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Research article

Multiple representations framework in technology acceptance: A structural equation modeling of science educational videos in teaching and learning redox reactions

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Abstract: This study explored the role of the Multiple Representations Framework (MR) within the Technology Acceptance Model (TAM) in understanding pre-service teachers' acceptance of science educational videos in teaching and learning redox reactions. Conducted within the context of an analytical chemistry course, the study employed partial least squares structural equation modeling (PLS-SEM) to analyze the relationships between perceived ease of use (PEU), perceived usefulness (PU), and intention to use (IU), integrating motivation as a key variable. Descriptive statistics revealed positive perspectives on macroscopic, microscopic, and symbolic representations, as well as favorable views on TAM constructs. The measurement model confirmed the reliability and validity of the instruments, with strong outer loadings, internal consistency, and discriminant validity. MR significantly impacted PU and mediated the relationships between PEU, PU, and IU, highlighting its central role in enhancing perceived usefulness. However, MR did not moderate the relationship between PEU and PU, and PEU alone did not directly influence IU. These findings underscore the significance of content quality and representation in influencing technology adoption. The study concludes that integrating MR into educational tools improves conceptual understanding and supports technology adoption. It recommends incorporating MR-based resources into STEM curricula and providing professional development for educators to optimize their design and application.

Keywords: multiple representations, redox reactions, science educational videos, technology

acceptance

1. Introduction

The abstract nature of chemistry concepts and the requirement to integrate learning across different levels make these concepts intrinsically difficult for students [1,2]. To understand these concepts, students must synthesize information from various perspectives. The Chemistry Triangle, developed by Johnstone [3], provides a framework for viewing these concepts from different perspectives using multiple representations (MR). In this framework, students can learn chemistry effectively if they can conceptualize and connect various representations: macroscopic (observable phenomena), microscopic (particulate interactions), and symbolic (mathematical equations and formulas). When appropriately utilized, each representation supports a more thorough understanding of complex concepts and is essential in helping students navigate the complexity of chemistry [4].

Technology is integrated and used in the science classroom to overcome the challenges of teaching and learning complex concepts [5]. Videos, animations, and simulations are examples of technology-integrated tools that can dynamically and interactively represent chemical phenomena. In particular, videos enable the integration of MR, allowing students to observe macroscopic changes in reactions, view the microscopic particulate behavior, and understand the symbolic equations that define and describe those reactions [6]. The multifaceted nature of videos that illustrate chemistry concepts helps students connect various modes of representation, which is particularly important for topics that involve complex changes in matter, such as oxidation-reduction (redox) reactions [7]. However, despite the apparent promise of such technology tools, challenges remain in exploring how well these videos affect learning and engagement, especially in pre-service science teacher education programs.

While the advantages of using videos are becoming increasingly acknowledged [8], a significant theoretical and practical gap remains in understanding how they can be effectively utilized to teach complex chemistry concepts. Although the advantages of employing MR in teaching and learning have been studied, few empirical studies have examined how videos can help integrate these representations in chemistry, as seen in the work of Erlina [9] and Fatmala et al. [10]. Additionally, limited studies discuss the use of videos to teach redox reactions, such as the research conducted by Astuti and Kamaludin [11], which focuses on how they affect students' conceptual understanding and engagement. More significantly, the research has not encountered studies on how the representations in the videos affect students' acceptance of the technology, including its perceived usefulness and ease of use, as studies focus only on technology acceptance, as evident in the investigations of Shukor et al. [12] and Guion et al. [13]. This gap highlights the need for studies examining the effectiveness of MR in video-based learning and the factors influencing students' acceptance of technology in science educational settings.

Frameworks such as the Technology Acceptance Model (TAM) provide valuable insights into how technology affects the learning of complex chemistry concepts. TAM focuses on two crucial factors influencing students' likelihood of accepting and adopting a technology: perceived ease of use (PEU) and perceived usefulness (PU) [14]. This makes TAM a framework for understanding how macroscopic, microscopic, and symbolic chemical modes affect the effectiveness and acceptance of instructional technologies when paired with MR. In particular, MR may act as a direct effect variable in improving students' acceptance of the value of videos in teaching redox reactions. On the other hand, MR may act as a mediating variable, influencing how learning outcomes are affected by the perceived ease and benefits of the videos for students. Lastly, depending on how well the representations are included in the video content, MR may serve as a moderating variable, affecting the degree of the association between student learning and technological acceptance.

Although MR and TAM may work well together in other contexts, such as immersive technologies [7], a significant gap remains in the literature regarding the specific roles that MR plays in technology acceptance. Although both frameworks are well-known in their fields, little is known about how they interact. Specifically, it remains unclear whether MR can have a direct, mediating, or moderating effect on technology acceptance or if these functions vary depending on the particular context in which the technology is employed. These gaps highlight the need for further examination, specifically studying how students perceive the usefulness and usability of the videos while evaluating the effectiveness of video-based learning for complex chemistry concepts.

This study investigated the impact of MR on pre-service science teachers' acceptance of technology, particularly when using videos to teach complex chemistry concepts, such as redox reactions, using structural equation modeling (SEM). Using the TAM, it investigated whether MR directly impacts and mediates the relationship between PEU and PU or moderates it. By understanding these roles, the study shed further light on how incorporating macroscopic, microscopic, and symbolic representations in video-based learning impacts pre-service teachers' acceptance and use of technology in chemistry instruction.

The study's findings have significant implications for how complex chemistry concepts are taught and learned, as they inform the design of more effective video-based learning resources for teaching redox reactions and other complex chemistry concepts. This is achieved by illuminating how MR affects the acceptance of technology. Understanding how MR influences pre-service science teachers' views on educational technology can help create more engaging, accessible, and effective teaching strategies. Additionally, the study can shed light on how video-based learning may be enhanced to improve future science teachers' understanding of chemistry and their overall teaching experience, eventually advancing student outcomes in the classroom.

1.1. Theoretical background

The study delved into the literature on MR, TAM, and the teaching and learning of redox reactions.

1.1.1. Multiple representations

Johnstone's Chemistry Triangle [3] highlights the importance of employing a variety of representational modalities to improve understanding in chemistry instruction. The framework asserts that combining macroscopic, microscopic, and symbolic modes can help students better understand complex chemistry concepts. Together, these three modes constitute the MR, providing a range of perspectives that help students understand chemical phenomena more comprehensively [15,16], as illustrated in Figure 1.

Macroscopic representations are the observable characteristics and phenomena visible to the unaided eye [17]. In practical work, macroscopic modes involve physical changes such as color shifts, temperature changes, or the formation of precipitates. These representations are effective in engaging students with the practical aspects of chemistry and help them make abstract concepts more meaningful in real-life applications. Students can connect abstract ideas to concrete observations through experiments on gas laws [18] and acid-base indicators [19,20].

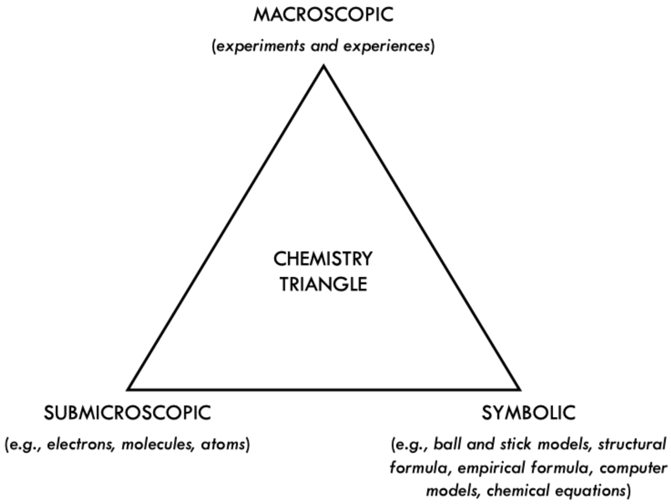

Figure 1. The chemistry triangle [3,15].

On the other hand, microscopic or submicroscopic representations describe the atomic and molecular perspective of chemical phenomena, which are frequently illustrated using molecular models or particulate diagrams [21,22]. This mode of representation provides a deeper understanding of the subatomic behavior of matter by explaining how atomic interactions give rise to macroscopic changes, which is crucial in chemistry. Microscopic depictions illustrate the movement of behavior and particles, offering a visual explanation of fundamental concepts such as stoichiometric phenomena [23] and kinetic molecular theory [24]. Trends in the microscopic mode include transforming particles into human interactions with one another to better understand chemical phenomena, such as chemical elements [25] and chemical bonding [22,26].

Lastly, using symbols, formulas, models, and equations to explain chemical phenomena is known as symbolic representation [3,16,27]. Students can convey their understanding precisely and consistently through symbolic representations, which is essential for expressing scientific concepts and resolving challenging issues. This mode of representation is also required for formalizing scientific knowledge, such as methane combustion modeling [28] and stoichiometric word problems [6].

Integrating all three modes of representation is essential to chemistry education because it fosters a more comprehensive and integrated understanding of matter. Studies [4,30,31] have shown that students who can easily switch between these modes exhibit improved problem-solving abilities and a deeper understanding of scientific concepts. Students taught using numerous representations could better understand abstract chemical concepts than those taught using the conventional strategy of teaching or only one form of representation [15,24,29,30]. By encouraging students to view the same phenomena from several perspectives, MR can increase cognitive flexibility and enhance their understanding of chemistry.

Furthermore, MR plays multifaceted roles in the learning process and can be operationalized in various ways depending on how it interacts with instructional and cognitive factors. As a direct consequence, MR can independently influence learners' understanding by enabling the integration of macroscopic, microscopic, and symbolic perspectives, thereby supporting a deeper conceptual comprehension. For instance, Ainsworth [66] discussed how MR enhances learning by directly facilitating the construction of richer mental models through representational complementarity and cognitive constraint. As a mediator, MR can explain how specific instructional inputs, such as the usability of a learning tool or the clarity of instruction, translate into improved learning outcomes by guiding learners in coordinating and translating across representations [67]. MR also functions as a moderator, influencing the strength of relationships between instructional design and learner performance. For example, Berthold et al. [68] demonstrated that the effectiveness of instructional explanations depended on the quality and coherence of accompanying representations, indicating that MR can alter how other instructional features impact learning. These prior studies provide evidence that a flexible, layered operationalization of MR supports its role as a direct, mediating, and moderating factor in complex learning environments, including in science education.

1.1.2. Technology acceptance

Davis [14] introduced TAM, a widely used theoretical framework for understanding and predicting how individuals will accept and use technology. According to TAM, two crucial factors, PEU and PU, can significantly impact an individual's behavioral intention to use technology (IU), influencing how they use it. This framework has been frequently employed in educational settings to understand how teachers and students perceive and utilize different technological tools.

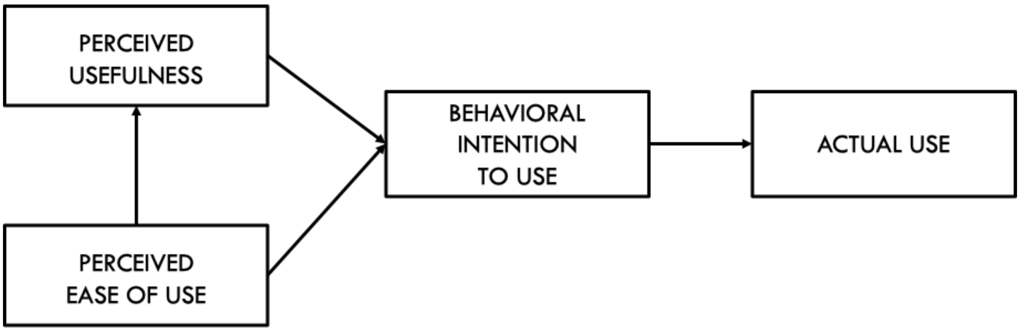

Figure 2. The TAM [14].

PEU is the degree to which an individual thinks utilizing a specific technology would be easy [14]. This could be due to the ease with which teachers or students can use a video, simulation, or other teaching tools in chemistry education. Technology is more likely to be accepted when people believe it is simple, since they are less likely to become frustrated or confused [32,33]. However, regardless of the technology's potential instructional usefulness, its adoption may be discouraged if it is challenging to navigate [32].

Conversely, PU describes how much an individual thinks utilizing a specific technology will improve performance or learning [14]. The perceived value of technology in chemistry instruction may be correlated with how well the resource enables students to understand complex ideas [13]. Students are more likely to embrace and utilize technology if they believe it enhances their understanding or adds value to their educational experience [32,33].

Understanding how PEU and PU relate is essential to understanding technology acceptance [14,33]. According to TAM, these factors significantly impact a user's IU or willingness to interact with the technology, and the technology's actual use (AU) follows from this purpose [14]. Research conducted in educational settings [13,34,35] indicates that students and teachers are more likely to utilize technology if they perceive it as easy to use and valuable. However, AU is not included as a variable in the present study as it focuses on pre-service science teachers. Instead, the present study focuses on how future science teachers' PEU and PU affect their IU in teaching complex chemistry concepts using educational technology, such as videos. Students and teachers are more likely to plan to utilize technology if they believe it to be valuable and easy to use. Studies [35–37] revealed that teachers' IU in their teaching practices were directly impacted by their views on how beneficial and straightforward it was to use. Alejandro et al. [35] found that pre-service teachers' acceptance of AI applications in education was significantly driven by how beneficial and easy to use they perceived the tools to be. Similarly, Sayaf et al. [36] demonstrated that students' media and computer skills impacted their perceived usefulness and ease of use of ICT, which in turn influenced their intention to adopt digital learning technologies. Cooper [37] further emphasized that while tools like ChatGPT show promise in science education, their effective integration depends on educators' critical evaluation and perception of their practical benefits and usability. Hence, TAM is crucial for understanding the dynamics of educational technology adoption, especially in science education.

While TAM has been widely used to explain user acceptance of technology, it has also received critiques for its simplicity, particularly in complex educational contexts. As noted by Venkatesh et al. [65], TAM may not fully capture the nuanced factors influencing technology adoption in learning environments, such as pedagogical quality, content complexity, and learner characteristics. This study addresses these limitations by integrating MR into TAM, thereby enriching the model with a content-centered perspective. By examining the role of MR, specifically macroscopic, microscopic, and symbolic representations, in influencing PU, PEU, and IU, the study extends TAM beyond interface usability and general attitudes. It incorporates cognitive and pedagogical dimensions critical to understanding how learners evaluate educational technologies. This integration enables a more comprehensive analysis of technology acceptance in science education, particularly when addressing abstract and conceptually demanding topics such as redox reactions.

1.1.3. Teaching and learning redox reactions

The abstract nature of redox reactions makes teaching and learning them difficult. Students often struggle to make connections between different levels, which can result in misconceptions and fragmented comprehension. Widarti et al. [38] found that, despite interventions, misconceptions about redox titration, including those related to microscopic and symbolic features, persisted. Similarly, Li and Arshad [39] found that teachers often place too much emphasis on macroscopic representations, which causes students to struggle with understanding microscopic and symbolic levels. These problems underscore the challenges of learning redox reactions and the importance of employing effective and innovative teaching strategies.

Similar difficulties are evident in the teaching of redox reactions. According to Goes et al. [40], seasoned teachers employ more application-oriented strategies, while pre-service teachers frequently depend on conventional, content-focused approaches that overlook the interconnectedness of chemical representations. Additionally, the study found that domain-specific evaluation procedures were lacking, indicating a need for improved pedagogical content knowledge (PCK). Without specialized training, teachers may continue to employ inefficient teaching strategies, making it even more challenging for students to grasp the concepts of redox phenomena.

Various interventions have been implemented to enhance the teaching and learning of redox reactions and to address the issues above. Through cognitive engagement, Adu-Gyamfi et al. [41] enhanced students' conceptual knowledge by introducing a participatory teaching paradigm that prioritized insight, interaction, tasks, and forums. Morales et al. [42] employed a context-based teaching approach that emphasized chemistry-specific vocabulary and integrated real-life applications, resulting in a 41.9% conceptual gain. Syamsuri et al. [43] developed instructional materials validated by chemistry education experts, which appropriately and systematically connected macroscopic, microscopic, and symbolic representations using the four-step teaching material development approach. By successfully connecting representation levels, technological interventions like the blended-reality immersive environment developed by Wang et al. [7] enhanced students' understanding of molecular interactions. Other strategies, such as guided inquiry [44], activity-based learning [45], and collaborative learning [46], have shown notable improvements in student performance and engagement.

Despite advancements in teaching and learning redox reactions, gaps remain in the complete integration of macroscopic, microscopic, and symbolic representations, as well as in correcting enduring misconceptions. Even if existing strategies enhance learning outcomes, they overlook how MR affects the acceptance, adoption, and use of educational technologies. By integrating MR with TAM, this study addressed these gaps by investigating the effects of MR on pre-service teachers' acceptance of videos used to teach redox reactions. This study aimed to enhance pre-service teachers' pedagogical content knowledge (PCK) and promote the effective use of innovative, representation-based resources to address the challenges of teaching and learning redox reactions.

1.2. Hypothesis development

Based on the theoretical background of MR and TAM, the following hypotheses were formulated to examine how MR influences the acceptance of educational videos in teaching and learning redox reactions:

H_1: PEU significantly influences PU.
H_2: PEU significantly influences IU.
H_3: PU significantly influences IU.
H_4: MR significantly influences PU.
H_5: MR significantly mediates the link between PEU and PU.
H_6: MR significantly mediates the link between PEU with PU and IU.
H_7: MR significantly moderates PEU and PU.

1.3. Proposed models of the study

To test the study's hypotheses, three structural models were proposed (Figures 3–5), each examining the role of MR in TAM as a direct effect variable, a mediating variable, and a moderating variable.

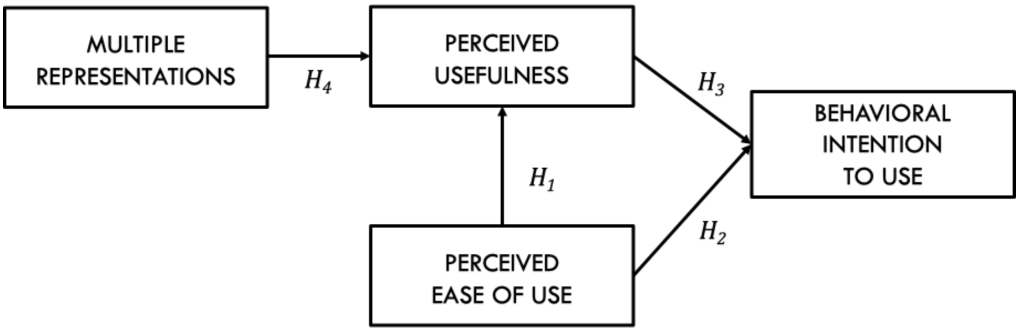

Figure 3. Proposed model 1 (MR as a direct effect factor).

In Figure 3, MR is proposed to directly influence PU in TAM. Integrating macroscopic, microscopic, and symbolic representations in educational videos is expected to enhance their perceived value, making the technology more effective for teaching complex chemistry concepts, such as redox reactions.

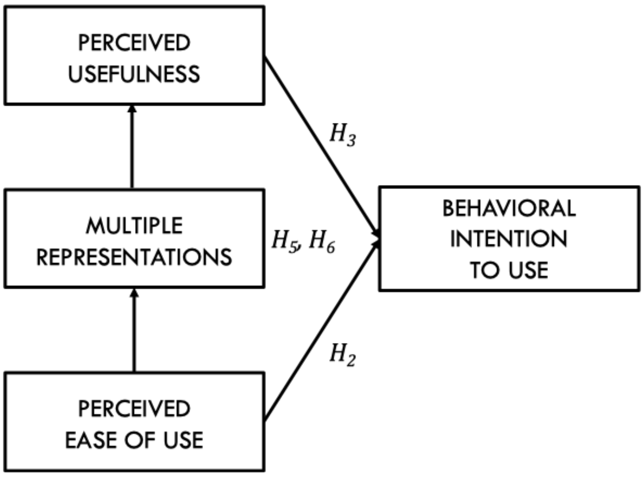

Figure 4. Proposed model 2 (MR as a mediator).

As illustrated in Figure 4, MR acts as a mediator between PEU, PU, and IU. MR is expected to enhance users' ease of engagement with the technology and its perceived usefulness, thereby increasing pre-service teachers' intention to use it in their future teaching.

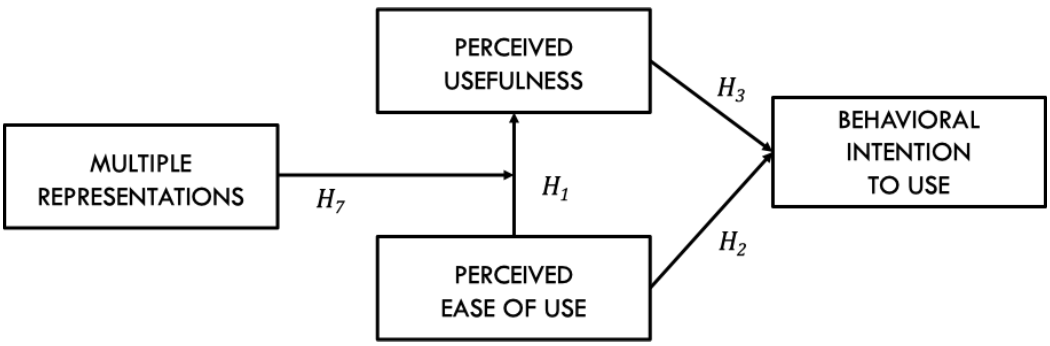

Figure 5. Proposed model 3 (MR as a moderator).

According to Figure 5, MR moderates the relationship between perceived ease of use (PEU) and perceived usefulness (PU). The quality of MR in educational technology can amplify or diminish perceived usefulness, depending on how well the technology supports understanding, which in turn influences the overall user experience.

1.4. Research questions

To guide the development of the proposed models, this study examined how MR affects pre-service science teachers' acceptance of technology, particularly when using videos in teaching and learning redox reactions. Specifically, it answers the following questions:

1. What is the level of the pre-service teachers’ perspectives on MR (macroscopic, microscopic, symbolic representations) and TAM (PEU, PU, IU)?
2. How valid are the proposed models of MR in TAM among pre-service teachers?
3. Does MR significantly influence PU?
4. Does MR significantly mediate the relationship between PEU, PU, and IU?
5. Does MR significantly moderate between PEU and PU?

2. Methods

To empirically test the hypothesized relationships grounded in the MRF and TAM frameworks and to address the research questions aligned with the proposed models, the study employed a quantitative methodological approach using structural equation modeling to analyze the relationships between key variables.

2.1. Design

This study examined the link between MR and TAM using a descriptive-correlational design with partial least squares structural equation modeling (PLS-SEM) to investigate how MR, comprising macroscopic, microscopic, and symbolic representations, affects the technology acceptance of videos in teaching redox reactions. This design thoroughly explored the direct and indirect impacts of MR in the context of the pre-service teachers’ PEU, PU, and IU.

2.2. Context

Third-year pre-service teachers enrolled in the Bachelor of Secondary Education in Science (BSEd-Science) program at a state university in Central Visayas, Philippines, participated in the study, following the inclusion and exclusion criteria in Table 1. Based on Table 1, these pre-service teachers were enrolled in a 5-unit course on analytical chemistry, which included a chapter on redox reactions as part of the broader unit on analytical reactions in aqueous solutions. They were exposed to educational videos designed to teach redox reactions throughout the unit. These videos integrated MR, allowing them to view the chemical phenomena in both macroscopic and microscopic representations.

Table 1. Inclusion and exclusion criteria of the study participants.

Aspect	Inclusion criteria	Exclusion criteria
Academic level	Third-year pre-service teachers	Students from other year levels
Program	Enrolled in BSEd-Science program	Students from other degree programs
Course enrolment	Officially enrolled in the analytical chemistry course during the semester of data collection	Not enrolled in the analytical chemistry course
Instructional unit	Completed the unit on redox reactions within the analytical chemistry course	Did not complete the redox reactions unit
Video exposure	Watched and engaged with the MR-integrated educational videos	Did not watch or skipped the MR-integrated educational videos
Consent	Provided informed consent to participate in the study	Did not provide informed consent

In total, there were 115 participants from three BSEd sections who participated in the study. This sample size is appropriate for PLS-SEM based on established guidelines. Following the 10-times rule [69,70], the minimum required sample size is ten times the maximum number of indicators per construct or structural paths directed at any latent variable. In this study, the highest number of indicators per construct is five, and the most structural paths directed at a latent construct is two, both well within the acceptable range for a sample of 115. Additionally, an a priori power analysis using the Free Statistics Calculator for structural equation modeling (version 4.0) confirms that a minimum of 100 participants is sufficient to achieve 0.80 power with six latent variables and 30 observed indicators [29]. Therefore, the sample size is methodologically sound for the analysis conducted.

2.3. Instruments

Two research instruments were employed in the study. The first tool is the Multiple Representations Perception Questionnaire (MRPQ), which assessed how much the videos integrate the macroscopic, microscopic, and symbolic representations in teaching and learning redox reactions in the Analytical Chemistry class. MRPQ consists of 15-item Likert scale items using a five-point response scale ranging from Strongly Agree (SA) to Strongly Disagree (SDA). The other tool is the Technology Acceptance Model Questionnaire (TAMQ), which evaluates the degree to which the videos are accepted in teaching and learning redox reactions. TAMQ is a modified version of existing technology acceptance tools, incorporating 15 Likert scale items using the five-point response scale from SA to SDA. These tools were administered to the pre-service science teachers and tested for reliability and validity through measurement models derived from PLS-SEM results. The items in MRPQ and TAMQ are presented in Table 2.

2.4. Data gathering

Before the study commenced, necessary permissions were obtained, and informed consent was secured from all participants. Participants were assured of the confidentiality and anonymity of their responses, with data used solely for research purposes and stored securely to protect their privacy. The study also ensured that participation was voluntary, with no academic risks or adverse consequences, and that the educational intervention posed no harm but aimed to enhance their learning experience.

Table 2. Items in MRPQ (Macro, Micro, Symb) and TAMQ (PEU, PU, IU).

Code	Item
Macro1	The science videos effectively convey how redox reactions occur in everyday life.
Macro2	I can easily relate the content of the science videos to real-world chemical processes.
Macro3	The videos help me grasp the overall picture of redox reactions without delving into intricate details.
Macro4	The science videos enhance my understanding of the practical applications of redox reactions.
Macro5	I find it easy to connect the concepts in the videos to macroscopic observations of redox reactions.
Micro1	The science videos provide a clear understanding of the molecular-level processes involved in redox reactions.
Micro2	I can visualize the interactions between atoms and molecules during redox reactions after watching these videos.
Micro3	The videos effectively explain the electron transfer mechanisms in redox reactions.
Micro4	The microscopic details presented in the videos aid in deepening my understanding of redox chemistry.
Micro5	I feel that the science videos provide a comprehensive insight into the molecular aspects of redox reactions.
Symb1	The science videos effectively use chemical symbols and equations to represent redox reactions.
Symb2	I find it easy to interpret and work with the chemical notations used in the videos.
Symb3	The videos successfully convey the balance of chemical equations in redox reactions.
Symb4	The symbolic representations in the videos contribute to my overall understanding of redox equations.
Symb5	I believe that the use of chemical symbols and notations in the videos is crucial for learning about redox reactions.
PEU1	The interface of the science videos on redox reactions in the environment is user-friendly.
PEU2	It is easy to navigate through the science videos to find specific content on redox reactions.
PEU3	Learning from the science videos about redox reactions in the environment is straightforward.
PEU4	I find it easy to comprehend the concepts explained in the science videos.
PEU5	Overall, I feel that using science videos for learning about redox reactions in the environment is convenient.
PU1	Science videos on redox reactions in the environment enhance my understanding of chemistry concepts.
PU2	Using these videos as instructional materials improves my interest in studying redox reactions.
PU3	I believe that science videos on redox reactions contribute to better retention of knowledge.
PU4	These videos are valuable resources for supplementary chemistry learning.
PU5	The use of science videos on redox reactions in the environment enhances my overall chemistry learning experience.
IU1	I intend to incorporate science videos on redox reactions into my chemistry study routine.
IU2	I plan to use these videos regularly as a part of my chemistry learning process.
IU3	I am motivated to use science videos on redox reactions to enhance my chemistry knowledge.
IU4	I am willing to allocate time and effort to integrate these videos into my chemistry studies.
IU5	Using science videos on redox reactions aligns with my intention to excel in chemistry.

During the regular class sessions in the analytical chemistry course, videos incorporating macroscopic, microscopic, and symbolic representations of redox reactions were shown to the pre-service science teachers, highlighting their applications in the home, environment, and industry. After viewing the videos, these pre-service teachers were asked to complete an online survey to assess the videos according to the MR and TAM models. This survey was administered through Google Forms, making distributing and gathering responses easy. The survey link was shared with the pre-service teachers through their Google Classroom, where they were instructed to answer the survey after viewing the videos during class sessions. The responses from the Google Forms were downloaded as a spreadsheet file, which was then cleaned and organized. The data were reviewed for completeness, and incomplete or duplicate responses were eliminated, ensuring the integrity and reliability of the data for analysis.

2.5. Data analysis

Data was analyzed using PLS-SEM through SmartPLS version 4.1.0.9 software. This analysis had three components: descriptive statistics, measurement model, and structural models. Descriptive statistics (means and standard deviations) were used to describe the level of pre-service teachers' perspectives on the videos when teaching redox reactions regarding MR and TAM. The measurement model was also derived to assess the reliability and validity of the MRPQ and TAMQ tools through the PLS-SEM algorithm. Indices such as outer loadings, Cronbach's alpha, AVE, discriminant validity, and model fit were calculated to ensure the quality and robustness of the models [47]. Lastly, the structural models were examined to ascertain the role of MR in TAM through PLS-SEM bootstrapping with 5000 subsamples and a path weighting scheme [48]. Path coefficients were analyzed to determine the strength and significance of the direct, mediating, and moderating effects of MR in the relationships between PEU, PU, and IU. All tests were conducted at a 95% confidence level, and all p-values lower than 0.05 were considered significant.

3. Results and discussion

This section presents the descriptive statistics, measurement model, and structural models derived from MR and TAM data analysis pertinent to using videos to teach and learn redox reactions.

3.1. Descriptive statistics

The levels of pre-service teachers' perspectives on MR (macroscopic, microscopic, symbolic) and TAM (PEU, PU, IU) based on the use of videos in teaching and learning redox reactions in the analytical chemistry course are shown in Table 3.

According to Table 3, pre-service teachers held positive perspectives about using videos that incorporated MR to teach redox reactions. Macroscopic representations enabled them to connect theoretical knowledge with observable phenomena. Microscopic representations, including electron transfer mechanisms and particle interactions, provided a better understanding of redox chemistry. Symbolic representations enabled them to explain redox reactions by accurately interpreting chemical symbols and balancing equations.

The findings also reveal that the pre-service teachers had highly favorable views on using videos to teach and learn about redox reactions. They found the videos easy to navigate and understand, perceived them as highly beneficial in enhancing their understanding and interest in redox reactions, and manifested strong intentions to incorporate videos into their chemistry teaching and learning process. These findings indicate that the videos are well-designed to meet their usability, utility, and engagement needs.

Table 3. Perspectives on MR and TAM.

MR item	Mean	SD	TAM item	Mean	SD
Macro1	4.65	0.59	PEU1	4.71	0.46
Macro2	4.60	0.64	PEU2	4.61	0.58
Macro3	4.50	0.67	PEU3	4.60	0.60
Macro4	4.55	0.66	PEU4	4.60	0.62
Macro5	4.46	0.70	PEU5	4.67	0.53
Overall Macro	*4.55*	*0.60*	*Overall PEU*	*4.64*	*0.48*
Micro1	4.49	0.72	PU1	4.68	0.53
Micro2	4.49	0.67	PU2	4.60	0.60
Micro3	4.42	0.71	PU3	4.66	0.57
Micro4	4.47	0.70	PU4	4.62	0.58
Micro5	4.48	0.72	PU5	4.62	0.57
Overall Micro	*4.47*	*0.63*	*Overall PU*	*4.64*	*0.63*
Symb1	4.57	0.67	IU1	4.62	0.63
Symb2	4.54	0.61	IU2	4.50	0.67
Symb3	4.58	0.64	IU3	4.69	0.51
Symb4	4.52	0.69	IU4	4.53	0.64
Symb5	4.66	0.57	IU5	4.59	0.61
Overall Symb	*4.57*	*0.56*	*Overall IU*	*4.59*	*0.55*
Overall MR	*4.53*	*0.57*	*Overall TAM*	*4.62*	*0.49*

3.2. Measurement models

Data were subjected to the PLS-SEM algorithm, and the outer loadings of each item in the MRPQ and TAMQ proved acceptable. These outer loadings are presented in Table 4.

Table 4. Outer loadings of MRPQ and TAMQ items.

MR item	**Outer loadings**	**TAM item**	**Outer loadings**
Macro1	0.94	PEU1	0.82
Macro2	0.92	PEU2	0.87
Macro3	0.89	PEU3	0.85
Macro4	0.94	PEU4	0.84
Macro5	0.89	PEU5	0.87
Micro1	0.92	PU1	0.91
Micro2	0.92	PU2	0.86
Micro3	0.84	PU3	0.92
Micro4	0.91	PU4	0.90
Micro5	0.90	PU5	0.91
Symb1	0.88	IU1	0.90
Symb2	0.91	IU2	0.88
Symb3	0.83	IU3	0.89
Symb4	0.93	IU4	0.90
Symb5	0.89	IU5	0.92

As presented in Table 4, the outer loadings of the MRPQ and TAMQ show strong correlations between each question and its corresponding construct. The findings show that the items are valid and reliable measures of the related dimensions. Their robustness in measuring the constructs is indicated by their high outer loadings, which imply that they successfully capture the essence of the macroscopic, microscopic, and symbolic representations of MRPQ and the PEU, PU, and IU constructs of TAMQ.

Aside from outer loadings, the construct reliability and validity indices were also obtained. These values are shown in Table 5.

Table 5. Construct reliability and validity of the constructs.

Construct	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Macro	0.95	0.95	0.96	0.84
Micro	0.94	0.94	0.95	0.81
Symb	0.93	0.93	0.95	0.79
PEU	0.90	0.91	0.93	0.72
PU	0.94	0.94	0.96	0.81
IU	0.94	0.94	0.95	0.81

Based on the construct reliability and validity indices in Table 5, the MRPQ and TAMQ have highly valid and reliable measures for their respective constructs. The items for each construct consistently measure the same underlying concept, as confirmed by Cronbach's alpha and composite reliability values, which show strong internal consistency for all constructs. Convergent validity is confirmed by the AVE values, which show that their corresponding constructs explain a significant amount of the variance in the items.

Discriminant validity was also explored in the measurement model. The Fornell-Larcker criterion results are shown in Table 6.

Table 6. Fornell-Larcker criterion results.

Construct	IU	Macro	Micro	PEU	PU	Symb
IU	0.90					
Macro	0.71	0.90				
Micro	0.77	0.87	0.90			
PEU	0.81	0.71	0.71	0.85		
PU	0.82	0.70	0.74	0.80	0.90	
Symb	0.77	0.82	0.89	0.71	0.76	0.89

The findings of the Fornell-Larcker criterion, based on Table 6, confirm that the measurement model's constructs exhibit discriminant validity. This indicates that the constructs are distinct and measure different viewpoints, and each construct exhibits more significant variation with its items than with items from other constructs. This discrimination guarantees the conceptual independence of MR and TAM within the study context.

Lastly, the model fit indices, highlighted in Table 7, were also obtained from the PLS-SEM algorithm.

Table 7. Model fit indices.

Indices	Saturated Model 1	Estimated Model 1	Saturated Model 2	Estimated Model 2	Saturated Model 3	Estimated Model 3
SRMR	0.07	0.07	0.07	0.08	0.07	0.07
d_ULS	4.53	5.02	4.49	6.82	4.53	5.04

As the model fit indices in Table 7 indicate, all three models meet the acceptable thresholds for structural model assessment. Based on the standardized root mean square residual (SRMR) values, there are a few differences between the observed and predicted associations, indicating that the data and the suggested models align well. The model fit for describing the data is further supported by the d_ULS values, which evaluate the difference between the observed and modeled covariance matrices. These values fall within acceptable ranges.

3.3. Structural Model 1: Multiple representations as a direct effect factor

Structural Model 1 examines the role of MR as a direct factor influencing PU in TAM. The statistical values are presented in Table 8.

Table 8. Path coefficients of Model 1.

Path	Original sample	Sample mean	t-value	p-value	Results	f^2	Description
PEU→PU	0.63	0.63	7.40	0.000	Supported	0.76	Very strong
PEU→IU	0.08	0.08	0.89	0.376	Not supported	0.01	Weak
PU→IU	0.86	0.86	10.54	0.000	Supported	1.36	Very strong
MR→PU	0.30	0.30	3.55	0.000	Supported	0.18	Moderate

The results of Structural Model 1 in Table 8 validate three of the four hypotheses, suggesting critical connections between the constructs. PEU has a strong and favorable impact on PU, demonstrating its significance in shaping the acceptance of video value. Moreover, PU substantially affects IU, indicating that pre-service teachers are more likely to integrate videos into their learning routines when they perceive them as helpful. However, there is no evidence to support the direct relationship between PEU and IU, indicating that, in the absence of the mediating effect of PU, ease of use alone does not directly affect the intention to use the videos.

The findings also demonstrate that MR has a significant impact on PU. This result suggests that incorporating macroscopic, microscopic, and symbolic representations into videos increases their perceived utility. MR enhances perceptions of the video’s value as a helpful teaching tool for understanding redox reactions by catering to varying levels and relating abstract ideas with tangible facts.

3.4. Structural Model 2: Multiple representations as mediator

Structural Model 2 examines the role of MR as a mediator between PEU, PU, and IU in TAM. Table 9 shows the statistical results of MR's mediating effects in this model.

Table 9. Path coefficients of the mediators in Model 2.

Mediator	Path	Original sample	Sample mean	t-value	p-value	Results	VAF	Description
MR	PEU→PU	0.58	0.58	7.97	0.000	Supported	1.00	Full mediation
MR, PU	PEU→IU	0.49	0.49	6.98	0.000	Supported	0.85	Full mediation

According to Table 9, the link between PEU and PU is significantly mediated by MR. This indicates that the ease of navigating and understanding the videos enhances usefulness primarily through the practical application of MR. Additionally, the association between PEU and IU is mediated by MR and PU combined, demonstrating that although usability is significant, its impact on intention to use is mainly indirect, working through MR's influence on PU and, in turn, PU's effect on IU. These results demonstrate the interrelated ways that perceived utility, representation quality, and ease of use influence the adoption of new technologies.

The other effects in Model 2 are presented in Table 10.

Table 10. Path coefficients of the other effects in Model 2.

Path	Original sample	Sample mean	t-value	p-value	Results	f^2	Description
PEU→MR	0.75	0.75	12.83	0.000	Supported	1.26	Very strong
MR→PU	0.77	0.77	15.58	0.00	Supported	1.46	Very strong
PEU→IU	0.09	0.09	0.96	0.338	Not supported	0.01	Weak
PU→IU	0.85	0.85	10.49	0.000	Supported	1.37	Very strong

The path coefficients in Figure 10 illustrate the direct relationships between PEU and MR, indicating that video usability improves when integrating macroscopic, microscopic, and symbolic representations. There is also a direct link between MR and PU, indicating that the perceived value of the videos increases with the pre-service teachers' skillful integration of different representations. The relationship between PU and IU is also significant, highlighting the crucial role that perceived usefulness plays in encouraging them to use the videos. However, like Model 1, PEU had no direct effect on IU, suggesting that their intention to utilize the videos is not influenced by ease of use alone in the absence of any mediating factors.

3.5. Structural Model 3: Multiple representations as moderator

Structural Model 3 examines the role of MR as a moderator between PEU and PU in TAM. Table 11 presents the statistical results of MR's moderating effect in this model.

Table 11. Path coefficients of the MR as moderator in Model 3.

Moderator	Path	Original sample	Sample mean	t-value	p-value	Results	f^2	Description
MR	PEU→PU	-0.01	-0.01	0.21	0.833	Not supported	0.05	Weak

As Table 11 shows, MR does not significantly moderate the relationship between PEU and PU, indicating that the level of multiple representations in the videos does not influence the effect of usability on perceived usefulness. This finding aligns with the view that MR may function more effectively as a direct or mediating factor rather than a contextual variable that changes the strength of usability's influence. Although prior studies have shown MR can act as a moderator under certain instructional conditions, its role in this study may be more aligned with content delivery than interaction design. The sample size was adequate, meeting the requirements for PLS-SEM, and MR was consistently integrated into the videos, which may have limited the variability needed to observe a moderating effect.

The other effects in Model 3 are shown in Table 12.

Table 12. Path coefficients of the other effects in Model 3.

Path	Original sample	Sample mean	t-value	p-value	Results	f^2	Description
PEU→PU	0.62	0.63	6.73	0.000	Supported	0.71	Very strong
PEU→IU	0.08	0.08	0.89	0.376	Not supported	0.01	Weak
PU→IU	0.96	0.86	10.54	0.000	Supported	1.36	Very strong

The results in Table 12 indicate that PEU significantly impacts PU, confirming that the videos' usability enhances pre-service teachers' perception of their value for learning. Additionally, PU strongly influences IU, demonstrating that they are more likely to adopt videos as part of their learning practices when they find them beneficial. However, PEU's direct effect on IU is insignificant, suggesting that ease of use alone does not directly drive the intention to use the videos without the mediating influence of PU.

3.6. Observed model of the role of multiple representations in technology acceptance

Figure 6 illustrates the observed model for the role of MR in TAM, integrating the statistically significant results from Models 1, 2, and 3.

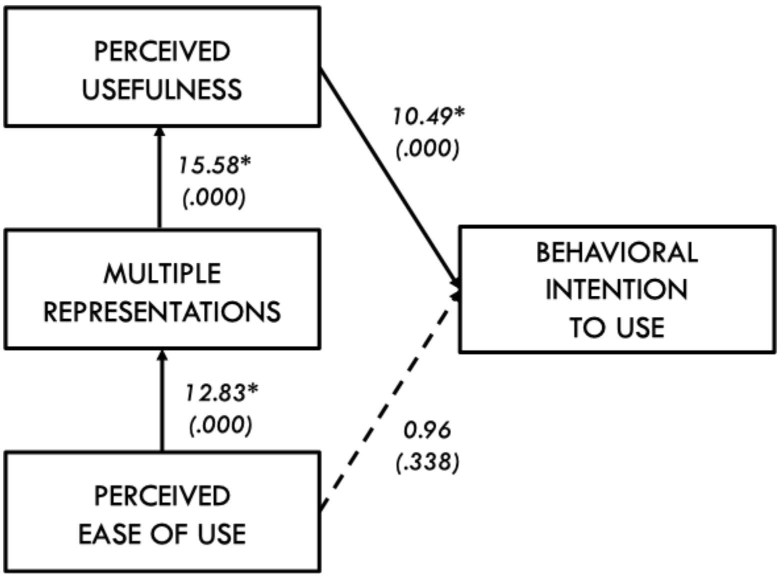

Figure 6. Observed model of the role of MR in TAM.

The observed model indicates that MR significantly mediates the relationships between PEU, PU, and IU. Additionally, MR has a direct impact on PU, underscoring its significance in enhancing the perceived value of the video. However, the link between PEU and PU is not significantly moderated by MR, indicating that the influence of usability on PU is not affected by the quality of multiple representations. Furthermore, PEU does not directly affect IU, highlighting that ease of use alone is insufficient to drive behavioral intention without the mediating effects of PU and MR. This model highlights the crucial role of MR in enhancing technology acceptance, particularly in supporting the PU of educational tools.

4. Discussion

With positive perspectives on the general integration of MR, the findings emphasize the critical role that macroscopic, microscopic, and symbolic representations play in improving pre-service teachers' understanding of redox reactions. These results highlight how the videos effectively bridge a gap in traditional chemistry education by connecting observable phenomena, molecular-level interactions, and symbolic equations. Pre-service teachers could make meaningful connections between abstract ideas and real-world instances using macroscopic representations to bridge theoretical knowledge to practical applications [17–20]. Likewise, the microscopic depictions clarified molecular-level mechanisms, such as electron exchanges, establishing a connection between atomic-scale phenomena and observable macroscopic findings [21–26]. Their proficiency with chemical equations was further strengthened by symbolic representations, which facilitated their transition between theoretical and applied dimensions [3,16,27]. Combining these three levels resulted in a comprehensive learning process, demonstrating MR's effectiveness in reducing cognitive load and fostering a deeper conceptual understanding [4,30,31].

The strengths of the TAM components are reflected in the pre-service teachers' perspectives regarding the videos' usefulness and usability. The high PEU showed that the videos' design, with clear topic presentations and easy-to-use navigation, reduces barriers to engagement. Because of the smooth experience, they can concentrate on learning the concepts rather than struggling with the medium, which directly affects PU. Their assessment of the videos as essential for boosting understanding, stimulating interest, and strengthening knowledge retention further supported the PU. The high IU suggests that videos are supplemental resources and crucial tools for understanding complex ideas. The videos meet practical and instructional requirements and align with TAM's focus on user attitudes and intentions as catalysts for technology acceptance [13,49,50].

The measurement model's validity and reliability supported the credibility of the findings. High outer loadings (>0.70) indicated precise measurement, showing that the items in each construct strongly represent their respective dimensions [51]. Cronbach's alpha and composite reliability scores (>0.70) validated the constructs' internal consistency, ensuring that the items consistently measured the desired variables [52]. The AVE values (>0.50) demonstrated convergent validity, indicating that the constructs sufficiently explained the variance in their indicators [53]. The Fornell-Larcker criterion ensured the discriminant validity of each construct, ensuring that it measured a distinct dimension with minimal overlap [47]. These thorough validations attest to the measurement model's accuracy in capturing the MR and TAM constructs, offering a solid basis for examining structural relationships. The SRMR (<1.00) and other model fit indices confirmed that the proposed models were adequate [54]. These indices confirmed that the models' theoretical configurations align with the observed data, ensuring the validity and interpretability of the structural relationships. Since they attest to the theoretical soundness and applicability of the constructs under study, the fit indices are necessary before moving on to the structural models. This stage would provide empirical support for later interpretations of the structural relationships [55].

The significant influence of PEU on PU highlights the fundamental role of usability in determining value perceptions. Pre-service teachers can concentrate their cognitive resources on understanding the material rather than navigating the medium when they find the videos easy to use, as supported by the study by Basuki et al. [56]. This relationship highlights the significance of intuitive design in educational technologies by demonstrating how usability acts as a doorway to perceived usefulness [56,57]. However, the negligible effect of PEU on IU highlights the intermediary role of PU in bridging PEU with IU, demonstrating that usability, by itself, does not directly translate to behavioral intention [58].

The direct correlation between MR and PU demonstrates how these representations can enhance the perceived value of the videos. MR ensures that complicated ideas, such as redox processes, are presented thoroughly and understandably by attending to the various cognitive needs of pre-service teachers, consistent with existing MR studies on the topic [38,39,59]. For instance, MR enables learners to observe color changes or gas evolution during a redox reaction at the macroscopic level, visualize electron transfers between atoms or ions at the microscopic level, and interpret the changes through balanced chemical equations at the symbolic level. These coordinated representations help learners bridge the gap between what they see, what occurs at the molecular level, and how these are communicated through chemical notation, making the abstract nature of redox reactions more concrete and easier to understand. This result supports the idea that content quality is as essential as usability when assessing the effectiveness of instructional technologies [60,61]. With the help of MR, they can connect macroscopic observations, microscopic interactions, and symbolic notations in meaningful ways, which improves the videos' ability to accomplish their learning objectives [6,7,62].

MR's integrative function within TAM is further demonstrated by its mediating involvement between PEU, PU, and IU. MR serves as a conduit via which perceived value is influenced by usability, motivating the pre-service teachers to use the videos. By demonstrating how representation quality enhances the influence of usability on PU, which in turn affects behavioral intention, this mediating effect highlights the interdependence of the constructs. This realization underscores the importance of content-rich designs that enhance usability and ensure that users perceive the tool as helpful and informative [56–58].

The lack of a significant moderating effect of MR on the relationship between PEU and PU indicates that although MR mediates meaningful interactions and directly improves PU, it does not change the degree to which usability influences usefulness. This study suggests that usability and representation quality independently shape the pre-service teachers' perceptions, working in parallel rather than interactively in this specific relationship [60,61]. Lastly, the insignificant impact of PEU on IU demonstrates that, in the absence of PU's mediating function, IU cannot be motivated just by PEU. This finding highlights the importance of perceived usefulness to TAM, as it links usability to learners' readiness to adopt the technology [62,63]. MR is essential to strengthen PU, close the gap between usability and intention, and enhance the educational value of the videos.

The final role of MR in TAM is multifaceted. It directly influences perceived usefulness, mediates between usability and intention, and is an essential component of content quality in educational tools. MR enhances TAM's approach by addressing the cognitive complexities of learning redox reactions, providing a more nuanced understanding of technology adoption in academic settings. These results underscore the importance of integrating usability and MR quality, illustrating how MR can effectively enhance instructional tools and facilitate the meaningful adoption of technology by pre-service teachers [13,56–58].

5. Implications for STEM teaching and learning

The study has significant implications for STEM teaching and learning, particularly in enhancing instructional strategies and effectively utilizing technology to teach complex topics, such as redox reactions. The positive perceptions of the macroscopic, microscopic, and symbolic modes of representation reinforce the significance of incorporating MR into STEM instruction. To help students connect observable phenomena to molecular interactions and symbolic chemical equations, educators should intentionally design lessons that use all three levels of representation. For example, when teaching redox reactions, teachers might begin with a real-world phenomenon (e.g., the rusting of iron), follow this with animations that show electron transfer at the molecular level, and then guide students through balancing corresponding redox equations. This layered approach addresses common misconceptions in chemistry and facilitates deeper conceptual understanding. Aligning instructional design with students' cognitive processes not only supports comprehension but also fosters more engaging and compelling learning experiences.

The study's TAM results further underscore the importance of both PU and PEU in fostering students' intention to use educational technologies. This highlights the need for STEM resources, such as videos, simulations, and digital platforms, to be not only content-rich but also user-friendly and accessible. Developers and educators must ensure that these tools are accessible, intuitive to navigate, and aligned with students' academic goals. Practical design features, such as interactive annotations, real-time feedback, and the ability to toggle between representational modes, can enhance usability while supporting deeper learning. These features allow students to engage actively with content and clarify their understanding at each level of representation.

Notably, the mediating role of MR in TAM demonstrates that the perceived educational value of digital tools increases significantly when high-quality, multi-representational content is present. This highlights the need for teachers to pay close attention to the pedagogical design of videos and related materials. For instance, MR-based videos should be structured to show chemical processes unfolding across macroscopic, microscopic, and symbolic dimensions within the same narrative or visual sequence. Educators may consider using guided narration, split-screen visuals, or overlays that connect experimental visuals to molecular animations and balanced equations. These approaches are particularly valuable in STEM disciplines, where learners must bridge abstract and tangible ideas to form meaningful understanding.

In response to these findings, professional development for STEM educators should be expanded to include explicit training on MR-based instructional video design and implementation. Training modules could consist of hands-on workshops where teachers analyze existing MR-rich videos, storyboard their video content, and evaluate how well different representations are coordinated. Additionally, teachers should be supported in addressing challenges, such as selecting age-appropriate visuals, aligning content with curriculum standards, and managing the cognitive load imposed by multi-layered content. Providing teachers with practical tools, such as video templates or software tutorials, can further aid in the integration of MR into classroom practice. Such training not only builds technical skills but also promotes instructional reflection and innovation.

Ultimately, the study provides valuable insights for designing future educational technologies in STEM, highlighting the importance of a learner-centered approach that strikes a balance between usability and representational quality. Developers and educators should incorporate interactive features that enable students to engage actively with MR. For example, this could include allowing learners to pause and examine symbolic notations in detail, zoom into molecular-level animations, or align real-world demonstrations with theoretical explanations on split screens. To guide educators' in-classroom implementation, MR-based videos should be structured with clear transitions between macroscopic, microscopic, and symbolic modes, using scaffolding techniques such as layered visuals and guided narration to build conceptual understanding progressively. Educators can also embed prompts or reflection questions at key points in the video to promote deeper processing of representations. However, challenges such as cognitive overload, time constraints in lesson planning, and limited access to editing tools may hinder implementation. These can be addressed by using existing open-source platforms with MR capabilities, co-creating resources through professional learning communities, and participating in targeted professional development programs focused on representational pedagogy and basic multimedia design. By integrating these strategies, STEM educators can create inclusive and dynamic learning environments that make complex concepts more accessible, equipping students for success in interdisciplinary scientific domains.

6. Conclusions and recommendations

Multiple representations play a crucial role in shaping the pre-service teachers' perspectives of technology-integrated resources, such as videos in teaching and learning redox reactions. These representations significantly influence the video's perceived usefulness and mediate between its ease of use, usefulness, and intention to use. However, said representations cannot moderate between their perceived ease of use and usefulness; the former alone has no discernible impact on their intent to use the videos, underscoring the centrality of the video's perceived usefulness. To achieve this, it is crucial to incorporate macroscopic, microscopic, and symbolic representations into instructional materials to enhance conceptual understanding and enrich content delivery. The findings offer a nuanced perspective on how the quality of representation and usability influence technology acceptance, providing valuable insights for improving STEM education.

This study is limited to a specific group of participants: pre-service teachers enrolled in an analytical chemistry course at a state university. Their experiences may not fully reflect those of in-service teachers, students in other disciplines, or learners at different educational levels. This narrow participant scope may affect the generalizability of the findings, as pre-service teachers may engage with educational technologies differently due to their training phase, limited teaching experience, and context-specific exposure to MR-based videos. Additionally, the study focuses solely on redox reactions, a specific topic in chemistry, which may limit the applicability of the results to other complex STEM concepts. These contextual constraints suggest that the positive perceptions of MR and its influence within TAM may vary across different content areas, learning environments, or student populations. To address these limitations, future research should explore the use of MR and TAM across diverse academic settings, including various science subjects, different student groups (e.g., high school or in-service teachers), and various instructional formats. Longitudinal studies are also recommended to examine the long-term effects of MR-based tools on learning outcomes such as retention, transfer, and problem-solving. Furthermore, integrating emerging technologies like augmented reality, virtual labs, or artificial intelligence into MR-TAM frameworks could provide deeper insights into how content quality, usability, and innovative design influence technology acceptance and meaningful learning in STEM education.

Use of AI tools declaration

The author declares no use of artificial intelligence (AI) tools when creating this article.

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Conflict of interest

The author declares no conflict of interest.

Ethics declaration

The study was conducted in accordance with local legislation and institutional requirements. The participants provided written informed consent to participate in this study.

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