

REPORT

Teachers' Perceptions of the Pedagogical Value and Classroom Integration of Immersive STEM Applications in Secondary Education

Training Event Evaluation Report

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Abstract

Immersive technologies offer opportunities to support the teaching of complex scientific concepts through visualization, experimentation, and interactive learning environments. However, their integration into secondary STEM education depends on teachers' perceptions of their pedagogical value and practical applicability. This study examines secondary school teachers' evaluations of five immersive STEM applications designed to address conceptual and procedural learning challenges through distinct instructional approaches. Using a quantitative approach, we collected data from 75 teachers across four European countries through a



STEM-IT questionnaire completed following professional development and classroom use. Each teacher evaluated one application in terms of usability, pedagogical suitability, perceived learning support, student engagement, and classroom integration. The findings indicate generally favorable perceptions of the applications' educational potential, although classroom integration received less positive evaluations. Following adjustment for multiple comparisons, significant differences between applications were identified only for perceived cross-curricular applicability. Furthermore, teachers' willingness to recommend an application was positively associated with perceived classroom integration, student engagement, and learning support. These findings highlight the importance of considering both pedagogical affordances and classroom implementation when designing immersive STEM resources and provide directions for their further development and evaluation.

Keywords: Augmented reality, Classroom integration, Immersive technologies, Secondary education, STEM education, Teacher perceptions, Virtual reality

Introduction

The integration of digital technologies into STEM education has introduced new opportunities for addressing the conceptual, practical, and pedagogical challenges associated with teaching complex scientific phenomena. Secondary school students are frequently required to develop an understanding of abstract concepts, interpret dynamic processes, and establish relationships between theoretical knowledge and observable phenomena (Christoforaki et al., 2026). However, conventional classroom instruction may offer limited opportunities for students to directly explore scientific phenomena that are difficult to observe, costly, impractical, or potentially dangerous to reproduce in physical learning environments (Blikstein et al., 2016; Koç & Kanadlı, 2025).

These challenges have encouraged the exploration of technology-enhanced learning environments that support scientific inquiry, experimentation, and the development of conceptual understanding. Within this educational landscape, augmented reality (AR) and virtual reality (VR) have emerged as promising technologies for creating interactive learning experiences that connect scientific knowledge with visual representations and simulated environments (Tene et al., 2024; Jiang et al., 2025).



STEM-IT AR and VR provide are distinct, however complementary approaches of representing and exploring scientific content (Jiang et al., 2025). AR integrates digital information, three-dimensional models, and interactive elements into the physical environment, enabling learners to examine scientific concepts within familiar educational contexts. In contrast, VR provides access to computer-generated environments in which users can explore simulated situations, manipulate virtual objects, and interact with representations of scientific phenomena. These technologies can be complemented by interactive three-dimensional learning environments and virtual laboratories that enable students to investigate scientific relationships through observation, experimentation, and the manipulation of variables. Such learning environments offer opportunities to visualize processes that are difficult to observe directly, including molecular interactions, energy transformations, biological structures, and environmental phenomena (Jiang et al., 2025).

The educational potential of immersive technologies extends beyond the visual representation of scientific information. Interactive learning environments can provide opportunities for students to engage in exploratory activities, formulate hypotheses, test alternative solutions, and examine the consequences of their actions (Udeozor et al., 2023). Through the manipulation of virtual objects and simulation parameters, learners can investigate relationships between scientific variables and connect theoretical principles with observable outcomes. Nevertheless, the educational contribution of these technologies depends on the relationship between their interactive features, the intended learning objectives, and the instructional activities through which students engage with the learning environment (Tene et al., 2024). Accordingly, the pedagogical integration of AR and VR requires consideration of how technological capabilities can support meaningful scientific inquiry rather than functioning as supplementary visual resources (Udeozor et al., 2023; Tene et al., 2024).

Teachers are responsible for selecting appropriate learning activities, aligning educational content with curricular objectives, adapting instructional approaches to students' developmental and cognitive characteristics, and organizing the conditions under which technology-enhanced learning takes place. Consequently, the educational value of AR and VR cannot be considered independently of the instructional contexts in which these technologies are implemented.



STEM-IT Research on digital technology integration in science education highlights the interdependence of technological resources, pedagogical practices, and disciplinary content (Walan, 2020). Teachers' positive perceptions of digital tools coexist with challenges in implementing inquiry-based teaching and adapting instruction to diverse learning needs, indicating that perceived usefulness does not necessarily translate into effective pedagogical integration (Walan, 2020). In immersive STEM education, teachers must therefore assess the alignment of applications with scientific concepts, cognitive demands, and instructional objectives (Udeozor et al., 2023). While AR facilitates the visualization of complex structures, virtual laboratories enable the manipulation of experimental variables and observation of simulated processes, and virtual exhibitions and interactive 3D environments support spatial exploration and multiple representations of scientific phenomena (Jiang et al., 2025). Selecting appropriate applications consequently requires consideration of their distinct pedagogical affordances, students' characteristics, and compatibility with existing classroom practices (Walan, 2020; Jiang et al., 2025).

These considerations are particularly relevant in secondary education, where teachers must balance curricular objectives, students' prior knowledge, instructional time, technological infrastructure, and classroom management. A systematic review of 117 studies on AR- and VR-supported K–12 STEM learning identified challenges related to instructional design, teachers' technological competence, classroom management, and institutional resources, while highlighting the limited representation of senior secondary education in the literature (Jiang et al., 2025). Understanding teachers' perspectives is therefore essential for evaluating the integration of immersive technologies into classroom practice. Their evaluations provide insights into application usability, content appropriateness, perceived contributions to student learning and participation, and compatibility with instructional requirements, while identifying opportunities to refine immersive educational resources for secondary STEM education.

Previous research has explored teachers' experiences with immersive technologies through professional development programmes and evaluations of educational applications. Lasica et al. (2020) examined teachers' acceptance of AR in STEM education in Cyprus and Greece, emphasizing the relationship between technological familiarization, pedagogical preparation, and classroom implementation. Similarly, Mystakidis and Christopoulos (2022)



STEM-IT investigated 41 in-service teachers' perceptions of VR escape rooms through questionnaires and a debriefing session, identifying factors influencing their potential integration into STEM instruction. While these studies highlight the importance of teachers' perspectives, further research is needed to examine how secondary school teachers evaluate the pedagogical and practical characteristics of different immersive learning environments following classroom use, particularly regarding usability, pedagogical suitability, and instructional integration.

The present study investigates secondary school teachers' evaluations of five immersive STEM applications with distinct instructional purposes and technological features, drawing on questionnaire responses from 75 educators following classroom use. It examines perceived usability, age appropriateness, learning support, student engagement, classroom integration, content reliability, and cross-curricular applicability, alongside teachers' willingness to recommend the applications and their suggestions for improvement. By considering the distinct pedagogical affordances of each application, the study explores the relationship between perceived educational value and practical classroom applicability, providing insights to inform the design and integration of immersive learning environments in secondary STEM education. Guided by this rationale, the present study addresses the following research questions:

(R.Q.1) How do secondary school teachers evaluate the usability, pedagogical suitability, perceived learning support, and classroom integration of the five immersive STEM applications following their use in instructional practice?

(R.Q.2) How are teachers' perceptions of the applications' usability, pedagogical value, and classroom integration associated with their willingness to recommend these applications to other educators?

By addressing these questions, the study seeks to provide empirical evidence concerning secondary school teachers' perceptions of immersive educational technologies following classroom use and to contribute to the understanding of how different AR-, VR-, and three-dimensional learning environments can be incorporated into STEM instructional practices.



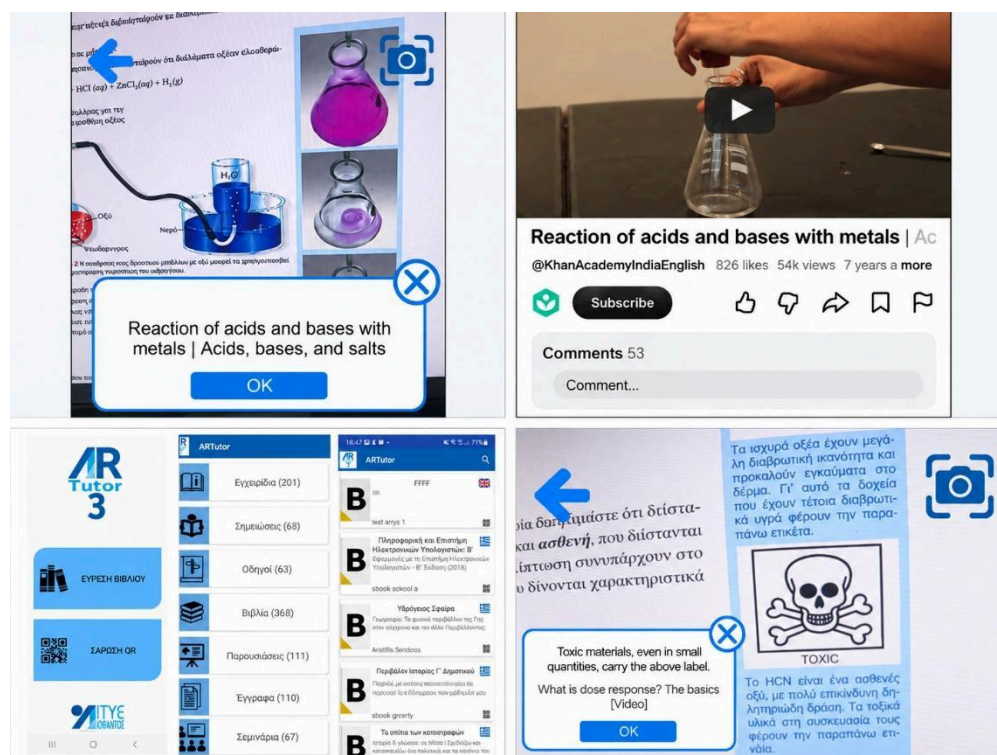
STEM-IT Immersive STEM applications

The five educational applications were designed in response to a systematic review of 204 empirical studies on secondary school students' comprehension and retention of STEM knowledge (Christoforaki et al., 2026). The review identified persistent difficulties in connecting conceptual understanding (knowing why) with procedural knowledge (knowing how), particularly in topics involving abstract representations, dynamic processes, and interdisciplinary relationships, including energy transformations, chemical bonding, biological processes, and climate and Earth systems. It also revealed limited evidence on long-term knowledge retention, with only four studies explicitly addressing this dimension. These findings directly informed the development of five pedagogically distinct applications, augmented instructional materials, a virtual exhibition, an interactive scientific laboratory, a three-dimensional model viewer, and a scenario-based learning environment, designed to offer complementary opportunities for scientific visualization, exploration, experimentation, and contextualized reasoning.

AR Tutor

The first application comprises two augmented chemistry learning units on acids, bases, and salts, prepared for middle- and high-school students using the existing AR Tutor platform (Image 1). Students scan designated images in printed or digital educational materials to access supplementary resources, including visual and interactive representations. The application retains the structure of conventional instructional material while providing additional ways to examine the scientific content. Its inclusion was informed by the review's identification of difficulties in connecting chemical representations and procedures with the concepts underlying observable phenomena. Within this context, the augmented materials were intended to complement written explanations and classroom discussion by making additional representations accessible at relevant points in the learning activity.

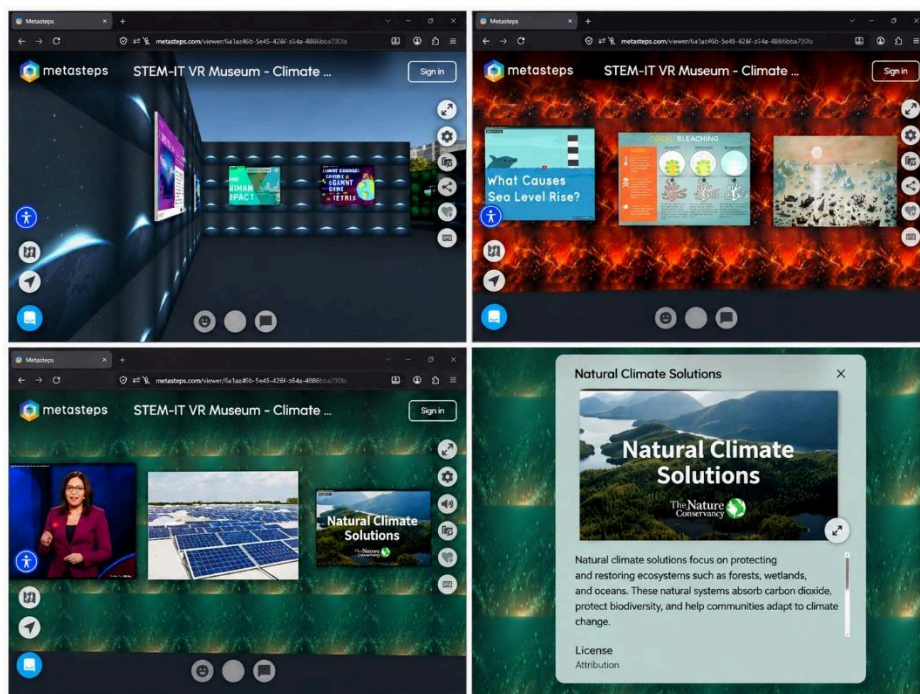
Image 1 The AR Tutor



VR Museum

The second application is a virtual museum (Image 2) addressing climate change through six thematic rooms. Students explore the exhibition by navigating between sections devoted to fundamental concepts, scientific evidence, climate mechanisms, environmental consequences, population displacement, and potential responses. Information is presented through a combination of text, images, videos, and three-dimensional elements, followed by a concluding quiz. The selection of this format was informed by the review's identification of difficulties in understanding climate systems and reasoning about interactions between environmental processes and human activities. By organizing related topics within a navigable exhibition, the application was designed to support the exploration of climate change as an interconnected scientific and societal issue.

Image 2 VR Museum



EnergyLab VR

The third application, EnergyLab VR, is an interactive virtual laboratory comprising six experiments related to heat, energy, and thermodynamics (Image 3). Students engage in activities involving liquid mixing and heat transfer, friction, an electric-motor scenario, solar-panel orientation, and other relationships between energy input and observable outcomes. Some activities require students to reach teacher-defined targets, whereas others permit the exploratory manipulation of variables. This format was selected in response to the review's identification of difficulties in connecting the procedural application of physical relationships with explanations of the mechanisms governing energy transfer and transformation. Unlike applications primarily intended for the presentation or examination of scientific information, EnergyLab VR places the manipulation of experimental conditions and interpretation of simulated outcomes at the center of the learning activity.

Image 3 EnergyLab VR



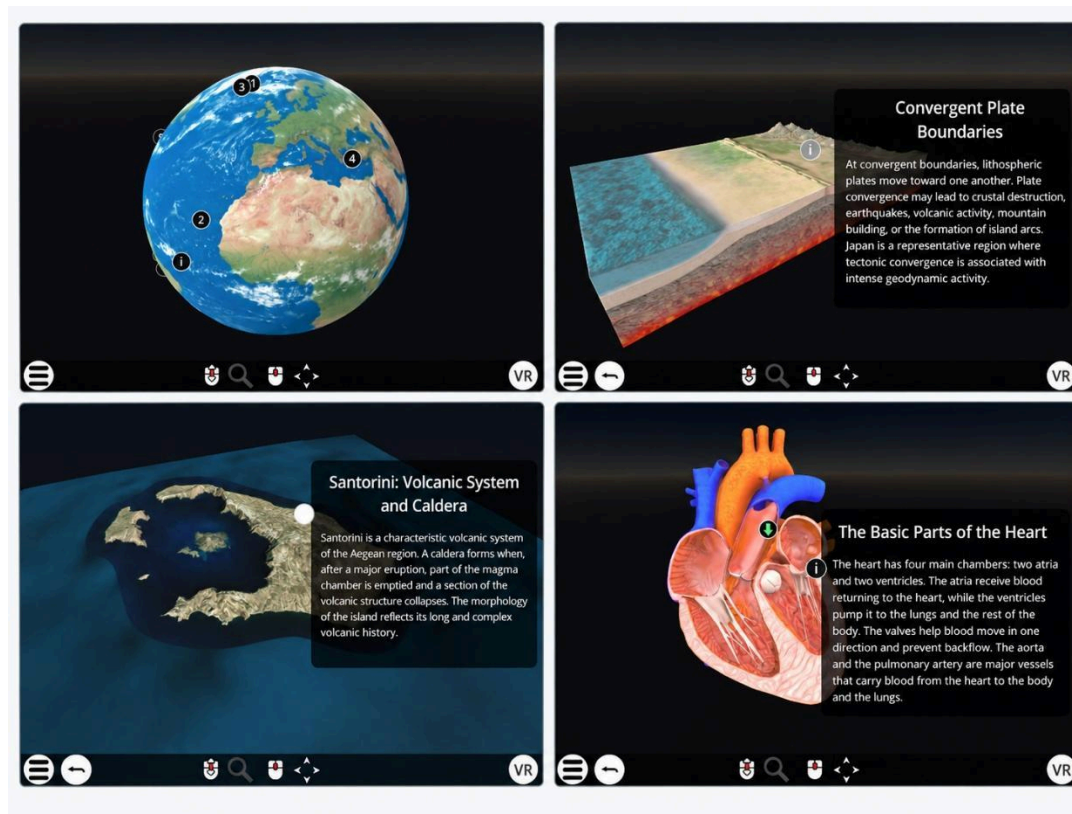
SCP 3D Model Viewer

The fourth application, SCP 3D Model Viewer (Image 4), allows students to rotate, enlarge, and inspect three-dimensional models while accessing contextual information through selectable points of interest. Its educational scenarios address the human heart and earthquakes, enabling the examination of biological structures and Earth-related phenomena through interactive spatial representations. The application was included to provide a form of exploration distinct from both virtual experimentation and navigation through an exhibition. Its instructional emphasis is the examination of structures and spatial relationships, offering opportunities to connect information about scientific phenomena with representations that can be manipulated and viewed from



STEM-IT different perspectives. This approach is consistent with the review's broader identification of difficulties associated with interpreting complex scientific structures and processes, although the two scenarios should not be understood as directly addressing every biological or Earth-science topic identified in that review.

Image 4 SCP 3D Model Viewer



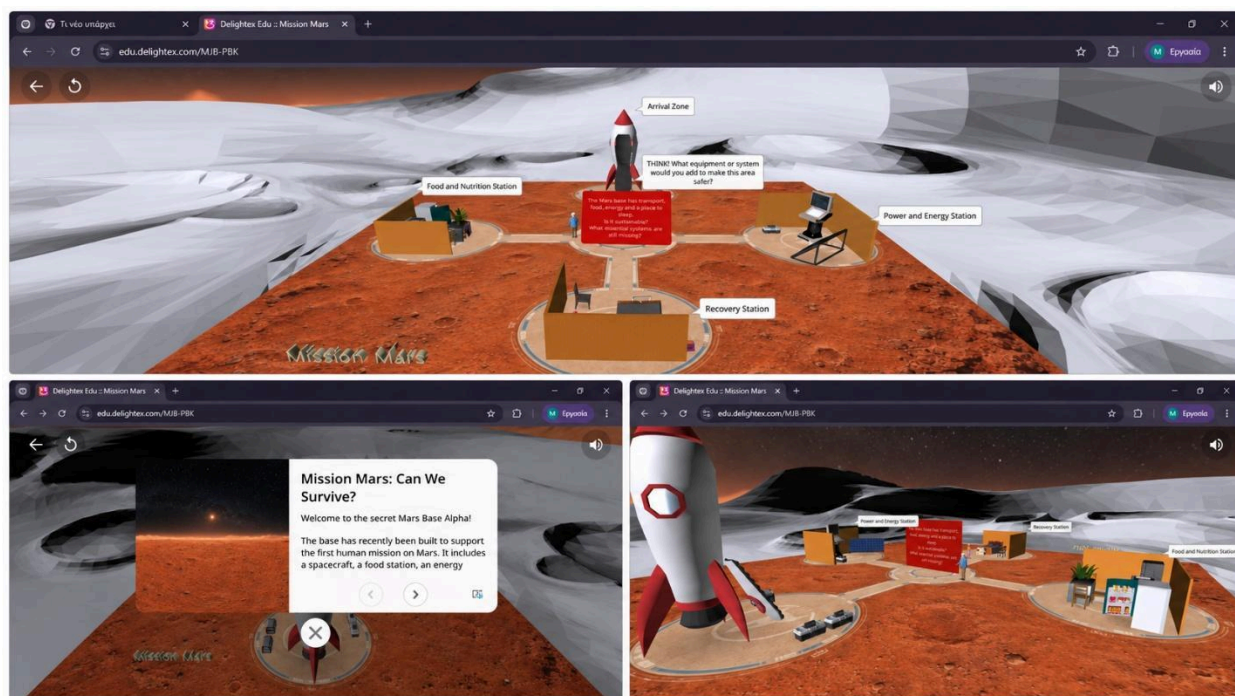
Scenario-Based Learning: “Mission Mars: Can We Survive?”

The fifth application, “Mission Mars: Can We Survive?”, is an interactive three-dimensional learning scenario created using Delightex Edu (Image 5). Students explore a fictional human base on Mars and examine areas associated with arrival, energy supply, accommodation, and food provision. Guided by a character who introduces questions at successive locations, they identify essential systems that are missing from the base and discuss whether it could support sustained human habitation. The application was included to extend the range of instructional approaches from the examination of individual scientific phenomena towards the investigation of a contextualized problem requiring the coordination of knowledge from different domains. This



STEM-IT design responds to the review's emphasis on the challenges associated with interdisciplinary synthesis and systems-level reasoning in integrated STEM contexts.

Image 5 “Mission Mars: Can We Survive?”



The selection of these five applications with distinct instructional purposes was informed by the conceptual and procedural challenges identified in the preceding systematic review and aimed to address them through complementary pedagogical approaches. AR Tutor enriches conventional instructional materials with augmented content; the VR Museum supports the exploration of interconnected scientific concepts within a spatially structured exhibition; EnergyLab VR enables experimentation through the manipulation of variables; SCP 3D Model Viewer facilitates the examination of complex scientific structures; and “Mission Mars” promotes the application of interdisciplinary knowledge to a contextualized problem. Together, these applications provide diverse opportunities for scientific visualization, exploration, experimentation, and reasoning through different forms of interaction with scientific content.

Materials and methods

Participants

The study involved 75 secondary school teachers from four countries: Greece ($n = 37$), Cyprus ($n = 17$), Italy ($n = 12$), and Malta ($n = 9$). Participants were recruited through voluntary participation using a convenience sampling approach. The teachers were introduced to the immersive STEM applications during professional development activities and subsequently used an application in their own classrooms. Each participant completed one questionnaire evaluating the specific application they had used, rather than assessing all five applications collectively. The responses were recorded between 29 and 30 June 2026.

Research design

We adopted a quantitative, cross-sectional research design to investigate secondary school teachers' perceptions of five immersive STEM applications following their use in instructional practice. The study employed a post-use digital questionnaire to assess the perceived pedagogical and practical characteristics of each application. Participants evaluated the application they had used, resulting in separate groups of teacher evaluations corresponding to the five educational tools. This design allows for the examination of teachers' perceptions within each application group and, where the data permit, comparisons of evaluation patterns across applications with different instructional purposes and technological characteristics. As participants were not randomly assigned to applications, the study was designed to identify differences in reported perceptions rather than establish causal effects attributable to an application's technological format.

Research instrument

A digital questionnaire (Table 1) was used to assess secondary school teachers' perceptions of the immersive STEM application they had used, comprising the application name, country of employment, and eight statements rated on a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The evaluation dimensions were consistent with established frameworks addressing perceived ease of use and usefulness (Davis, 1989), educational resource quality



STEM-IT (Leacock & Nesbit, 2007), and the integration of technology, pedagogy, and disciplinary content (Mishra & Koehler, 2006). Face validity was assessed by two science education experts, who reviewed the questionnaire items for clarity, relevance, and appropriateness. The questionnaire was limited to eight items to assess distinct pedagogical and practical characteristics while minimizing respondent burden (Galesic & Bosnjak, 2009). All items were positively worded, therefore, no reverse coding was required, although this design may increase susceptibility to acquiescence bias (Chyung et al., 2018). The items were analyzed separately rather than assumed to constitute a validated, unidimensional scale.

Table 1 Items of the teacher evaluation questionnaire

Item	Statement
Q1	The application was easy to use and navigate.
Q2	The content and features of the application are appropriate for the students' level.
Q3	The application can effectively support the learning process.
Q4	The application enhances students' interest and participation.
Q5	The application can be easily integrated into classroom teaching.
Q6	The content and information provided by the application are considered reliable and appropriate.
Q7	The application could also be used in other subjects.
Q8	I would recommend the application to other teachers.

The eight items demonstrated high internal consistency (Cronbach's $\alpha = .926$), all above acceptance levels according to Nunnally (1978). Nevertheless, as the statements address conceptually distinct aspects of application evaluation, they were examined individually rather than assumed to constitute a validated, unidimensional scale (Table 2).

Table 2 Item-Level Descriptive Statistics and Internal Consistency of the Teacher Evaluation Questionnaire

Item	M	SD	Mdn	Q1–Q3	Agreement (%)	Corrected item–total r	α if deleted
Q1	3.81	1.01	4	3–5	65.3	.657	.923
Q2	4.13	0.98	4	4–5	78.7	.794	.912
Q3	4.12	1.00	4	3–5	73.3	.793	.912
Q4	4.27	0.88	5	4–5	80.0	.744	.917
Q5	3.64	1.14	4	3–5	56.0	.800	.912
Q6	4.16	0.90	4	4–5	80.0	.803	.912
Q7	4.12	1.09	5	3–5	74.7	.595	.929
Q8	4.00	0.97	4	3–5	73.3	.835	.909

Note. $N = 75$ for each item. M = mean; SD = standard deviation; Mdn = median; $Q1$ – $Q3$ = first and third quartiles. Agreement represents the percentage of responses rated 4 (agree) or 5 (strongly agree). Corrected item–total r is the correlation between each item and the sum of the remaining seven items.

Usability, pedagogical suitability, learning support, and classroom integration

The analysis included 75 teacher evaluations distributed across five applications: AR Tutor (n = 13), VR Museum (n = 10), EnergyLab VR (n = 14), SCP 3D Model Viewer (n = 23), and Mission Mars (n = 15). The seven items addressing the applications' pedagogical and practical characteristics were examined separately (Table 3).

Table 3 Descriptive Statistics for Teachers' Evaluations of the Five Immersive STEM Applications

Item	AR Tutor (n = 13)			VR Museum (n = 10)			EnergyLab VR (n = 14)			SCP 3D Model Viewer (n = 23)			Mission Mars (n = 15)		
	M	SD	AP	M	SD	AP	M	SD	AP	M	SD	AP	M	SD	AP
Q1. Ease of use	4.15	0.90	84.6%	3.70	1.16	60.0%	3.29	1.07	42.9%	3.91	0.85	69.6%	3.93	1.10	66.7%
Q2. Appropriateness for students' level	4.15	0.80	76.9%	3.90	1.45	60.0%	3.57	1.02	57.1%	4.48	0.73	95.7%	4.27	0.88	86.7%
Q3. Perceived learning support	4.00	1.00	69.2%	4.20	0.92	70.0%	3.64	0.93	50.0%	4.43	0.84	87.0%	4.13	1.25	80.0%
Q4. Perceived student interest and participation	4.08	0.86	69.2%	4.10	0.88	70.0%	3.71	1.14	50.0%	4.65	0.49	100.0%	4.47	0.83	93.3%
Q5. Ease of classroom integration	3.46	1.13	53.8%	3.60	1.26	60.0%	3.29	1.20	35.7%	3.96	0.98	60.9%	3.67	1.23	66.7%
Q6. Content reliability and appropriateness	4.23	0.73	84.6%	4.00	1.05	70.0%	3.71	0.91	57.1%	4.52	0.59	95.7%	4.07	1.16	80.0%
Q7. Cross-curricular applicability	4.54	0.66	92.3%	4.80	0.42	100.0%	3.07	1.07	35.7%	4.13	1.10	73.9%	4.27	1.10	80.0%

Teachers' evaluations varied across the five applications. AR Tutor received favorable ratings for ease of use (M = 4.15; 84.6% agreement), content reliability (M = 4.23; 84.6%), and cross-curricular applicability (M = 4.54; 92.3%), while classroom integration received a lower rating (M = 3.46; 53.8%). Similarly, the VR Museum was positively evaluated for learning support (M = 4.20; 70.0%) and student interest and participation (M = 4.10; 70.0%), with unanimous agreement on its cross-curricular applicability (M = 4.80), although ease of use and classroom integration received lower ratings (M = 3.70 and 3.60, respectively; 60.0% agreement).



STEM-IT each). EnergyLab VR received ratings of 3.64 for learning support and 3.71 for student interest and participation (50.0% agreement each), compared with 3.29 for both ease of use and classroom integration (42.9% and 35.7% agreement, respectively) and 3.07 for cross-curricular applicability (35.7%). SCP 3D Model Viewer received favorable evaluations for student interest and participation ($M = 4.65$; 100.0% agreement), content reliability ($M = 4.52$; 95.7%), appropriateness for students' level ($M = 4.48$; 95.7%), and learning support ($M = 4.43$; 87.0%), whereas classroom integration received a rating of 3.96 (60.9%).

Mission Mars was positively evaluated for student interest and participation ($M = 4.47$; 93.3%), appropriateness for students' level ($M = 4.27$; 86.7%), learning support ($M = 4.13$; 80.0%), and cross-curricular applicability ($M = 4.27$; 80.0%), while ease of use and classroom integration received ratings of 3.93 and 3.67, respectively (66.7% agreement each). Across the applications, classroom integration generally received less favorable evaluations than their perceived pedagogical characteristics.

To examine differences in teachers' evaluations across the five independent application groups, a Kruskal–Wallis test was conducted for each of the seven items (Table 4). The resulting p values were adjusted using the Holm procedure to account for multiple testing. Table 4 presents the omnibus test statistics and adjusted significance levels.

Table 4 Kruskal–Wallis Tests Comparing Teachers' Evaluations Across the Five Applications

Item	H(4)	p	Holm-adjusted p	ϵ^2
Q1. Ease of use	5.515	.238	.477	.022
Q2. Appropriateness for students' level	8.538	.074	.369	.065
Q3. Perceived learning support	6.993	.136	.467	.043
Q4. Perceived student interest and participation	9.805	.044	.263	.083
Q5. Ease of classroom integration	3.243	.518	.518	.000
Q6. Content reliability and appropriateness	7.387	.117	.467	.048
Q7. Cross-curricular applicability	18.937	<.001	.006	.213

Note. $N = 75$. $H(4)$ = Kruskal–Wallis test statistic with four degrees of freedom; p = unadjusted significance level; Holm-adjusted p = significance level adjusted for seven comparisons; ϵ^2 = epsilon-squared effect size. Statistical significance was assessed at $\alpha = .05$. The values for 17 were completed using the results presented in the preceding analysis.

After adjustment for multiple testing, only cross-curricular applicability differed significantly across applications, $H(4) = 18.94$, $p < .001$, Holm-adjusted $p = .006$, $\epsilon^2 = .213$; the



STEM-IT other six items, including perceived student interest and participation (unadjusted $p = .044$; adjusted $p = .263$), were not statistically significant. Holm-adjusted post hoc Mann–Whitney U tests identified differences between EnergyLab VR and AR Tutor ($U = 158.5$, adjusted $p = .007$), VR Museum ($U = 130.0$, adjusted $p = .003$), and Mission Mars ($U = 44.0$, adjusted $p = .0499$), with EnergyLab VR receiving lower cross-curricular applicability ratings in each comparison; no other pairwise differences were significant. These findings reflect teachers’ perceptions following classroom use and, given the non-randomized design, cannot establish that the observed differences resulted from the applications’ technological characteristics or indicate differences in students’ actual learning or participation.

Association between teachers’ perceptions of usability, pedagogical value, classroom integration, and willingness to recommend the five immersive STEM applications

Teachers’ willingness to recommend the applications was assessed through item I8. Descriptive statistics were calculated separately for each application (Table 5), followed by Spearman’s rank-order correlations between I8 and the seven remaining evaluation items (Table 6). The correlations were examined both within individual application groups and across the complete sample.

Table 5 Descriptive Statistics for Teachers’ Willingness to Recommend the Five Immersive STEM Applications

Application	n	M	SD	Mdn	Agreement (%)
AR Tutor	13	4.15	0.69	4	84.6
VR Museum	10	4.00	0.94	4	60.0
EnergyLab VR	14	3.21	1.19	3	42.9
SCP 3D Model Viewer	23	4.43	0.66	5	91.3
Mission Mars	15	3.93	1.03	4	73.3
Overall	75	4.00	0.97	4	73.3

Note. M = mean; SD = standard deviation; Mdn = median. Agreement represents the percentage of teachers selecting 4 (agree) or 5 (strongly agree) in response to I8: “I would recommend the application to other teachers.”

Teachers’ willingness to recommend the applications was generally favorable for AR Tutor ($M = 4.15$, $SD = 0.69$; 84.6% agreement), VR Museum ($M = 4.00$, $SD = 0.94$; 60.0%), SCP 3D Model Viewer ($M = 4.43$, $SD = 0.66$; 91.3%), and Mission Mars ($M = 3.93$, $SD = 1.03$; 73.3%), while EnergyLab VR received a mean rating of 3.21 ($SD = 1.19$; 42.9%). Across all five applications, willingness to recommend was positively associated with perceived learning support ($\rho =$



STEM-IT

.591–.909), student interest and participation ($\rho = .603$ –.949), and classroom integration ($\rho = .491$ –.930). Associations with ease of use varied, ranging from negligible for AR Tutor ($\rho = .041$) to positive for VR Museum ($\rho = .803$), EnergyLab VR ($\rho = .506$), SCP 3D Model Viewer ($\rho = .467$), and Mission Mars ($\rho = .491$). These application-specific correlations should be interpreted cautiously given the small group sizes, particularly for VR Museum ($n = 10$).

Table 6 Associations Between Application Evaluation Items and Teachers' Willingness to Recommend the Applications

Item	AR Tutor	VR Museum	EnergyLab VR	SCP 3D Model Viewer	Mission Mars	Overall ρ	Adjusted ρ
Q1. Ease of use	.041	.803	.506	.467	.491	.547	.529
Q2. Appropriateness for students' level	.068	.891	.910	.589	.483	.646	.599
Q3. Perceived learning support	.591	.909	.731	.664	.666	.711	.685
Q4. Student interest and participation	.669	.949	.756	.624	.603	.736	.722
Q5. Classroom integration	.717	.930	.850	.491	.897	.756	.759
Q6. Content reliability and appropriateness	.390	.796	.818	.589	.602	.692	.654
Q7. Cross-curricular applicability	.281	.559	.820	.593	.579	.581	.570

Across the complete sample, willingness to recommend an application was positively associated with all seven evaluation dimensions, with Spearman's coefficients ranging from .547 to .756 (Table 6). The associations with classroom integration ($\rho = .756$), perceived student interest and participation ($\rho = .736$), and perceived learning support ($\rho = .711$) were particularly pronounced. Positive associations were also observed with content reliability ($\rho = .692$), appropriateness for students' level ($\rho = .646$), cross-curricular applicability ($\rho = .581$), and ease of use ($\rho = .547$). All seven associations remained statistically significant after Holm adjustment for multiple testing ($p < .001$).



STEM-IT To account for differences between application groups, partial rank correlations were calculated by removing application-group effects from the ranked responses. Statistical significance was assessed using 50,000 permutations restricted within application groups, followed by Holm correction across the seven comparisons. The associations remained positive and statistically significant after adjustment, with coefficients ranging from .529 to .759 (all Holm-adjusted $p < .001$). Classroom integration retained a correlation of $\rho = .759$, followed by student interest and participation ($\rho = .722$) and perceived learning support ($\rho = .685$). Thus, the associations observed in the complete sample were not solely attributable to differences between the five application groups.

The application-specific analyses showed variation in the magnitude of the observed associations, particularly for ease of use and classroom integration. Nevertheless, these differences between correlation coefficients were not formally tested and should not be interpreted as evidence that the relationships differ statistically across applications. Furthermore, the cross-sectional, self-reported nature of the data does not establish that any particular application characteristic independently determines teachers' willingness to recommend it.

Discussion

The present study investigated secondary school teachers' perceptions of five immersive STEM applications following their use in classroom instruction, examining both their perceived pedagogical and practical characteristics and the relationship between these evaluations and teachers' willingness to recommend the applications. The selection of pedagogically distinct tools was informed by a preceding systematic review that identified persistent difficulties in secondary school students' conceptual and procedural understanding of STEM subjects, particularly when scientific phenomena require the coordination of abstract representations, dynamic processes, and knowledge across disciplines (Christoforaki et al., 2026). The present findings provide evidence of how teachers perceive educational resources designed to offer different forms of scientific visualization, exploration, experimentation, and contextualized reasoning. They also indicate that favorable perceptions of an application's educational potential do not necessarily coincide with equally favorable evaluations of its practical integration into classroom teaching.



STEM-IT Across the five applications, teachers generally expressed positive perceptions of their potential to support learning and enhance students' interest and participation. The latter received 80.0% agreement across the full sample, compared with 56.0% for ease of classroom integration. This distinction suggests that teachers may recognize the educational possibilities of immersive resources while encountering greater uncertainty about incorporating them into established instructional practices. Similar considerations emerge in Walan's (2020) investigation of digital technology use in secondary science classrooms, which highlights the relationship between technological resources, pedagogical decisions, and the conditions of classroom implementation. Furthermore, Jiang et al. (2025), in their systematic review of AR- and VR-supported K–12 STEM learning, identified challenges concerning instructional design, teachers' technological competence, classroom management, and institutional resources. Although the present questionnaire did not directly measure these factors, the comparatively less favorable evaluations of classroom integration suggest that the practical conditions of implementation warrant further investigation.

The application-specific findings provide a more differentiated perspective. AR Tutor received favorable evaluations for usability, content reliability, and cross-curricular applicability, whereas classroom integration was rated less positively. Its use of augmented instructional materials may offer opportunities to introduce additional scientific representations without replacing familiar teaching resources; nevertheless, the teachers' responses indicate that the perceived accessibility of an application should be distinguished from the ease with which it can be incorporated into a lesson. Similarly, the VR Museum received positive evaluations for perceived learning support and student engagement, while all ten respondents considered it potentially applicable to other subjects. The exhibition's coverage of scientific mechanisms, environmental consequences, and societal responses may help explain this perception of cross-curricular potential, although the study did not establish whether teachers subsequently used the application beyond its original instructional context.

EnergyLab VR exhibited a different evaluation pattern. Half of its respondents agreed that the application could support learning and enhance students' interest and participation, while 35.7% agreed that it could be easily integrated into classroom teaching or used in other subjects. The application's concentration on thermodynamics and the manipulation of experimental



STEM-IT variables provides a possible explanation for its more restricted perceived cross-curricular applicability: teachers may have associated its activities primarily with specific physics learning objectives. Its classroom-integration ratings may also reflect the demands of organizing simulation-based activities, although the questionnaire did not investigate these demands directly. These findings therefore identify aspects of EnergyLab VR that merit closer examination, without establishing that its technological format or instructional design caused the observed evaluations. The distinction between technological possibilities and pedagogical implementation is consistent with the broader challenges identified by Jiang et al. (2025).

The SCP 3D Model Viewer received favorable evaluations for content reliability, appropriateness for students' learning level, and perceived learning support; all 23 respondents agreed that it enhanced students' interest and participation. Mission Mars was also positively evaluated for perceived student engagement, with 93.3% agreement, alongside favorable assessments of learning support and cross-curricular applicability. These responses may reflect the different opportunities offered by the two applications: SCP 3D Model Viewer allows students to examine scientific structures through interactive spatial representations, whereas Mission Mars situates scientific information within a problem requiring consideration of several interdependent systems. Their instructional characteristics are consistent with the rationale established in the preceding review, which emphasized difficulties in interpreting complex scientific representations and integrating knowledge across STEM domains (Christoforaki et al., 2026). Nevertheless, the present results concern teachers' perceptions of these opportunities. They do not demonstrate that students developed stronger conceptual understanding, interdisciplinary reasoning, or problem-solving skills as a result of using either application.

Despite the descriptive variation across the five applications, the inferential analysis identified a statistically significant between-application difference only for perceived cross-curricular applicability after correction for multiple testing, $H(4) = 18.94$, Holm-adjusted $p = .006$, $\varepsilon^2 = .213$. Post hoc comparisons indicated lower ratings for EnergyLab VR than for AR Tutor, the VR Museum, and Mission Mars, with the comparison involving Mission Mars close to the adjusted significance threshold. No statistically significant between-application differences remained for the other six pedagogical and practical evaluation items. Consequently, the descriptive differences in usability, learning support, student engagement, and classroom



STEM-IT integration should not be interpreted as established differences between applications. The cross-curricular finding instead draws attention to teachers' perceptions of the scope within which an educational resource can be used. It may reflect differences in subject-specific content and instructional purpose, rather than the relative educational value of the technologies themselves. Moreover, perceived applicability to other subjects should not be equated with demonstrated transfer of students' knowledge across disciplines.

The second research question examined how teachers' evaluations were associated with their willingness to recommend an application to colleagues. Across the full sample, willingness to recommend was positively correlated with all seven evaluation dimensions. The strongest observed associations concerned classroom integration ($\rho = .756$), perceived student interest and participation ($\rho = .736$), and perceived learning support ($\rho = .711$). These associations remained positive after accounting for application-group membership, suggesting that they were not explained solely by differences in the evaluations of the five applications. The findings indicate that teachers who reported more favorable perceptions of an application's educational contribution and practical applicability also tended to express greater willingness to recommend it. This pattern is compatible with research on technology acceptance that identifies perceived usefulness and ease of use as relevant to users' acceptance of digital systems (Davis, 1989). However, the present questionnaire was not designed as a validated Technology Acceptance Model instrument, and willingness to recommend an application is distinct from both an intention to use it routinely and observed classroom adoption.

The association between classroom integration and willingness to recommend deserves particular attention because classroom integration received less favorable descriptive evaluations than several of the pedagogical items. Teachers may regard a resource as educationally promising without considering it straightforward to implement, whereas those who perceive it as compatible with classroom practice may also be more inclined to recommend it. The application-specific correlations provide further descriptive support for examining this relationship, although their magnitudes varied and the subgroup samples were small. These findings reinforce the importance of evaluating immersive educational resources in relation to their intended instructional activities and the contexts in which teachers use them. They do not



STEM-IT establish that improving classroom integration would, by itself, increase recommendation rates: the study's cross-sectional design cannot determine the direction of the observed associations.

An additional distinction concerns the relationship between perceived student engagement and learning. Teachers' favorable evaluations of the applications' contribution to interest and participation should not be interpreted as evidence of improved learning outcomes. In an experimental study involving university students, Makransky et al. (2019) found that an immersive version of a science laboratory simulation increased participants' sense of presence but produced lower learning performance than a desktop version. Although that study involved a different population and design, it illustrates why positive experiences with immersive technology should not be treated as interchangeable with demonstrated learning gains. In the present research, teachers' perceptions offer information about the applications' potential role in STEM instruction, while direct assessments would be required to establish their effects on students' conceptual understanding, procedural knowledge, or retention.

The findings have implications for the subsequent development and implementation of the five applications. The comparatively less favorable evaluations of classroom integration suggest the value of examining how each resource fits within lesson objectives, available instructional time, classroom organization, and teachers' existing practices. For EnergyLab VR, further investigation could focus on the conditions required to incorporate virtual experimentation into physics lessons and on whether its activities can be adapted to other instructional contexts. For applications perceived as broadly applicable across subjects, subsequent research could examine how teachers adapt their content to different curricula and whether such adaptations support interdisciplinary learning. Professional development could address these questions through application-specific lesson planning and opportunities for teachers to reflect on classroom use, rather than focusing exclusively on familiarity with the technology. Such an approach is consistent with research emphasizing that meaningful integration depends on pedagogical preparation and instructional context (Walan, 2020; Jiang et al., 2025).



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Overall, the study contributes to the evaluation of immersive STEM resources by examining five applications with distinct instructional purposes through a common teacher-evaluation framework. Teachers generally perceived opportunities for learning support and student engagement across the applications, while their assessments of classroom integration were less consistently favorable. Cross-curricular applicability was the only evaluation dimension for which the analysis established a statistically significant difference across application groups after adjustment for multiple testing. At the same time, perceived classroom integration, student engagement, and learning support were positively associated with willingness to recommend an application. These findings suggest that the educational development of immersive STEM resources should consider both the learning activities they are intended to support and the practical conditions of their classroom use. Their contribution to students' learning, including the conceptual and procedural challenges that originally informed their design, remains an important question for subsequent research.

Limitations

The study's convenience sampling, small and unequal application groups, and non-random assignment limit the generalizability of the findings. Self-reported evaluations may be subject to response bias, while the brief questionnaire did not capture potentially relevant teacher- and classroom-related factors. Although the items demonstrated high internal consistency, the instrument was not established as a validated, unidimensional scale. Future research should employ larger, more representative samples and combine teachers' evaluations with classroom observations and direct assessments of students' learning and knowledge retention.

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