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Stimulating Change at the Human–Computer Interface: Cultivating Cognitive and Critical Thinking Through Immersive Virtual Reality as an Innovative Pedagogy in STEM Education

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Abstract

Crafting STEM teaching into meaningful experiences can transform facts into knowledge. Immersive virtual reality (IVR) represents a significant pedagogical disruption, offering novel modalities of engagement with science content, extending beyond passive reception towards enhanced critical inquiry, reflective evaluation, and the cultivation of higher-order thinking skills. This study investigated how 20 Maltese students (mean age 12) adjusted their perceptions and acceptance of IVR when encountering it for the first time in formal STEM education. A quasi-experimental design was employed over six weeks, with data collected through pre- and post-intervention questionnaires. The analytical framework combined the Technological Frames of Reference (TFR) and Technology Acceptance Model (TAM) to capture perceptual snapshots and attitudinal shifts. While IVR initially stimulated enthusiasm, sustained exposure prompted critical reflections on its potential and limitations, particularly in relation to subject relevance, peer communication, and ease of use. Such deliberations are themselves suggestive indicators of reflective engagement. Rather than being demonstrated evidence of cognitive skill development, they are consistent with the early exercise of analytical and evaluative reasoning. These insights underscore the recursive dialog between technology-in-use and user contextualization, revealing how perceptions mature through experience. By examining how young learners engage with emergent technologies, this research highlights education's role in cultivating adaptability, reflective judgment, and critical thinking capacities—central to innovative pedagogy and support for uncertain futures.

Keywords: critical cognitive thinking skills; human–computer interaction; immersive virtual reality; perceptions; STEM; technology acceptance; Technology Frames of Reference

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1. Introduction

In 2009, a group of scientists participated in an international seminar directed to elucidate the essential concepts that students should experience to understand science education (Harlen, 2010). The idea was to find modalities by which students could enjoy learning science, therefore enabling them to comprehend science concepts better. It was also recognized how the fragmented way in which science was prescribed in curricula was causing students to view the discipline as a mere assortment of unrelated facts without broader relevance. To address this issue, science education was redefined with ten principles (Harlen, 2010)

that envisioned learning to go beyond the mastery of facts and theories to embrace the relation and comprehension of important concepts pertinent to students' lives, both in and beyond the classroom. In this respect, and as part of the relevance underlying the wider significance of science education, STEM (Science, Technology, Engineering and Mathematics) Literacy (Zollman, 2012) was formalized as a multidisciplinary approach enabling learners to connect knowledge domains in addressing complex, real-world challenges.

All of this can be attributed to the fact that, as Harlen (2010) states, to thrive in this modern age of innovation, one must learn to recognize common traits even in consciously different threads, combining them holistically to make sense of the bigger picture. With global issues such as climate change, population growth, and the rapid socioeconomic transformations associated with the Fourth Industrial Revolution (Himmetoglu et al., 2020) that are actively blurring the boundary between humans and machines (Aziz, 2018), students must be equipped not only with scientific reasoning skills but also with the ability to adapt to uncertainty. Education has historically contributed to social and economic needs (Aoun, 2017), yet the discrepancy between the pace of change inside classrooms and the fast-changing realities of life outside is profound. This disjuncture situates STEM education and its integration with emerging technologies, such as virtual reality (VR), within a broader critical examination of lifelong education and learning. Thus, in an era characterized by interconnected global challenges, education must cultivate adaptability, reflective judgment, and agency—qualities that are increasingly associated with lifelong learning (Dishon, 2021; Kalimullina et al., 2021). In context, notwithstanding sustained investment in digital technologies, their transformative potential often remains underutilized (Gudmundsdóttir & Hatvelik, 2017; Selwyn & Facer, 2013; Watted & Barak, 2024). This can easily be attributed to resistance or, rather, opposition to change. However, the resistance towards the employed technology cannot merely be correlated with the fact that users do not wish to employ it. Rather, the same users towards whom the technology is being directed may lack the knowledge of how it can best be put into practice (Lauterbach & Mueller, 2014). Ultimately, the viability of technology use in education does not merely depend on access but also on the recursive dialog between the properties of the technology and users' contextualization of it (Camilleri, 2018).

This paper therefore examines how students' perceptions evolve when engaging with IVR in formal STEM education. Attention is given to how immersive and innovative pedagogy contributes to the cultivation of cognitive and critical skills in young learners. Specifically, the use of IVR headsets in the learning of STEM-related subjects was employed as an instructional strategy designed to foster higher-order thinking through experiential and inquiry-driven engagement within the provided science content. It should be noted that the employment of IVR in a formal educational setting represented a relatively new experience both for the participating students and also in the broader Maltese national educational context. This perceived uniqueness of the situation allowed the researchers to gain distinctive insights into IVR adoption in formal educational settings and, more broadly, into the potential of digitally enhanced learning environments to facilitate conceptual shifts and cognitive appraisal within the students concerned. This research therefore matured as a result of the recursive dialog that the authors engaged in, with the design of a research tool that was not only formalized through but essentially conveyed the nature of the specific questions that follow.

Accordingly, the underlying motivations were addressed in a process manner approach and formalized in three questions. These questions were designed to define the observed attitudinal shifts within the framework of IVR use by the respondents as a first-time hands-on experience in learning STEM-related topics as follows:

1. Scaife (2012) confirms how, in general, even away from science education, assessing learning (unlike teaching) is challenging. This arises because learning cannot be observed and quantified as easily as teaching outcomes. Thus, notwithstanding the elusiveness underlying learning, which features of IVR do students identify as making STEM learning meaningful and appealing, and how do these features relate to the perceived usefulness of the technology for learning?
2. Walsh (1995) argues that, once perceptions around a technology form, they are secured, consolidated, and difficult to change. Adaptive structuration theory (Orlikowski & Scott, 2016) and the principles of technology-in-use (Tyre & Orlikowski, 1994) state otherwise. In short, do students' perceptions of IVR change between a pre-intervention and post-intervention measure taken over six weeks?
3. If perceptions change, in what direction and along which dimensions (perceived usefulness, perceived ease of use, behavioral intention, and collaboration) do students' post-intervention attitudes differ from their pre-intervention attitudes—in this case, with IVR use in the learning of STEM?

Critically, this study is not only concerned with attitudinal shifts towards IVR as a technology. At a deeper pedagogical level, it also interrogates the extent to which immersive virtual environments can serve as platforms for enhancing cognitive and critical skills. By its very nature, IVR confronts learners with simulated scenarios that demand observation, interpretation, problem-solving, and reflective judgement (Lampropoulos & Kinshuk, 2024). These are precisely the higher-order thinking competencies that correspond to Bloom's Revised Taxonomy traits—including Analyze, Evaluate, and Create Levels (Anderson & Krathwohl, 2001)—which innovative pedagogies must nurture if education is to remain meaningful and transformative in the 21st century. This study therefore contributes to both the theoretical and empirical understanding of immersive pedagogies as tools that—rather than being merely part of technological novelty—will become vehicles for cognitive development.

Consequently, this paper epitomizes research at the human–computer interface by examining the cognitive and critical thinking dimensions of immersive learning. It therefore investigates how IVR, as an innovative pedagogy, cultivates higher-order thinking and cognitive reflection in young STEM learners, as evidenced through the attitudinal shifts observed before and after sustained IVR use.

In context, an adaptive composite theoretical lens is employed. The conceptual framing of this study draws on the Technological Frames of Reference (TFR) (Orlikowski & Gash, 1994) and the Technology Acceptance Model (TAM) (Davis, 1989), which together provide a composite theoretical lens for analyzing attitudinal shifts in relation to technology use. TFR allows for identifying perceptual snapshots of participants' assumptions, expectations, and working knowledge, while TAM helps to explain how constructs such as "perceived usefulness", "perceived ease of use", and "behavioral intentions" evolve through sustained engagement. This study contributes to current scholarship on the human–technology interface and its implications for the role of education in preparing learners for uncertain futures.

2. Theoretical Overview: Immersive Pedagogies and the Development of Higher-Order Thinking in STEM Education

The purpose of this overview is to establish a focused argument where the distinctive contribution of IVR lies in its capacity to provoke higher-order critical thinking. The foundational material that follows is therefore intended as brief scaffolding for this argument and is accordingly condensed, placing emphasis on the relation between IVR and critical thinking. Students attend school to learn the things that they do not know (Howland

et al., 2013). The same will naturally hold for the learning of science, which has traditionally focused on incrementally building related knowledge over the years (Bolstad & Buntting, 2013). Ideally, by learning certain concepts, students will gain the necessary enabling qualities and insights to intrinsically learn what will be of value to them (Heick, 2019), eventually helping them to choose their own learning paths. In the meantime, while the presence of digital technology in schools has increased, alongside digitally proficient students and teachers, the ways in which technology can be critically employed in the formation of knowledge requires more attention (Kalimullina et al., 2021). The use of digital technology must go beyond mere tool familiarity. It must be deliberately harnessed to cultivate and enhance already native critical thinking skills that will enable learners to analyze, evaluate, and construct knowledge on their own (Anderson & Krathwohl, 2001). Therefore, this critical use of technology will meaningfully situate learning not only in classrooms but also within the broader trajectory of lifelong education, where learners must continuously adapt their skills and knowledge to evolving socioeconomic, technological, and environmental conditions. Thus, instead of focusing on how best to make these digital technologies work, teachers need to bridge the gap between the technology, the pedagogy, and content knowledge (TPACK, Mishra & Koehler, 2006; Tondeur et al., 2019).

Of the twelve key themes that Tondeur et al. (2019) mention to enhance technology integration, scaffolding and mediating authentic learning experiences through the same digital technologies are taken to be important motivations in technology use for learning (Tondeur et al., 2019; Kaufman, 2014; Bruce & Chiu, 2015). When considering the ever-dominant internet and therefore a digitally imbued reality, any form of required content, including that for science, is readily available and easily accessible. This has resulted in a change, where the emphasis has shifted from being solely focused on the acquisition of existing knowledge to recognizing the importance of developing skills such as adaptability, advanced communication (including multimodal and social skills), problem-solving, and systems thinking (Bolstad & Buntting, 2013). These are not incidental competencies but hallmarks of higher-order cognitive functioning, requiring cultivated pedagogical designs that actively evoke analysis, synthesis, and evaluative reasoning, rather than passive content consumption (Anderson & Krathwohl, 2001; Howland et al., 2013).

These lifelong learning skills align with the demands of the 21st century, enabling students to respond critically and creatively to global challenges. However, the degree of success in learning outcomes and students' understanding can also be amalgamated with the modality of delivery. Unfortunately, test preparation is still prevalently the most common and relevant practice within school curricula (Howland et al., 2013). Indeed, this practice has been fruitful in student academic preparation, but it is now outdated as it fails to reflect a digitally saturated culture that empowers students to access content in uncontrolled learning bubbles away from school authority (Palfrey & Gasser, 2008). Teaching should align with students' abilities and be contextualized within their existing knowledge to make learning more meaningful. This framing also connects with broader discussions on lifelong education, where meaningful learning is understood as enabling learners to transfer and apply knowledge beyond immediate academic contexts into social and civic life (Formenti & Hoggan-Kloubert, 2023).

To contribute effectively and meaningfully, people need to articulate their ideas by listening to others, seek clarification, and collectively negotiate learning by merging theory within their network's contexts. This would therefore allow participants to make theory meaningful by relating it with practice. Meaningful learning can therefore be described as a form of learning where, rather than just memorization, relating information to one's existing knowledge and experiences leads to understanding and better long-term retention (Ausubel, 1963; Bruner, 1966, Vergara et al., 2019). As expressed in Figure 1, meaningful

learning requires an active, engaged process of discovery and construction, in which learners create their own understanding of the material based on their existing knowledge and experiences (Gardner, 1991, 2006; Howland et al., 2013). This constructivist learning vision therefore directly aligns with the principles of an innovative pedagogy that goes beyond the mere transmission of content and is designed to promote learning environments and instructional strategies that stimulate higher-order thinking (Lampropoulos & Kinshuk, 2024; Anderson & Krathwohl, 2001). Thus, rather than stimulating students with "inert knowledge" (Howland et al., 2013), the articulation and formation of knowledge should be instigated through tasks that are intentional, authentic, cooperative, constructive, and active, as expressed in Figure 1 below.

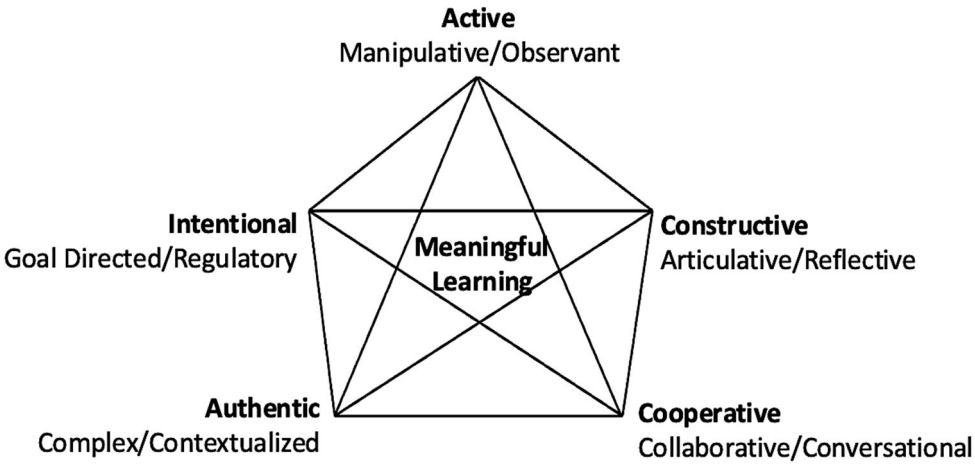


Figure 1. Characteristics of meaningful learning (Howland et al., 2013).

The use of digital technology within formal educational settings can be of benefit. Digital technologies may provide rich and flexible multimedia and multimodal qualities, but they cannot teach students better than teachers themselves. Thus, rather than availing oneself of digital technologies as delivery vehicles that contribute to the provision of content that students have to absorb, digital technology should be used to facilitate processes that students can themselves employ to actively construct their own learning within their own changing contexts and realities. In this regard, the pedagogical value of IVR as a digital technology does not only lie within its capacity to deliver content more efficiently but also considers the potential and opportunity to create learning environments, embodied cognition, situated reflection, and the construction of a new understanding (Lampropoulos & Kinshuk, 2024). This is also in line with the fact that, while the demand in STEM-related professions is always high, many still decide not to pursue STEM-related subjects because they are perceived as too challenging (Pew Research Center, 2018).

STEM was developed to address the challenges of the 21st century (Heick, 2019; Widya & Rahmi, 2019). Widya and Rahmi (2019) also claim that STEM education is directed to improving critical thinking skills. This enables students to liaise with real conditions actively, logically, and productively, encompassing the abilities to formulate questions, evaluate evidence, and analyze competing explanations while drawing reasoned conclusions. As expressed within Bloom's Revised Taxonomy (Anderson & Krathwohl, 2001), the capacities of Analysis, Evaluation, and Creation align with higher-order cognitive domains. Thus, innovative pedagogies that leverage immersive digital environments are particularly well positioned to cultivate such competencies as they confront learners with complex, open-ended scenarios that resist simple answers while demanding sustained cognitive effort (Lampropoulos & Kinshuk, 2024; Liu et al., 2020).

Incidentally, such required prerequisites already resonate within the practiced traits that constitute digital technologies. Digital technologies and the internet are already empowering the same students to express their creativity, produce and direct their own content, voice their opinions, and learn independently away from the classroom. As expressed below in Figure 2, such qualities should therefore be integrated and leveraged in formal educational settings to support the required productive thinking (Howland et al., 2013) in STEM education.

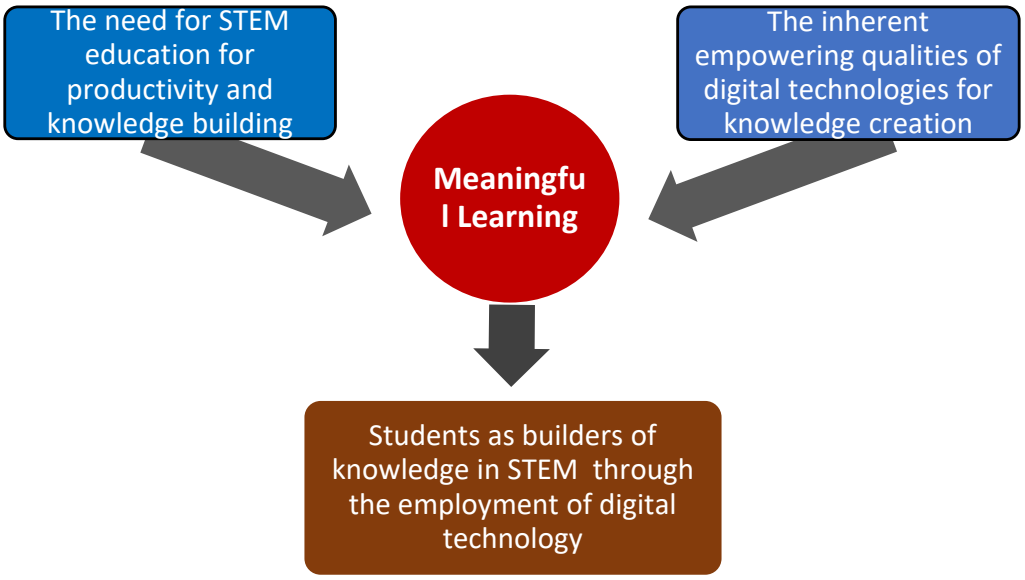


Figure 2. Merging STEM learning prerequisites with the qualities of digital technologies for a meaningful learning experience.

VR brings forth a heightened sense of physical presence in computer-generated 3D simulations (Oigara, 2018). In addition, Suh and Prophet (2018) have noted that IVR can provide novel cognitive experiences, positioning IVR as an innovative pedagogy with meaningful potential in cultivating critical thinking for novel cognitive experiences. Thus, when learners are immersed in scientifically accurate virtual environments, rather than being passive observers, the technology enables them to become active cognitive agents, encouraging them to observe, question, interpret, and make sense of complex phenomena (Liu et al., 2020; Lampropoulos & Kinshuk, 2024). This process of sense-making in immersive contexts directly activates higher-order cognitive skills, as defined by Anderson and Krathwohl (2001), moving learners beyond recall and comprehension towards analysis, evaluation, and the construction of new knowledge. Consequently, there is an increasing inclination towards utilizing virtual reality learning environments (VRLEs) in the realm of education, particularly in STEM fields. Liu et al. (2020) suggest that the scientific process involves exploring and investigating scientific phenomena through inquiry-driven and open-ended methods, which stimulates students to construct personal experiences.

To enhance learning's effectiveness, teachers must therefore provide opportunities for students to engage in hands-on activities and search for information. Using IVR in science education is particularly promising as it enables students to engage in scientific inquiry in ways that were not previously possible. These include the ability to visualize complex and inaccessible knowledge, abstract concepts, experiential learning, motivation for learning and performance, involvement and interactivity, multimodality of perception, compatibility with distance learning, and the possibility of gamifying the educational process (Alekseyeva et al., 2022). These affordances are not merely technical features but pedagogical enablers. When thoughtfully orchestrated by the teacher, such tools serve as a

scaffold for higher-order thinking. In context, visualization supports comprehension and analysis, inquiry-driven exploration promotes evaluation and synthesis, while gamified challenges foster problem-solving and creative application (Bicalho et al., 2023; Anderson & Krathwohl, 2001). The pedagogical power of IVR therefore does not only rest on the technology itself but in the intentional instructional design that surrounds it. Consequently, provided that its integration is guided by clear pedagogical objectives and grounded in an understanding of how immersive environments can be designed to instigate higher-order thinking (Lampropoulos & Kinshuk, 2024), encouraging and bolstering the application of IVR within formal educational settings should be seen as an opportunity of great significance to learning in STEM.

VR has also become a viable alternative to conventional learning methods (Shen et al., 2019). Furthermore, the integration of IVR into education offers a secure training environment by eliminating the potential hazards of real-life training scenarios, while simultaneously expanding the scope of learning and boosting students' involvement and drive. The use of wearable head-mounted displays provides a three-dimensional (3D) computer-generated immersive experience that users can actively interact with. The creation of an enhanced, fully immersive learning experience should therefore promote novel teaching and learning activities and enhance learning involvement to captivate the audience in a potentially realistic and therefore more interesting learning experience (Hanson & Shelton, 2008; Shen et al., 2019). Importantly, this enriched engagement is not an end; rather, it should serve as the motivational foundation upon which deeper cognitive processing can be built. Research consistently demonstrates that learner engagement in immersive environments creates the conditions for reflective thinking, evaluative reasoning, and the cultivation of intellectual engagement and monitoring capabilities (Lampropoulos & Kinshuk, 2024; Liu et al., 2020; Anderson & Krathwohl, 2001).

Nonetheless, examining and understanding the ways in which users perceive and relate to the technology in question will be an important prerogative for its successful implementation. A growing body of research is already proving the capabilities and practicality of IVR for a more contextualized STEM learning experience (Liu et al., 2020). However, as Shen et al. (2019) express, understanding the processes underlying the adoption of digital technologies is crucial in the field of information systems. This highlights the need for the right tools to recognize and assess such human–technology dialogs, generically expressed as "technology acceptance", for the enhancement of meaning in STEM learning. Ultimately, such recognition can potentially provide insights into the processes that dictate technology acceptance as a prerogative for the employment of IVR to digitally enhance the meaningful STEM learning experience. Consequently, as per the theories of "Reasoned Action" and "Planned Behavior" (Ajzen & Kruglanski, 2019), both directed towards understanding the modification of human actions, the adaptation to and accommodation of IVR by the participants who took part in this research initiative were subsequently examined.

As will be expressed in more detail in the description of the analytical instrument, this research was performed through the employment of two theoretical frameworks: Technology Frames of Reference (TFR), as originally proposed by Orlikowski and Gash (1994), and the Technology Acceptance Model (TAM), as depicted by Davis (1989). Together, these frameworks provide the conceptual scaffolding for the study. TFR highlights how learners' assumptions and expectations about technology shape their engagement, while TAM explains how perceptions of usefulness, ease of use, and behavioral intention evolve through sustained interaction. Within the broader pedagogical context of this study, these frameworks do more than just trace technology acceptance. They show how immersive learning experiences cultivate the cognitive critical thinking skills that lie at the heart of innovative pedagogy. As learners move away from initial assumptions about IVR towards

grounded experience-based evaluations of its affordances and limitations, they engage in higher-order thinking processes including analysis, evaluation, and reflective judgement, as underlined within this study (Anderson & Krathwohl, 2001; Lampropoulos & Kinshuk, 2024). Together, these frameworks support an inquiry into how immersive technologies like IVR can nurture reflective judgment and adaptability—qualities that are central to lifelong education in times of global transformation (Lampropoulos & Kinshuk, 2024; Wei et al., 2025).

Technology Acceptance Processes at the Human–Computer Interface

Technology Frames of Reference (TFR) (Orlikowski & Gash, 1994) provided the theoretical backdrop against which the perceptions of the respondents towards IVR could be recognized and subsequently interpreted. Frames have the potential to offer clear and powerful qualities through which to discern assumptions that may even at times be taken for granted (Camilleri, 2021; Olesen, 2014; Orlikowski & Gash, 1994). Consequently, as TFR utilizes the concept of frames to refer to categories or specific knowledge within a theme or domain of technology acceptance (Davidson, 2006), it was therefore chosen to discern and analyze the expectations and assumptions of the participants regarding IVR. TFR was also considered useful in evaluating the working knowledge that users may have had in respect to the technology in question. Subsequently, the framework served to evaluate the perceptual snapshots provided by the respondents regarding IVR before and after use.

While TFR offers different domains of categorization, the two domains that were taken to be suitable for this research were the following:

1. The *sentiment towards the technology*—This addresses the beliefs, expectations, and working knowledge that users displayed regarding IVR.
2. *Technology-in-use*—This helps to discern any motivational changes among users before and after using IVR.

The snapshots that such domains of categorization provided before and after IVR use in the STEM exercise were taken, provide a brief overview of the facilitations underlying adaptation mechanisms that evolve over time. This, in turn, offered the foundation and opportunity for comparison between the before and the after of using IVR. Therefore, the significance in the comparison of these two instances led to the employment of another analytical model, the Technology Acceptance Model (TAM) (Davis, 1989), whose traits provided insights into the processes of adaptation, accommodation, and enactment.

Specifically, the subdomain variables of TAM employed were as follows:

- Perceived Usefulness (PU)—This reflected the ways that respondents regarded the practicability of IVR for learning.
- Behavioral Intention (BI)—This was adopted to see if the use of IVR enabled the respondents to leave their comfort zones and utilize the newly acquired user-generated insights to plan their next steps forward with the mentioned technology.
- Perceived Ease of Use (PEU)—This reflected users' familiarity with the digitally mediated tasks as they gained hands-on experience and formed new connections with the IVR that enabled them to learn and evaluate the nature of the tasks given.

The merging of TFR and TAM in this study therefore allowed us to move beyond assessing attitudes to interrogating how learners' frames of reference shift in relation to new technologies and how these shifts reflect broader capacities for adaptability and reflective engagement.

3. Materials and Methods

This study employed an exploratory and quasi-experimental design to investigate how middle school students in a local Maltese school adjusted their perceptions towards IVR when introduced to immersive experiences for the first time in STEM education. Given the small, single-site convenience sample, the design is framed as exploratory rather than as a controlled experiment. It was intended to surface and characterize perceptual changes at first contact and not to support causal or generalizable inference. To support comparability across the lessons, the intervention followed a standardized procedure where each session ran for a comparable duration. Using the same head-mounted display (HMD) kit and teacher-led workflow app, an equivalent block of time was devoted to the immersive activity, followed by a structured discussion. Therefore, the task consistency and IVR "dosage" were held broadly constant, while the science topic varied from week to week.

The pedagogical design of the intervention was intentionally structured to position IVR as an innovative instructional strategy capable of instigating higher-order intellectual engagement and critical thinking in young STEM learners (Anderson & Krathwohl, 2001; Lampropoulos & Kinshuk, 2024). The disruption under analysis was the pedagogical introduction of IVR, which had not yet been widely implemented in the Maltese educational system. Meanwhile, the research initiative was part of a science awareness program that students could attend during summer, away from normal school days.

While the offered program was linked to students' typical activities at school, it was not particularly related to one specific topic. Rather, it was set to actively engage the students concerned in several science principles. It therefore covered various topics that ranged from space awareness with a virtual tour on Mars to climate change and to marine biology, which also involved a first-hand experience of a scuba diver.

The sample chosen comprised 20 students (mean age 12) drawn from a Maltese middle school, selected through convenience sampling as a result of the school's readiness to participate in the initiative. The choice of a relatively small but contextually unique sample reflects the exploratory nature of the study, directed at capturing perceptual adjustments during initial encounters with IVR in formal education.

The study was conducted with 14 boys and 6 girls in 2 mixed-gender classes. The intervention spanned a period of six weeks, during which students were introduced to STEM content using IVR headsets in classroom sessions. The duration was selected to allow for the initial novelty effect to settle, thereby enabling the study to capture both enthusiasm and critical reflections as perceptions matured over time.

The exercise made use of a RedboxVR immersive virtual reality kit (Redbox VR Ltd., Blackpool, UK), consisting of 15 PICO G2 4K Enterprise head-mounted displays (HMDs) and a teacher's tablet (Qingdao Pico Technology Co., Ltd., Qingdao, China). For each HMD, there was a controller that allowed the user to maneuver in the virtual world. Each HMD operated on Android 8.1 and incorporated a Qualcomm Snapdragon 835 processor, 6 GB of RAM, 128 GB of storage, a 4K display with a 101° field of view and a 75 Hz refresh rate, Bluetooth 4.2 and Wi-Fi connectivity. Each HMD contained the immersive virtual reality educational applications used during the teaching exercise. The IVR devices that the students used were connected to the teacher's mobile tablet by making use of the appropriate app, allowing them to follow the teacher's guidance in the virtual scene. The tablet and the HMDs were networked through a dependable high-speed 5G internet connection. Each student availed her/himself of an HMD. In the process, the teacher used the mobile tablet to present the specific virtual scenes, manage students' experience times, and monitor the IVR devices' connections. IVR-based activities were embedded throughout 6 different lessons. This ensured that the students had the opportunity to process and discuss the outcomes of the IVR activities within the context of the specific topic being

dealt with. Each lesson dealt with a different science topic, which included microscopic organisms, the human body, space exploration, ocean exploration, different animals and their habitats, and ecology. Group work and think-pair-shared tasks were also included to reach all lesson outcomes in an effective manner. These collaborative strategies, chosen as pedagogical scaffolds, allowed the students to move towards more active analysis, peer-mediated reasoning, and evaluative discussions, defined as competences that are central to the cultivation of critical thinking skills (Liu et al., 2020).

Data collection relied on pre- and post-intervention questionnaires, designed to capture changes in perceptions, ease of use, perceived usefulness, and behavioral intention towards IVR. The instrument was informed by constructs from the Technology Acceptance Model (TAM) (Davis, 1989) and Technology Frames of Reference (TFR) (Orlikowski & Gash, 1994), operationalized into student-friendly survey items. The questionnaires combined Likert-scale items with open-ended questions, thereby allowing for both quantitative comparisons and qualitative insights into students' evolving frames of reference.

For data analysis, a mixed-methods approach was employed. Quantitative data from the Likert-scale items were analyzed using descriptive statistics only, including frequencies and percentage shifts between the pre- and post-intervention measures. Given the small and attrition-reduced sample (N = 20 pre, N = 16 post), no inferential significance tests (e.g., paired-samples t-tests or repeated-measures ANOVA) were conducted, as the data did not satisfy the distributional and sample-size assumptions that such tests require and would not have supported generalizable quantitative inference. Accordingly, all quantitative findings are interpreted as descriptive, cohort-specific indicators rather than as statistically significant effects. The qualitative data were analyzed through a structured coding process. Open-ended responses were independently read and assigned initial codes, which were then organized under the two pre-specified Technological Frames of Reference (TFR) domains, namely "sentiment towards the technology" and "technology-in-use", as guiding categories. Coding decisions were reviewed by both authors to improve consistency and reduce single-coder bias. This triangulation provided a richer understanding of how perceptions changed before and after IVR use. Thus, by situating the methodology within the frameworks of TFR and TAM, the study not only examines shifts in technology acceptance but also contextualizes these within the broader educational mandate of fostering adaptability and reflective judgment.

Ethical approval was secured through the university's research ethics process. Informed consent was obtained from parents/guardians and through assent from the students. Anonymity and confidentiality were strictly maintained, and participation was voluntary. In all instances, data collection included the formulation and presentation of an information letter for all, consent forms given to the legal guardians/parents of the participants, and assent forms given to the participating students themselves, which had to be duly read and signed before participating in the research exercise. Hence, prior to the study procedure, parents/guardians and all participating students were provided with an age-appropriate consent and assent form, respectively. Both parties, i.e., parents/guardians and students, had to duly sign and return their respective documents to the researchers as proof of their consent to participate. The note provided relevant information regarding the goals of the research in question. It also assured the participants and their parents/guardians that the research instruments—in this case, two questionnaires, with one at the beginning, before using IVR, and one at the end, after making use of IVR—would both be anonymous. The form provided also included a note stating that, while the participants were being allowed to avail themselves of the IVR as part of the summer programme that they were attending, the questionnaires were to be filled on a voluntary basis only. The researchers assured all those concerned that the questionnaires contained no information that could

allow any individual, including the researchers, to identify the participants from their answers. Moreover, while no identifiable personal details or information, including gender or age, were collected, the note also included a guarantee that participants' guardians/parents had to sign as an assurance to the researchers that none of the students concerned had any physical or psychological issues that could possibly influence them while the IVR headsets were being used.

To examine cognitive changes towards the material being taught and any perceptual and attitudinal changes before and after using IVR in the classroom, a pre- and post-exercise questionnaire was administered to the participants. The two questionnaires were separated by a six-week interval, corresponding to the full duration of the study unit. This timeframe was intentionally selected to allow the initial enthusiasm to subside and provide space for reflective engagement with IVR. The research instruments consisted of two related questionnaires structured around both closed-ended and open-ended components. The pre-intervention questionnaire contained 10 Likert-type items, while the post-intervention questionnaire included the same 10 items plus four additional items, resulting in 14 items in total. All closed-ended items were rated on a 5-point Likert scale ranging from 1 (strongly agree) to 5 (strongly disagree). Each Likert item was accompanied by an open-ended comment prompt, allowing participants to elaborate on their responses. Thus, the instrument generated both quantitative perceptual data and qualitative explanatory comments.

The items set were similar but not identical. The first ten items addressed perceptions associated primarily with perceived usefulness (PU) and initial orientations towards IVR, including learning value, enjoyment, collaboration, safety, immersion, and preferences for classroom use. The second questionnaire retained these 10 items to enable a comparison over time, while introducing four additional items targeting other TAM qualities beyond PU, specifically perceived ease of use (PEU) and behavioral intention (BI). These additional items examined usability, transferability of skills, confidence after training, and intended future uses of IVR, thereby procuring further insights into accommodation processes, user confidence, developments in critical thinking processes, and attitudinal shifts after participants had engaged with IVR for a substantial period of time, allowing them to reflect on the content being taught and "digest" the experience gained.

While 3 of the participants had previously experienced IVR, none had used IVR for learning. This lack of prior exposure to IVR in formal STEM settings was central to the study's disruption analysis, as it positioned the students at a genuine point of first contact with immersive technologies in education. Accordingly, the first questionnaire was directed towards gauging participants' initial perceptions of IVR, essentially focusing on perceived usefulness (PU) before use. The first 10 items in the second questionnaire were designed to identify any changes in perception through a comparison with the outcomes of the initial questionnaire. The additional four items were set not only to gauge newly acquired knowledge and intentions towards IVR use in STEM but also to capture emergent shifts in learners' TFR, highlighting processes of frame evolution and attitudinal change.

Figure 3 below illustrates the dual-structured analytical mechanism employed in this study. The TFR framework provided temporal "snapshots" of students' perceptions of IVR before and after use, enabling the identification of perceptual alignments, misalignments, and subsequent shifts. In parallel, TAM was applied not to compare these snapshots directly but to explain the causal mechanisms—such as perceived usefulness, perceived ease of use, and behavioral intention—that underpinned the observed perceptual changes.

Taken together, this complementary framing allowed the study to move beyond documenting change to understanding the processes of adoption, accommodation, and enactment at the human–computer interface as reflected in Figure 3. This methodological alignment also reflects the broader focus of lifelong education research, examining how

emerging technologies like IVR cultivate adaptability and reflective judgment in learners encountering new and disruptive modalities of learning. Ultimately, the methodological choices made, starting from the design of the IVR intervention to the analytical frameworks employed, were guided by the notion that immersive and innovative pedagogies can instigate and cultivate higher-order critical thinking within digitally enhanced environments (Anderson & Krathwohl, 2001; Lampropoulos & Kinshuk, 2024).

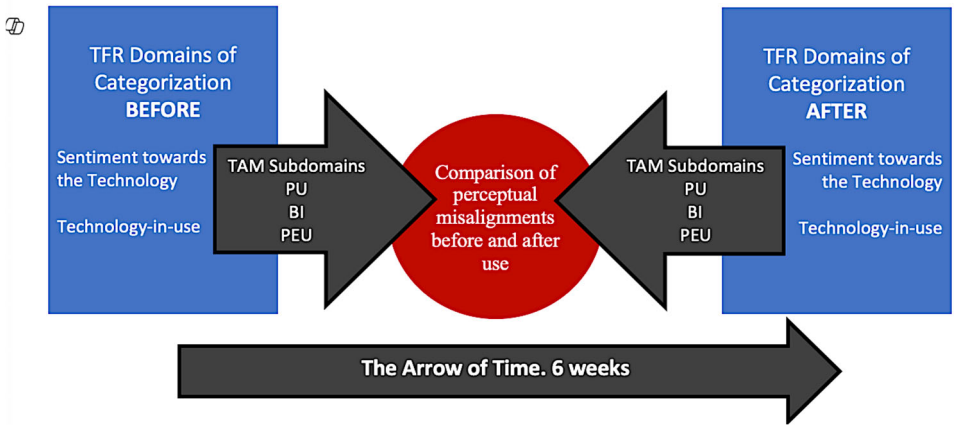


Figure 3. The sentiment and perceptual comparison of IVR before and after use.

4. Results

Before discussing the outcomes of this research, it must be highlighted that the number of students who completed the first questionnaire and the number that eventually participated in the second one were different. While the initial exercise included 20 participants, after six weeks, the number of attendees who completed the second questionnaire dropped to 16. This attrition, while modest, reflects the realities of longitudinal school-based interventions and is acknowledged as a limitation in interpreting generalizability. It should be acknowledged that this attrition may not have been entirely incidental. As reported regarding the outcomes below, several participants experienced physical discomfort, notably dizziness and headaches, especially during the prolonged use of the head-mounted displays. It is plausible that the discontinuation of the four students who did not complete the second questionnaire was linked, at least in part, to this physiological intolerance. Although the voluntary, summer program context means that the precise reasons for non-completion cannot be confirmed, this possibility is noted here because such discomfort represents a substantive structural barrier to the sustainable, large-scale implementation of IVR in formal education.

As expressed earlier, the second questionnaire was longer than the first and included four extra statements/questions. Consequently, it is deemed necessary to divide the Section 4 into two parts. The first section is composed of five outcomes directed towards comparing the overall results attained in the first ten questions. This is then followed by the analysis of the remaining four questions in the second questionnaire, directed to investigating participants' matured reflections gained from use. In this way, Section 4.1 primarily reflects perceptual snapshots (TFR), while Section 4.2 highlights explanatory mechanisms (TAM subdomains). Subsequently, across both sections, the findings are interpreted both in terms of technology acceptance and in terms of what they reveal about the cultivation of intellectual capacities and critical thinking skills. This includes the learners' capacity to move from uncritical enthusiasm towards grounded, evaluative, and reflective engagement with an innovative pedagogy (Anderson & Krathwohl, 2001).

4.1. Section A

4.1.1. Outcome 1—Using IVR to Learn More About the World

The comparison of participants' familiarity and, therefore, as framed within the TFR domains of categorization—their *sentiment towards the technology* and *technology-in-use*—produced interesting results.

As conveyed in Figure 4, comparing participants' sentiments across the TFR domains yielded an increase of roughly 10% in those who "strongly agreed" or "agreed" that IVR could help them learn about the world. Before the exercise, 70% (N = 14/20) "strongly agreed". Afterwards, the combined "strongly agree" and "agree" share rose to 80% (N = 14/16), but with a marked shift from "strongly agree" towards "agree". This recalibration—less idealization and more grounded recognition of IVR's contextual usefulness—was reflected in open comments noting that IVR was well suited to biology, physics, and some humanities (history, languages) rather than mathematics (which requires arithmetical work) or chemistry (where IVR does not yet replicate sensory cues such as smell). Neutral respondents saw little advantage of IVR over on-demand video clips, indicating that the immersive novelty is weighed against readily available alternatives. Such distinctions are consistent with the early exercise of evaluative comparison (the Evaluate level in Anderson & Krathwohl, 2001). However, they may equally reflect simple preference formation. This spread may also explain why the post-use responses included a single "strongly disagree" instance (6.25%, N = 1).

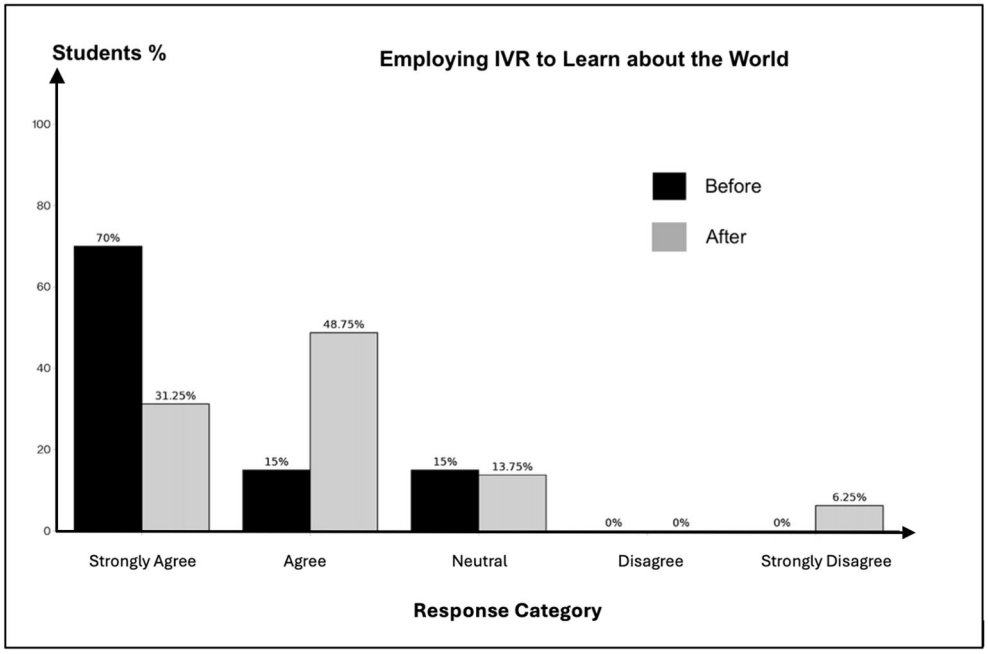


Figure 4. Employing IVR to learn about the world.

4.1.2. Outcome 2—The Fun Underlying Learning Through IVR

The analysis of the expectation that IVR would make learning fun produced mixed results as shown in Figure 5. Initially, all participants (N = 20; 100%) "strongly agreed" that IVR could be fun after sustained use. Six of the remaining 16 (37.5%) expressed a "neutral" view or "disagreed". Open comments revealed that those who still "agreed" emphasized interest but flagged physical discomfort (dizziness and headaches) from extended use. Neutral respondents saw multimedia richness as both an advantage and a distraction, and those who "disagreed" described IVR as confusing. Here, the decline implicates TAM's perceived ease of use as much as any deepening of judgement. The dampened "fun factor" appears to be driven substantially by usability and ergonomic friction (a

pragmatic objection) rather than solely by a more reflective appraisal of the medium. The two interpretations are not mutually exclusive, but the comments caution against reading the shift as cognitive growth.

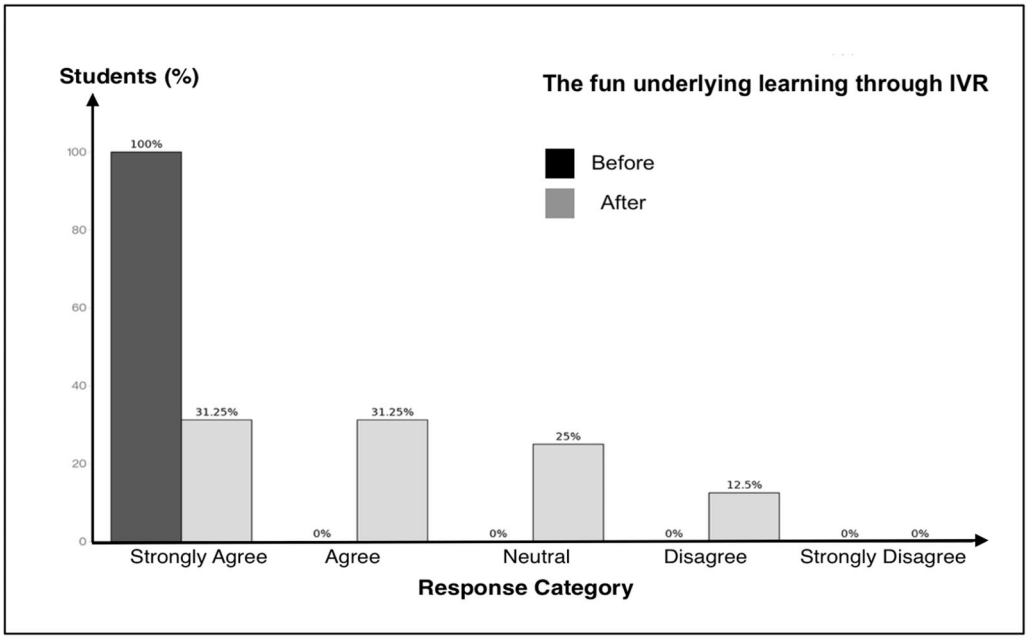


Figure 5. The fun underlying learning through IVR.

4.1.3. Outcome 3—Enhancement of Peer Communication and IVR

Collaboration is central to contemporary STEM learning (Aziz, 2018; Rusk & Rønning, 2020). As displayed in Figure 6, participants' views remained varied before and after use and even after six weeks, with more than a third (37.5%, $N = 6/16$) holding a neutral attitude. While the participants found IVR useful for immersing in content, its immersive qualities were seen to hinder peer-to-peer communication. This is a practical paradox given that the intervention deliberately incorporated group work and think-pair-share tasks. HMDs occlude vision and hearing, so a learner wearing a headset is effectively cut off from the very peers with whom collaboration is required. No participant "strongly agreed" that IVR enhanced collaboration, underscoring cautious adoption. This finding has direct design implications. Collaborative pedagogies cannot simply be layered onto individually worn HMDs; they must be engineered around the device—for example, by alternating headset and headset-free phases, pairing an immersed "explorer" with a non-immersed "navigator" who can see a shared screen, using synchronized teacher-cast views so that the group observes the same scene, and arranging the physical layout (seating, spotting, shared displays) to reduce the isolation that HMDs impose. Such mitigations reframe the tension between individual immersion and collective collaboration as a solvable design problem rather than an inherent limitation of IVR.

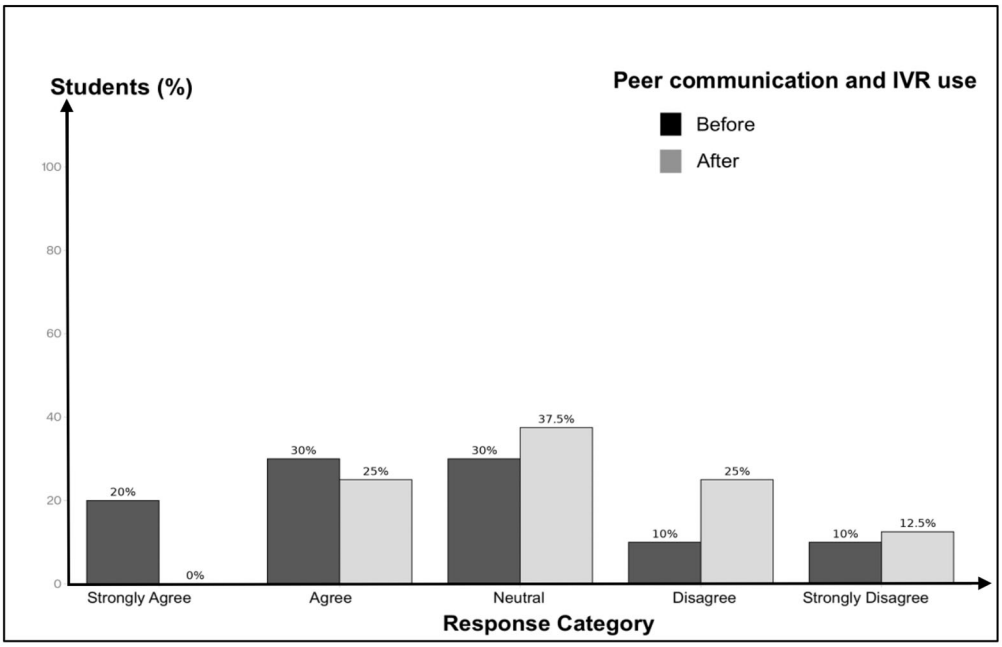


Figure 6. Peer communication and IVR use.

4.1.4. Outcome 4—Traditional Versus IVR-Induced Learning

The spread of the results above was also observed further in the results depicted in Figure 7 below.

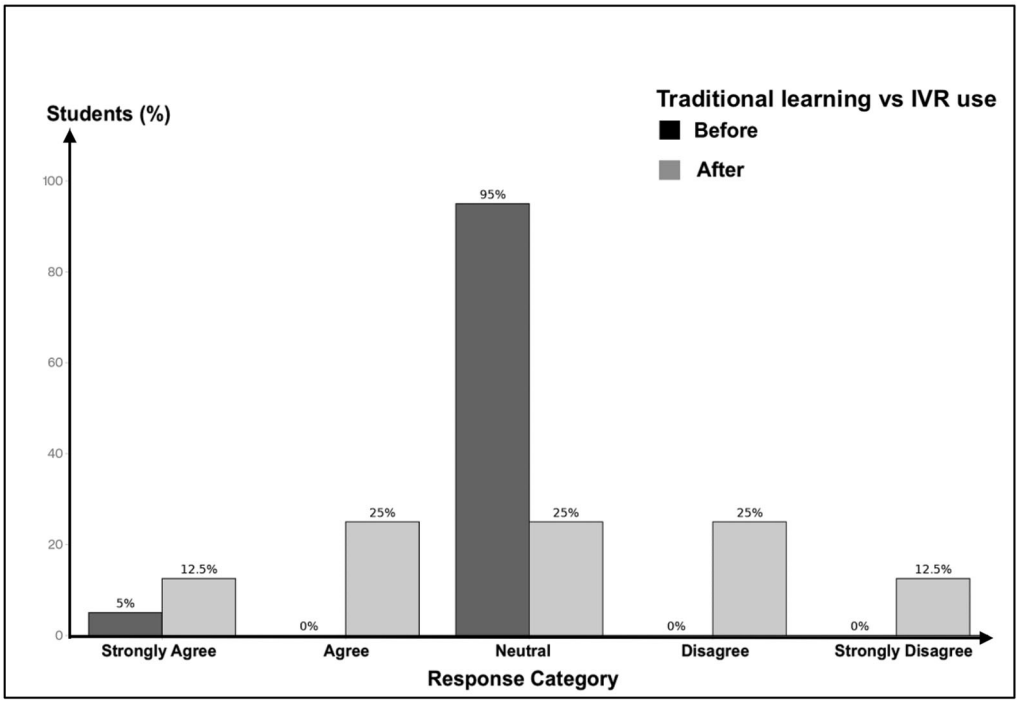


Figure 7. Traditional learning vs. IVR use for learning.

Preferences diversified after the intervention. Initially, 95% (N = 19/20) held no strong opinion and 5% (N = 1/20) "strongly agreed" that IVR was useful. Afterwards, opinions spread, where those favoring traditional methods cited the value of real human presence, fewer distractions, better focus, and the avoidance of discomfort (e.g., headaches), while others noted that, although traditional learning could be boring, IVR was not indispensable. These responses indicate that acceptance is contingent on thoughtful orchestration and on

perceived value relative to alternatives (consistent with TAM's account of behavioral intention). The willingness to weigh modalities and articulate context-based preferences is, again, best read as a suggestive indicator of reflective engagement rather than as demonstrated cognitive development.

4.1.5. Outcome 5—Expectancy of Further Future Employment of IVR by Teachers

The results for this outcome were used to review how participants' behavioral intentions towards the future employment of IVR for learning changed after its use for a period of 6 weeks as reflected in Figure 8.

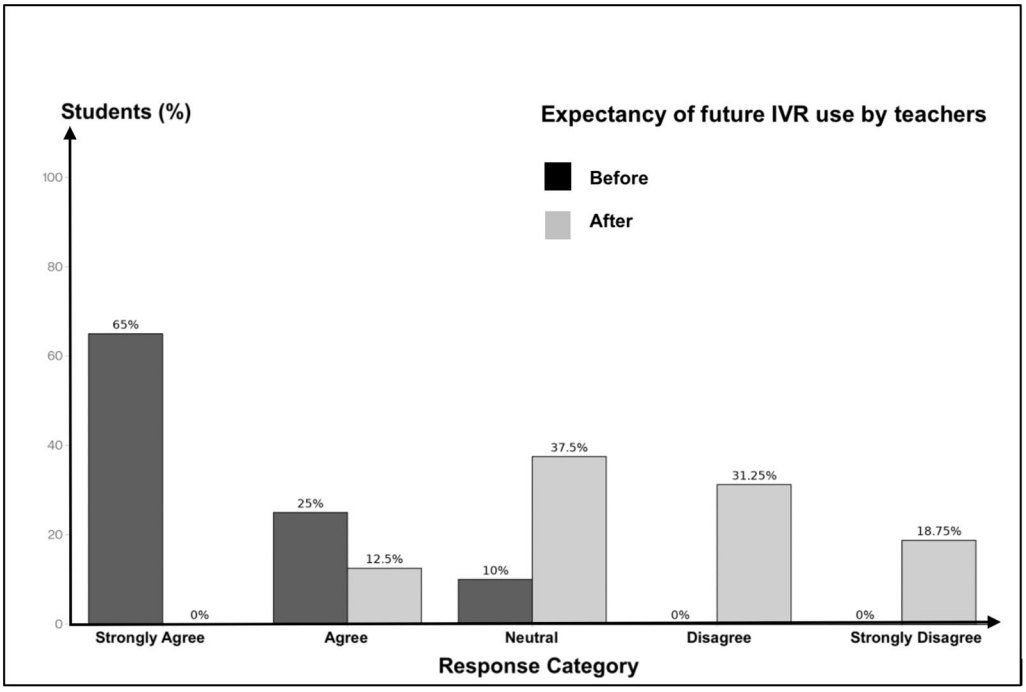


Figure 8. Expectancy of further future employment of IVR by teachers in class.

Behavioral intention shifted substantially. Before use, 65% (N = 13/20) "strongly agreed" and 25% (N = 5/20) "agreed" that they looked forward to teachers' future use of IVR (a combined 90%); after use, only 12.5% (N = 2/16) maintained that IVR should be widely employed. The recursive dialog between initial assumptions (TFR) and adjusted behavioral intentions (TAM) shows perceptions moving from excitement to cautious appraisal.

This decline should be interpreted with care. In part, it reflects more context-specific judgement. IVR was seen to be suited to history but not mathematics, and traditional methods were considered to maintain focus better. However, the data do not allow this drop to read primarily as "cognitive growth". First, several objections made were emphatically pragmatic. Discomfort, connectivity failures, and device-syncing frustration were described by the students as contributing to "a waste of time", although none of these led to an evaluative judgement about the pedagogy. Second, the decline may reflect novelty fatigue or simple preference formation as much as deepened reflection. Third, the quality of the intervention itself is a confounding variable that the data cannot rule out. Thus, the specific lesson plans, and the ways that the teacher orchestrated the IVR devices over the six weeks, may not have been sufficiently engaging or effective, so that students' preferences for "a real human presence" and fewer distractions could indicate a shortfall in execution rather than a limitation intrinsic to IVR. Ultimately, the interpretation is therefore that these post-intervention attitudes are a suggestive indicator of reflective engagement, consistent with the early exercise of analytical and evaluative reasoning, but entangled with ergonomic,

motivational, and instructional factors that this exploratory design cannot isolate (Anderson & Krathwohl, 2001; Lampropoulos & Kinshuk, 2024).

4.2. Section B

This section is distinct from the previous one as the questions employed in the second stage were not replicated in the first questionnaire. They were unique to the post-intervention questionnaire and extended Outcome 5, probing the participants' perceived ease of use (PEU) and behavioral intention (BI) in order to enhance the learning experience through the further use of IVR.

In context of PEU, as per Figure 9, most participants claimed either that they were tech-savvy or that, through the experience gained during the course, they had learned to use IVR effectively. For those with a neutral opinion, the inconvenience was not due to IVR itself but rather due to ancillary aspects such as connectivity, hardware compatibility, and syncing across multiple platforms. While IVR use was experienced as relatively easy, the effort of coordinating devices and connections was frustrating and often described as a waste of time that detracted from learning. A small fraction admitted that, even after six weeks, they still were not proficient in using IVR and did not find it easy to manage.

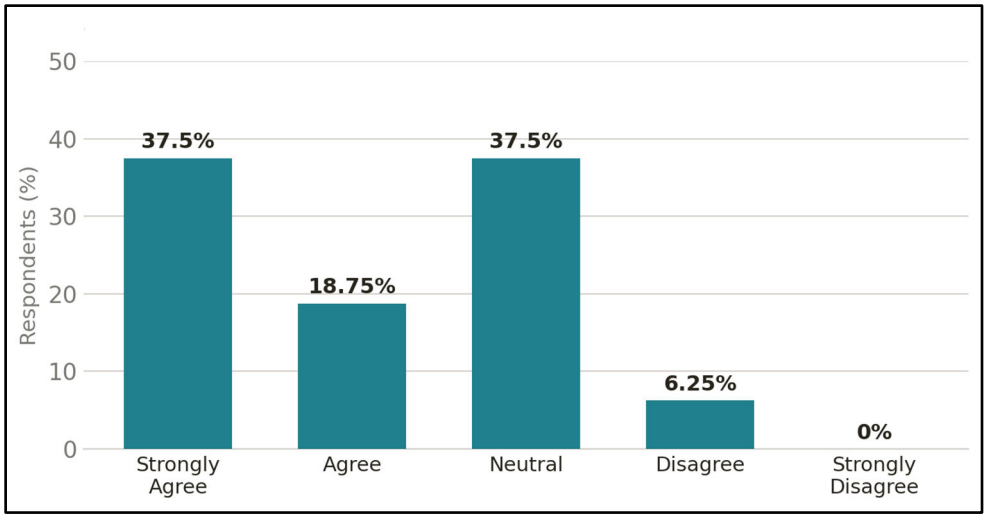


Figure 9. Participants' beliefs that using virtual reality is easy.

Ultimately, these findings reinforce TAM's construct of PEU. Perceived ease of use is not an inherent property of the tool but is shaped by the broader technological ecosystem in which it is embedded. The students' reflections reveal an emergent capacity for systems thinking, recognizing that smooth use depends on multiple interdependent factors. Such awareness signals a valuable quality for education in times of rapid change, where adaptability and resilience are crucial to sustaining engagement with evolving technologies.

In context of behavioral intention (BI), all participants indicated that they would consider using IVR again. Most (N = 8/16) anticipated using it primarily for games, while many kept their options open, acknowledging IVR's flexibility for both leisure and academic work. The 12.5% (N = 2/16) who gave a "neutral" response were open to using IVR again but could not identify a specific future application. Notably, and as portrayed in Figure 10, no participant rejected IVR outright, suggesting that even cautious respondents saw some potential relevance.

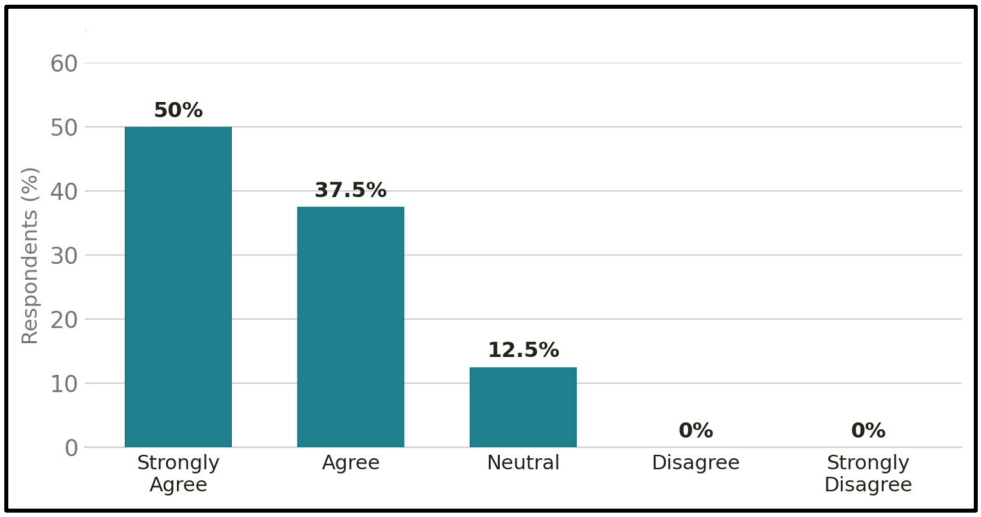


Figure 10. Behavioral intentions for use.

This outcome shows that behavioral intention did not fade with extended exposure. Rather, it became more differentiated and context-sensitive, with students distinguishing between entertainment and education. Here, TFR captures the recalibration of assumptions, while TAM highlights the behavioral orientations that evolve through experience. Such discernment therefore demonstrates adaptive intentionality—the ability to not only adopt new technologies but also determine their appropriate uses in relation to academic growth, personal development, and wider societal contexts.

Taken together, the findings of both Sections 4.1 and 4.2 therefore confirm that, when employing IVR as an innovative pedagogy within a structured and reflective instructional framework, it does more than shift attitudes towards technology. It can actively facilitate the development of higher-order cognitive functions through situated experiential learning—which is central to meaningful learning in the 21st century (Anderson & Krathwohl, 2001; Lampropoulos & Kinshuk, 2024).

5. Discussion

From a constructivist perspective, IVR has the potential to narrow the gap between abstract content and lived experience, rendering learning more meaningful (Huang & Liaw, 2018). The employed composite analytical framework (TFR and TAM) enabled us to capture perceptual snapshots and evolving attitudes. TFR allowed us to trace how students' expectations shifted, while TAM was used to interpret the usefulness, ease of use, and intention considerations that accompanied these shifts. Sentiments towards IVR were consolidated over time, with participants able to articulate both affordances and limitations.

When deployed as an innovative pedagogy, this study suggests that IVR functions as a catalyst for cognitive and critical thinking development, progressively moving learners from surface-level engagement towards the kind of analytical, evaluative, and reflective reasoning that characterizes higher-order thinking (Anderson & Krathwohl, 2001). However, more research is required to better establish how practices that stimulate meaningful learning through technologies (Huang & Liaw, 2018) in formal educational settings can be implemented. The study also illuminates the double-edged nature of immersive disruption. Over time, some learners came to prefer traditional classroom modes that better supported peer interaction, spontaneous questioning, and collaborative problem-solving. This resonates with Vergara et al. (2019), who caution that poorly aligned IVR environments may inhibit communication, and with Cheng and Tsai (2020), who argue that immersion can compromise attention and interaction if

not carefully designed. Crucially, the analysis here distinguishes two sources of the observed criticism that the original framing tended to merge. On one hand, there are the pedagogically meaningful reflections recognizing that IVR suits some disciplines better than others. On the other hand, there are pragmatic and ergonomic objections, such as dizziness, headaches, connectivity, and syncing failures, which signal a hardware and implementation problem rather than the development of evaluative judgements. Thus, the implication is that IVR should complement rather than replace existing practice and that its value depends on thoughtful orchestration, capable of provoking reflective questioning while minimizing ergonomic friction (Anderson & Krathwohl, 2001; Cheng & Tsai, 2020).

These tensions connect this study to recent work such as Lampropoulos and Kinshuk's (2024) systematic review of VR and gamification, which stresses that learning gains depend on instructional design rather than immersion per se. This is consistent with our findings showing that engagement is a means and not an end. Bicalho et al. (2023) similarly report that, across higher-education practice, IVR's benefits are only realized under deliberate pedagogical framing. Wei et al. (2025), in a systematic review of presence across tasks and disciplines, caution that heightened presence does not automatically translate into deeper cognition, directly supporting our decision to treat reflective engagement as suggestive rather than demonstrated. Finally, Watted and Barak's (2024) analysis of engagement and challenges in technology-mediated learning underscores that attitudinal data are sensitive to usability and motivational friction, reinforcing our caution about attributing the behavioral intention decline solely to maturing judgement.

Engaging this body of work situates our modest, exploratory findings within current debates rather than overextending them. Several limitations of this study temper its findings while simultaneously suggesting avenues for future inquiry. First, the decrease from 20 to 16 participants constrained the analysis and may itself be partly attributable to physical intolerance of prolonged IVR use. Future studies should monitor and report discomfort systematically and treat it as a primary implementation variable. Second, the single age group, single context, and STEM-specific scenarios limit transferability, as does the absence of triangulating data such as interviews or classroom observations. Third, because the design was exploratory and the data were ordinal and small in volume, no inferential statistics were warranted. Future work with larger samples and validated, reliability-tested instruments could support significance testing and stronger comparative claims. Fourth, the conventional, non-adapted classroom may have amplified both technical frustration and communication barriers (Liu et al., 2020). Future research should therefore examine the intersection of learning spaces, interface and collaboration design, and teacher facilitation and investigate longer-term engagement across academic years to see how dispositions stabilize, as well as broadening samples across cultural and educational settings. Critically, future designs should also separate the contribution of the intervention's quality, such as lesson design and teacher orchestration, from the contribution of the technology, so that declines in enthusiasm can be attributed accurately.

A further limitation stems from the participants' limited prior exposure to IVR. While this allowed valuable insights into first-time encounters, it also restricted the extent to which longitudinal adaptation could be traced. Future research should investigate longer-term engagement, potentially across multiple academic years, to capture how dispositions and competences stabilize or evolve with sustained use. Additionally, broadening the sample to include cross-cultural contexts and diverse educational settings would help to identify whether the patterns observed here are context-specific or generalizable.

Finally, this study points to the crucial role of teachers. If IVR is to be constructively merged within curricula, educators must be equipped with pedagogical strategies to

harness immersive experiences without compromising interaction and communication. Professional development should emphasize not only technical fluency but also the design of authentic learning scenarios that balance immersion with collaboration and reflection. In this way, both teachers and students can act as agents of adaptive educational practice, developing the capacities needed to engage critically and constructively with disruptive technologies. Ultimately, this study affirms that, with innovative pedagogies, the cultivation of both cognitive and critical thinking is not an aspirational goal reserved for future educational design. Rather, wherever teachers have the courage to introduce disruptive technologies with clear pedagogical intent, it is already happening.

Author Contributions: P.C., the corresponding author, was involved in the design of the theoretical lens directed to gauging the perceptual development of the participants during the use of IVR for learning before and after the exercise was performed. In the process, he designed the questionnaires and wrote most of the paper. C.S.F. designed the methodology and collected the data. C.S.F. was also directly involved in rechecking and enhancing the original write-up and question set. She was also involved, along with P.C., in evaluating the outcomes of the questionnaires. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Consent to the publication of anonymized data was obtained from all participants or their legal guardians where required.

Data Availability Statement: All processed data are included in this paper. Additional materials or datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

VR	Virtual Reality
IVR	Immersive Virtual Reality
STEM	Science, Technology, Engineering, and Mathematics
TFR	Technological Frames of Reference
TAM	Technology Acceptance Model
HMD	Head-Mounted Display
PU	Perceived Usefulness
PEU	Perceived Ease of Use
BI	Behavioral Intention

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