. (2021). The cognitive affective model of immersive learning (CAMIL): A theoretical research-based model of learning in immersive virtual reality. *Educational Psychology Review*, *33*, 937–958 (2021). https://doi.org/10.1007/s10648-020-09586-2.

Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learning and Instruction*, *60*, 225–236. https://doi.org/10.1016/j.learninstruc.2017.12.007.

Maraj, C. S., Badillo-Urquiola, K. A., Martinez, S. G., Stevens, J. A., & Maxwell, D. B. (2017). Exploring the impact of simulator sickness on the virtual world experience. In *Advances in human factors, business management, training and education*, 635–643. Springer. https://doi.org/10.1007/978-3-319-42070-7_59.

Mayer, R. E. (2006). Ten research-based principles of multimedia learning. In H. F. O'Neil, & R. S. Perez (Eds.), *Web-based learning: Theory, research, and practice* (pp. 371–390). Lawrence Erlbaum Associates Inc.

Miura, T., Ando, G., Onishi, J., Matsuo, M., Sakajiri, M., & Ono, T. (2018).). Virtual museum for people with low vision: comparison of the experience on flat and head-mounted displays. *Proceedings of the International Conference on Computers Helping People with Special Needs*, 246–249. Springer. https://doi.org/10.1007/978-3-319-94274-2_34.

Mohamed, A., & Örmecioğlu, H. T. (2022). Immersive virtual reality IVR, and the appreciatıon of architectural aesthetics. *Kent Akademisi, 15(DÜ 2. Uluslararası Mimarlık Sempozyumu Özel Sayısı)*, 195–207. https://doi.org/10.35674/kent.1014036.

Mystakidis, S. (2022). Metaverse. *Encyclopedia*, *2*(1), 486–497. https://doi.org/10.3390/encyclopedia2010031.

Nicolaidou, I., Pissas, P., & Boglou, D. (2023). Comparing immersive virtual reality to mobile applications in foreign language learning in higher education: A quasi-experiment. *Interactive Learning Environments*, *31*(4), 2001–2015. https://doi.org/10.1080/10494820.2020.1870504.

Ogbuanya, T. C., & Onele, N. O. (2018). Investigating the effectiveness of desktop virtual reality for teaching and learning of electrical/electronics technology in universities. *Computers in the Schools*, *35*(3), 226–248. https://doi.org/10.1080/07380569.2018.1492283.

Olmos-Raya, E., Ferreira-Cavalcanti, J., Contero, M., Castellanos, M. C., Giglioli, I. A. C., & Alcañiz, M. (2018). Mobile virtual reality as an educational platform: A pilot study on the impact of immersion and positive emotion induction in the learning process. *Eurasia Journal of Mathematics Science and Technology Education*, *14*(6), 2045–2057. https://doi.org/10.29333/ejmste/85874.

Pallavicini, F., & Pepe, A. (2019). Comparing player experience in video games played in virtual reality or on desktop displays: Immersion, flow, and positive emotions. *Extended Abstracts of the Annual symposium on Computer-Human Interaction in Play* 195–210. ACM. https://doi.org/10.1145/3341215.3355736.

Pallavicini, F., Pepe, A., & Minissi, M. E. (2019). Gaming in virtual reality: What changes in terms of usability, emotional response and sense of presence compared to non-immersive video games? *Simulation & Gaming*, *50*(2), 136–159. https://doi.org/10.1177/1046878119831420.

Pappa, G., Ioannou, N., Christofi, M., & Lanitis, A. (2018). Preparing student mobility through a VR application for cultural education. *Proceedings of the Advances in Digital Cultural Heritage*, 218–227. Springer. https://doi.org/10.1007/978-3-319-75789-6_16.

Parong, J., & Mayer, R. E. (2018). Learning science in immersive virtual reality. *Journal of Educational Psychology*, *110*(6), 785–797. https://doi.org/10.1037/edu0000241.

Parong, J., & Mayer, R. E. (2021a). Cognitive and affective processes for learning science in immersive virtual reality. *Journal of Computer Assisted Learning*, *37*(1), 226–241. https://doi.org/10.1080/10447318.2022.2108563.

Parong, J., & Mayer, R. E. (2021b). Learning about history in immersive virtual reality: Does immersion facilitate learning? *Educational Technology Research and Development*, *69*(3), 1433–1451. https://doi.org/10.1007/s11423-021-09999-y.

Porter, I. I. I., Boyer, J., M., & Robb, A. (2018). Guidelines on successfully porting non-immersive games to virtual reality: a case study in Minecraft. *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play*, 405–415. ACM. https://doi.org/10.1145/3242671.3242677.

Portman, M. E., Natapov, A., & Fisher-Gewirtzman, D. (2015). To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. *Computers Environment and Urban Systems*, *54*, 376–384. https://doi.org/10.1016/j.compenvurbsys.2015.05.001.

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

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education*, *147*, 103778. https://doi.org/10.1016/j.compedu.2019.103778.

Ramírez-Correa, P., Rondán-Cataluña, F. J., Arenas-Gaitán, J., & Martín-Velicia, F. (2019). Analysing the acceptation of online games in mobile devices: An application of UTAUT2. *Journal of Retailing and Consumer Services*, *50*, 85–93. https://doi.org/10.1016/j.jretconser.2019.04.018.

Rupp, M. A., Odette, K. L., Kozachuk, J., Michaelis, J. R., Smither, J. A., & McConnell, D. S. (2019). Investigating learning outcomes and subjective experiences in 360-degree videos. *Computers & Education*, *128*, 256–268. https://doi.org/10.1016/j.compedu.2018.09.015.

Selzer, M. N., Gazcon, N. F., & Larrea, M. L. (2019). Effects of virtual presence and learning outcome using low-end virtual reality systems. *Displays*, *59*, 9–15. https://doi.org/10.1016/j.displa.2019.04.002.

Sweller, J. (2020). Cognitive load theory and educational technology. *Educational Technology Research and Development*, *68*(1), 1–16. https://doi.org/10.1007/s11423-019-09701-3.

Taber, K. S. (2018). The use of Cronbach's alpha when developing and reporting research instruments in science education. *Research in Science Education*, *48*(6), 1273–1296. https://doi.org/10.1007/s11165-016-9602-2.

Tacgin, Z., & Dalgarno, B. (2022). Chapter iii evaluation of an immersive virtual reality learning environment from subject experts and instructional designers. In Z. Tacgin, & A. Hagan (Eds.), *Enhanced learning environments: Technology and Innovation* (pp. 49–87). Cambridge Scholars Publishing.

Tlili, A., Huang, R., Shehata, B., Liu, D., Zhao, J., Metwally, A. H. S., Wang, H., Denden, M., Bozkurt, A., Lee, L. H., Beyoglu, D., Altinay, F., Sharma, R. C., Altinay, Z., Li, Z., Liu, J., Ahmad, F., Hu, Y., Salha, S., Abed, M., & Burgos, D. (2022). Is metaverse in education a blessing or a curse: A combined content and bibliometric analysis. *Smart Learning Environments*, *9*(1), 1–31. https://doi.org/10.1186/s40561-022-00205-x.

Tzanavari, A., Charalambous-Darden, N., Herakleous, K., & Poullis, C. (2015). Effectiveness of an Immersive Virtual Environment (CAVE) for teaching pedestrian crossing to children with PDD-NOS. *Proceedings of the 2015 IEEE 15th International Conference on Advanced Learning Technologies*, 423–427. IEEE. https://doi.org/10.1109/ICALT.2015.85.

Villena Taranilla, R., Cózar-Gutiérrez, R., González-Calero, J. A., & López Cirugeda, I. (2019). Strolling through a city of the Roman Empire: An analysis of the potential of virtual reality to teach history in primary education. *Interactive Learning Environments*, 1–11. https://doi.org/10.1080/10494820.2019.1674886.

Villena-Taranilla, R., Tirado-Olivares, S., Cozar-Gutierrez, R., & González-Calero, J. A. (2022). Effects of virtual reality on learning outcomes in K-6 education: A meta-analysis. *Educational Research Review*, *35*, 100434. https://doi.org/10.1016/j.edurev.2022.100434.

Wenk, N., Penalver-Andres, J., Buetler, K. A., Nef, T., Müri, R. M., & Marchal-Crespo, L. (2023). Effect of immersive visualization technologies on cognitive load, motivation, usability, and embodiment. *Virtual Reality*, *27*(1), 307–331. https://doi.org/10.1007/s10055-021-00565-8.

Wu, B., Yu, X., & Gu, X. (2020). Effectiveness of immersive virtual reality using head-mounted displays on learning performance: A meta-analysis. *British Journal of Educational Technology*, *51*(6), 1991–2005. https://doi.org/10.1111/bjet.13023.

Zhao, Y., Forte, M., & Kopper, R. (2018). VR touch museum. *Proceedings of the 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 741–742. IEEE. https://doi.org/10.1109/VR.2018.8446581.

Zhao, J., LaFemina, P., Carr, J., Sajjadi, P., Wallgrün, J. O., & Klippel, A. (2020). Learning in the field: Comparison of desktop, immersive virtual reality, and actual field trips for place-based STEM education. *Proceedings of the 2020 IEEE conference on virtual reality and 3D user interfaces (VR)*, 893–902. IEEE. https://doi.org/10.1109/VR46266.2020.00012.