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Effect of Extended Reality Learning Experience on Student Engagement in Science and Engineering Courses

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Engagement increases the success rate of students in higher education. This work aimed to determine the effect of extended reality learning (XR) experience on student engagement in science and engineering courses, using the Marzano and Kendall´s taxonomy of education. Higher education students' perception of relevance, motivation, self-efficacy, and emotions after participating in an XR learning activity were measured. Two case studies corresponding to two technological institutions of higher education, one in Mexico and one in China, were investigated. The first employed an augmented reality (ART3D) application in a biology course, while the second used a virtual reality (Manta) technology in a chemistry course. Both sets of students answered the same questionnaire. A survey of four Likert-scale and one open-ended question was analyzed using a mixed-methods approach. Descriptive statistics analysis, normality tests, Mood's Median Test, Qualitative emotions codification was made over the answers to the open-ended question. Results show that engagement-related self-system thinking factors, relevance, motivation, and self-efficacy, are high when an XR is used as an educational strategy. In the case of an AR learning resource, relevance, motivation, and emotions were correlated. In contrast, in the case of a VR learning resource, self-efficacy in skills and critical-thinking competence were related to positive emotions.

Keywords: didactic design, educational innovation, higher education, STEM education

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INTRODUCTION

Nowadays, students have many distractors in their environment and personal technologies (Pennino et al., 2022). New generations have less time to get interested in a topic due to the inclusion of social networks in daily life (Caratozzolo et al., 2021). Faculty have to adapt the content and practices of classes using technological tools that have to be motivating and attractive (Kostaki & Karayianni, 2021). Extended reality (XR) is a technology with exponential growth that can be implemented in education to increase student engagement and student learning (Guo et al., 2021). XR refers to all real-and-virtual combined environments and human-machine interactions generated by computer technology and wearables. It includes, as representative forms, augmented reality (AR) and virtual reality (VR) and the areas interpolated among them. Today more than one modality of XR impacts entire communities and societies, ranging from partially sensory inputs to immersive virtuality (Slater et al., 2019). Owing to technological developments such as the smartphone, XR constantly evolves in many study areas (Ihemedu-Steinke et al., 2017). In addition, XRs are immersive learning technologies that account for authentic experiences in a controlled and low-risk environment. In laboratories that are not well-equipped, students can take advantage of XR resources for learning (Penn & Ramnarain, 2019).

Studies suggest that satisfaction with courses using XR is one of the main factors determining the student's learning status (Gu et al., 2022). The use of XR tools have increased critical thinking (Damopolii et al., 2022), spatial thinking (Ozcakir & Cakiroglu, 2021), learning and its relationship with engagement or motivation (Ackayir & Ackayir, 2017) in different contexts (Hsieh, 2021). However, a systematic review from 2010 to 2020 in the Science, Technology, Engineering, and Math (STEM) subjects showed that 67% of the published works, mainly using AR, were in the Engineering field, while 24% were in the Science field (Mystakidis, 2021). In a deeper look, only 7.6% of the AR-supported learning corresponded to Biology and Chemistry disciplines (Mystakidis, 2021). Although XR has been mentioned as a teaching resource in Higher Education (Liarokapis et al., 2010), there are few studies regarding the use of XR for student engagement in STEM courses of Higher Education in the last five years.

A reason could be that there are no available resources that teachers can use in their classes, or their development requires a lot of time investment or skills not provided for faculty in teacher training (Gill et al., 2022; Choate et al., 2021). Cost, accessibility, and technological requirements are also issues (García et al., 2021; Erturk & Reynolds, 2020; Razali et al., 2020). In typical scenarios, instructors use existing technology (i.e., metaverse from studio.gometa.io), but there are few studies in which teachers develop their own XR applications for their classes (Shiradkar et al., 2021; Sans-Cope et al., 2021; Zhao et al., 2022). Effectiveness in the development of virtual environments for learning requires a design that includes the creation of learning experiences that transfer knowledge in an emotionally safe environment, and promote autonomy and self-regulation; all this to keep the student engaged (Dumulescu et al., 2021; Pishchukhina, 2022; Alblehia, 2022).

An analysis of the effect of Mixed Reality Learning Environments (MRLE) in a Process Technology course at Southwest Louisiana Community and Technical College on engagement and motivation using a questionnaire after the experience reflected high motivational results (Lafargue, 2018). In 2020, a study in a Basic Introductory Lab found that AR increases the students' engagement in standing-out topic conversations at the level of small groups. This was verified through skin biosensors (Soltis et al., 2020). Ruiz-Cantisani and collaborators reported a certain level of engagement in Industrial Engineering students when VR was implemented in classes (Ruiz-Cantisani et al., 2020). As an emerging technology in chemistry, VR-enabled modeling exhibits great potential in the application of chemistry education (Gomollón-Bel, 2022).

Conceptual Framework

The importance of engagement has started to transcend beyond student learning, and it is being set as a critical element for student retention in Higher Education institutions (Tight, 2020; Owusu-Agyeman, 2022). The physiologist Ralph Tyler pioneered this term in 1930 (Salas-Pilco et al., 2022). Since then, many institutions worldwide have highlighted engagement as an indicator of Higher Education Quality (Groccia, 2018). Engagement can be defined generically as any interest, connection, involvement, or participation of students in their learning (Trowler, 2010; Groccia, 2018). However, this concept may be ambiguous; thus, no consensus exists yet (Bond et al., 2020; Moreira et al., 2020). In this sense, many concepts agree in a comprehensive definition, suggesting that student engagement is related to the time and quality of students' effort to participate in educationally purposeful activities. Both inside and outside the classroom, these activities encompass academic and non-academic aspects of the student learning experience, for which students have a role in assuring their quality (Kürtül et al., 2021).

The Australasian Survey of Student Engagement (ASSE) defines the concept as "student involvement with activities and conditions likely to generate high-quality learning" (Coates, 2009). It establishes six engagement scales: academic challenge, active learning, student and staff interactions, enriching educational experiences, supportive learning environment, and work-integrated learning (Trowler, 2010). In the same way, four research perspectives have been established for understanding engagement: behavioral, psychological, socio-cultural, and holistic. The first, behavioral, focuses on effective teaching practice, measuring the student behavior and satisfaction level with the limitation of evading thinking processes (Kahu, 2013). The psychological approach considers engagement as an internal, evolutionary, and individual process, including cognition and affective areas (Lester, 2013) but with an unclear differentiation between dimensions (Kahu, 2013). On the other hand, the socio-cultural perspective emphasizes the role of the context in engagement and encourages the relationship/participation of the whole institution staff in learning as well as culture, politics, and society (Kahu, 2013; Bowden *et al.*, 2021). The holistic approach attempts to link the previous perspectives, observing engagement as a multidimensional and dynamic "meta-construct" (Bowden et al., 2021), which not only can be quantified by tests but also through qualitative works (Kahu, 2013).

In the aspect of instruments for measuring engagement, these have been very diverse: interviews, observations, the National Survey of Student Engagement (Vega, 2014; Kürtül et al., 2021), psychological scales that consider academic, cognitive, social, and affective facets (Zhoc et al., 2019), with different degrees of appropriateness and relevance. For example, Campbel and Atagana (2022) define student engagement first as "the ability of an institution or instructor to capture a student's interest" and second as "a commitment toward a course, and the student's active use of various faculties toward learning the course". Bond et al. (2020) mention that engagement can be observable "via any number of behavioral, cognitive, or affective indicators across a continuum". However, its measurement has represented many challenges because of its interrelated dimensions. Thus, it depends on the context (Salas-Pilco et al., 2022). In this sense, advancements in measuring learning engagement using wearable technology and multimodal learning analytics have been described elsewhere (Salas-Pilco et al., 2022).

In the context of this work, we employed Marzano and Kendall´s taxonomy (MKT) (Marzano & Kendall, 2006) of education to determine how XR affects student engagement. Of the most common education taxonomies (Irvine, 2021), MKT takes engagement as critical for student learning and places self-system thinking as the top level of the taxonomy. Self-system thinking is the primary and first level of student engagement (Kendall et al., 2008). It consists of an interrelated arrangement of attitudes, beliefs, and emotions that determines motivation and attention, whether an individual will engage in or disengage in each task, and how much energy the individual will bring to the task (Marzano & Kendall, 2007). Once the self-system has determined what will be attended to, the functioning of all other elements of thought (i.e., the metacognitive system, the cognitive system, and the knowledge domains) are, to a certain extent, dedicated or determined (Marzano & Kendall, 2007). Self-system thinking involves four aspects (Zhou et al., 2021):

- RELEVANCE: the importance of specific knowledge/competence to self.
- MOTIVATION: individual's tendency toward and persistency in achieving goals.
- SELF-EFFICACY: individual's judgments and confidence in his or her ability to complete and execute specific domain tasks. If students believe they do not have the requisite ability, power, or resources to gain a specific skill, this might considerably lessen their motivation to learn that knowledge, even though they perceive it as important (Marzano & Kendall, 2007).
- EMOTIONS: Emotional response measures personal affective aspects, including positive and negative responses.

This work's objective is to determine the effect of an XR learning experience on student engagement in science and engineering courses. Two case studies were carried out in two technological institutes of higher education. The first used an AR learning intervention, and the other a VR learning intervention. The research question guiding the present study is: How do XR learning resources affect student engagement? To answer this question, we evaluate the students' perception of relevance, motivation, self-efficacy, and emotions as engagement indicators after carrying out the XR activity.

METHOD

This work was conducted using an action research strategy (Li et al., 2020) under a quasi-experimental approach. This method is helpful for re-designing classroom activities considering the students' opinions and reflections. To do this, in the two proposed cases, the problem was first defined to design an XR element to increase students' engagement in science and engineering classes. The XR element was created and applied. The students carried out the activity and finally answered a survey. The two case studies are described below.

Cases definition

The two case studies correspond to technological institutions of higher education, one in Mexico and one in China. The first employed an AR application in a biology course, while the second used VR technology in a chemistry course. Both sets of students answered the same questionnaire. The obtained results were compared regarding XR technology and context.

Case 1. Tecnologico de Monterrey – ART3D

The subject Fundamentals of Biological Systems (FBS) is taught in the academic department of Bioengineering of the School of Engineering and Sciences of the Tecnológico de Monterrey. Its associated discipline is biological engineering, but it is open to any professional career with no requirements. The course promotes the acquisition of the following skills:

- Digital culture
- Scientific thought
- Well-being and self-regulation
- Explanation of the operation of systems in engineering and science
- Demonstration of the operation of systems in engineering and science

FBS is an introductory level course that intends for the student to discover the relevance of biological systems and their application to the different environments of their personal and professional life, with emphasis on health care and the environment, through knowledge of the fundamentals of living systems (human beings and their environment) and the demonstration of some principles of industrial microbiology. Concepts of cellular and molecular biology, homeostasis, sustainability of ecosystems, biomimetics, control of microorganisms, and industrial microbiology will be included. As a result of learning, students design and implement a self-health-care plan, propose solutions to health problems and microbiological processes, and communicate them in digital environments.

Actions related to this work were designed to be carried out in the context of the FBS course of the Tec21 Educative Model to ensure the student understood the cell functions and location. This research was done during an online course for the fall semester of 2021. The second topic of the course is called Principles of cell biology, in which the type and function of the different cells and parts are taught. It is on this topic that the ART3D Cell and Organelles practice was carried out (Figure 1). The demography of the surveyed students can be observed in Table 1. The activity consists of students downloading an application from the university on their cell phones and using it to read a QR on one of the class slides. After this, they could visualize a cell with all its parts indicated in an AR environment. The didactic design intended for the student to live a unique experience, awakening the students' creative capacity.

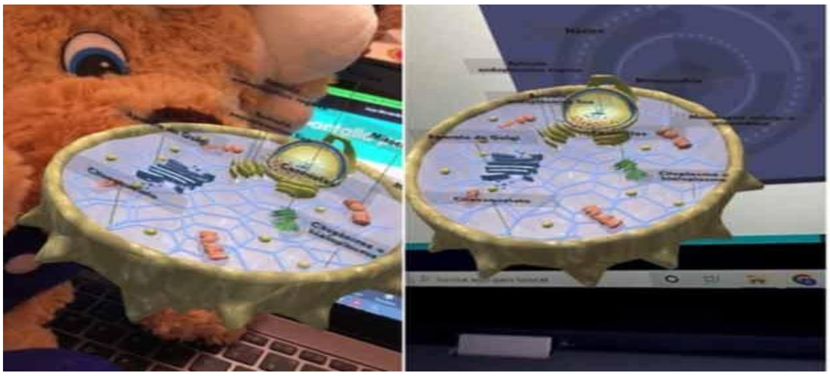


Figure 1
Example of images of ART3D in the biology course

Table 1
Demography of students taking foundation of biological systems (n=33).

Semester (students)	Career (students)
1st (23)	B.S. in Biomedical Engineering (1)
2nd (1)	Bachelor of Business Administration (1)
3rd (4)	B.A. in Biosciences (1)
5th (5)	B.A. in Communication (1)
	B.A. in Economics (1)
	B.A. in Marketing (2)
	Medical and Surgical Dentist (2)
	B.A. in International Business (3)
	B.S. in Industrial Engineering with a minor in Systems Engineering (3)
	B.A. in Nutrition and Wellness (3)
	B.S. in Clinical Psychology and Health (4)
	Physician & Surgeon (5)
	B.S. in Biotechnology Engineering (6)

Case 2. Beijing Institute of Technology (BIT) – VR Manta

Among all the available tools of VR-enabled modeling (Deeks et al., 2020; Lemonick, 2021), our team at BIT developed a unique tool: Manta (Zhao et al., 2021), for the education of chemical kinetics in combustion problems. It can be applied to help students understand the underlying collision process of chemical reactions at the atomic level, such as the reaction kinetics of hydrogen combustion (Zhao et al., 2021). Manta creates an interactive environment that allows users to manipulate complex 3D structures, providing an interactive style for students to explore potential reactions. For engineering students, Manta is a good teaching tool to interpret the macroscopic phenomenon of chemical reactions from the microscopic motions of atoms.

Experience shows that many students can hardly understand the combustion process's reaction mechanism only through textbook knowledge due to the complexity involving tens of intermediates and hundreds of reactions. To explore the education performance of Manta, we organized a class of chemistry experiments to study the reaction mechanism of methane combustion. The VR experiment of methane combustion was carried out for 18 junior students from the Department of Mechatronic Engineering. The purpose of this chemistry experiment class is: (1) to evaluate the influence of temperature on chemical reactions; (2) to observe how chemical reactions occur; and (3) to explore the potential intermediates and reactions involved in methane combustion. A snapshot of methane combustion in Manta is shown in Figure 2.

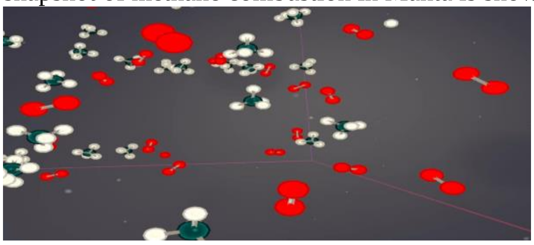


Figure 2
Methane combustion in Manta. The green, white, and red spheres represent the carbon, hydrogen, and oxygen atoms

The VR experiment was conducted in a typical classroom with a blackboard and a projector for slide presentation in front of the classroom, which was used to illustrate the class content. We divided 18 students into two groups and carried out experiments. First, we shared the teaching purpose and experimental content of the VR experiment with the students. One demonstrator from graduate school carried out practical operations and explained the Manta's functions. Students need to learn how to operate Manta and conduct experiments with Manta, including entering and interacting with atoms in the VR environment. Students can communicate, discuss, and help each other to enhance classroom interaction and facilitate fast completion of pre-experiment training. Finally, students in each group must complete the three experimental tasks within forty-five minutes. The specific process of the experiment is shown in Figure 3.

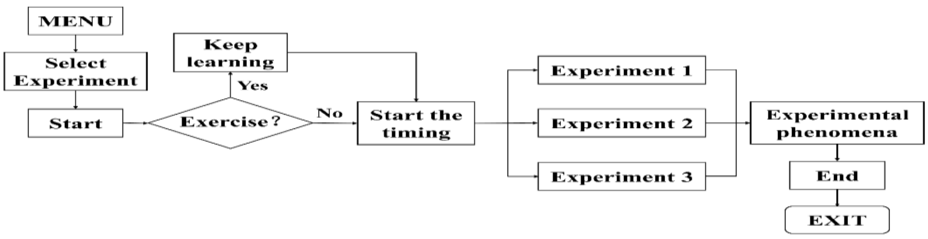


Figure 3
Flow chart of experimental design

The purpose of the experiment was to let the students understand the effect of temperature on the rate of chemical reactions, explore how chemical reactions occur at the atomic level, and study the reaction mechanism of methane combustion. Details about these three experiments are in Supplementary Materials. After the three experiments, we distributed questionnaires to 18 students participating in this experimental class. At the end of the class, 17 valid questionnaires were collected.

In a second round, the 17 students were divided into two groups, and each group was required to complete another set of three experimental tasks within the prescribed time. This second experiment was designed to understand the structure of nine chemicals, determine the bond energies in the compounds, and observe the decomposition process of the compounds by heating (Supplementary Material). The same questionnaire was applied at the end of this experiment.

Data collection and analysis

The data collection method employed was a questionnaire with four Likert-scale and one open-ended question (Supplementary Material). The survey items were designed to understand which factors are involved in student engagement when using an XR activity in a theoretical class (Table 2). For the Likert scale questions, students were asked to select from 1 to 10 how they felt about the proposed statements, where 10 was "the best".

Table 2
Factors related to the Self-system thinking of MKT and constructs elaborated to measure student engagement when using an XR learning resource. Factor tags are uppercase

Factor	Type of questions	Construct
Relevance	Likert scale	From 1 to 10, with 10 being the best, how RELEVANT did you consider the activity and learning experience for the professional practice of your discipline?
Motivation	Likert scale	From 1 to 10, with 10 being the best, what level of MOTIVATION did this activity and learning experience generate in you to improve your knowledge and performance for the professional practice of your discipline?
Self-Efficacy	Likert scale	From 1 to 10, with 10 being the best, at what level of SKILL do you consider yourself today after having carried out this activity, that is, did you manage to improve your performance or understanding of certain knowledge?
	Likert scale	From 1 to 10, with 10 being the best, how do you self-assess yourself in the COMPETENCE to assess the soundness of your own and others' reasoning, based on the identification of fallacies and contradictions that allow you to form an own judgment in the face of a situation or problem, as well as to basis own judgments in the face of a situation or problem, through a process of logical reasoning.
Emotions	Open-ended	Identify and share in this space what EMOTION(S) you had during or after the activity/learning experience, as well as the emotion when you achieved certain knowledge.

The factors studied were the relevance of the activity (1), motivation generated by the activity (2), self-efficacy (skills and competencies) (3), and emotions after doing the activity (4). In the self-efficacy factor, it has been studied that there is not a generalizable construct, such that learners could perceive high efficacy in one situation but low in another (Marzano & Kendall, 2006). Thus, apart from asking the student to evaluate their self-perceived efficacy in skills, they were also asked to evaluate their self-efficacy in critical-thinking competence. This competence (critical thinking) is a higher-order competence that is well-studied in engineering and essential for dealing with multi-dimensional problem-solving (Ahern et al., 2019; Miranda et al., 2021). It would give us answers about student engagement.

This research involves humans who need to pay attention to their rights. No personal data was collected, and by answering the survey, all students agreed that the information they answered was going to be employed for educational innovation purposes, which includes publications, according to the Privacy Notice.

The mixed method approach allows quantitative and qualitative analysis. Cronbach's alpha was calculated for the reliability and validity of the Likert scale constructs. The answers to the open-ended question were analyzed qualitatively. Answers were translated and tagged for emotions. Counted emotions were listed for the number of repetitions. The quantitative and statistical analysis (covariance, normality test, and nonparametric statistics) of the survey results was carried out using Minitab® 21.1 software (Minitab, LLC, State College, PA, USA).

FINDINGS

Due to a non-normal distribution in the three groups, the analysis was carried out using a non-parametric tool. The inferential statistical analysis was carried out with a non-parametric Mood's Median Test due to the lack of confidence about the similarity between the groups' shaped distributions. The intention was to determine whether the medians of two or more groups were equal. The non-parametric Mood Median Test with a significance level of 5% showed that the medians of ART3D, and Manta rounds 1 and 2 cases were not all equal. The statistical analysis results, which can be consulted in the Supplementary Materials, demonstrated that the samples should be analyzed separately.

Case 1. Tecnologico de Monterrey – ART3D

In the case of ART3D (Figure 4), students were very positive. They gave high punctuation to all four factors studied. However, for the efficacy elements, answers were more distributed between the range of 8 to 10.

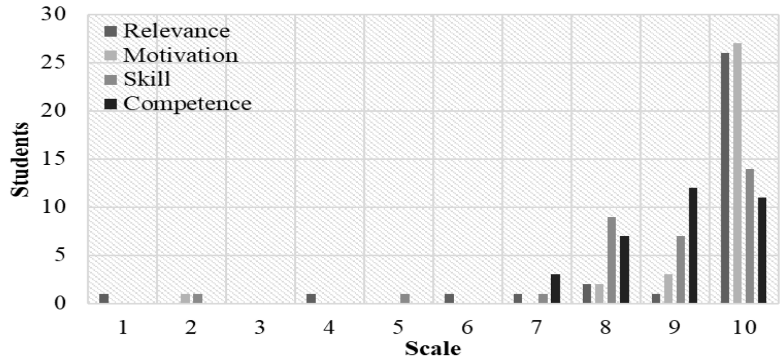


Figure 4
Students' response to the ART3D Cell and Organelles practice survey

Only one student from the 5th semester of a Bachelor in International Business answered with 1 or 2 for relevance, motivation, and skill. However, in terms of competence, this student gave an 8. The lowest punctuations (i.e., ≤ 5) for relevance were also from a student of B.A. in Economics. In the case of Motivation, there were no lower punctuations (all started in 8). In the case of skill, a B.S. in Clinical Psychology and Health student also gave punctuation of 5. In the case of competence, all students' answers were above 7. The means and standard deviations of the answers can be observed in Table 3.

Table 3
Total statistics of the instrument results in the ART3D practice

Variable	Total count	Mean	Std. Dev.
Relevance	33	9.182	2.007
Motivation	33	9.545	1.460
Skill	33	8.758	1.678
Competence	33	8.939	0.966

The Cronbach's alpha for the survey was 0.834, which implies that it has a high degree of reliability. There is stability or consistency between the results obtained. That is, in the repeated use of the instrument, the same results are produced.

As observed in the correlation matrix (Table 4), there is a good correlation between the activity's relevance and the student's motivation; also for motivation and skills. However, competence (critical thinking) did not correlate well with other factors.

Table 4
Correlation matrix of the factors involved in engagement in the ART3D case. *

	Relevance	Motivation	Skill
Motivation	0.882		
Skill	0.672	0.783	
Competence	0.312	0.290	0.453
*Pearson correlation values			

To the open-ended question, "Identify and share in this space what emotion(s) you had during or after the activity/learning experience, as well as the emotion when you achieved certain knowledge", answers were more in a positive context. Some positive answers are:

- *"I was very excited about this activity because it allowed me to visualize the cell and its structures in 4D; I think that the ability to recognize the organelles is much easier in this way compared to drawing from a textbook or images on the internet"*
- *"I felt very excited to know that we could learn through this type of media, of which, thanks to its innovation, it is more practical for us to learn while having fun, which is achieved in very few subjects; II also felt very satisfied because of the way of teaching."*
- *"I was very happy and amazed because it was something I had never seen; the images are very clear, and that helps to understand more easily and in greater depth."*

Only two answers had a negative connotation:

- *"Frustration because the teacher quickly removed the photo."*
- *"I feel like it was a lot of information in a very short time."*

These answers were translated from Spanish to English and coded manually for emotions. In Table 5, there is a list of the codes and the times that they were repeated.

Table 5
List of tags assigned to the open question answers of the ART3D practice

Tag	Count of Field	Tag	Count of Field
excitement	13	frustration	2
fun	6	entertainment	2
satisfaction	5	creativity	1
motivation	4	surprise	1
amazement	4	originality	1
happiness	4	fascination	1
likeness	3	easiness	1
enthusiasm	3	hurry	1
interest	3	attention	1
novelty	2	impressed	1

Case 2. Beijing Institute of Technology (BIT) – VR Manta

In the case of the Manta, only 17 students answered the questionnaire. Cronbach's alpha (0.546) was less than 0.7 in the first round. However, it was 0.778 in the second round, which mean that the results may not be consistent. However, the appropriate reference value might be flexible due to the amount of observed data compared to the ART3D case.

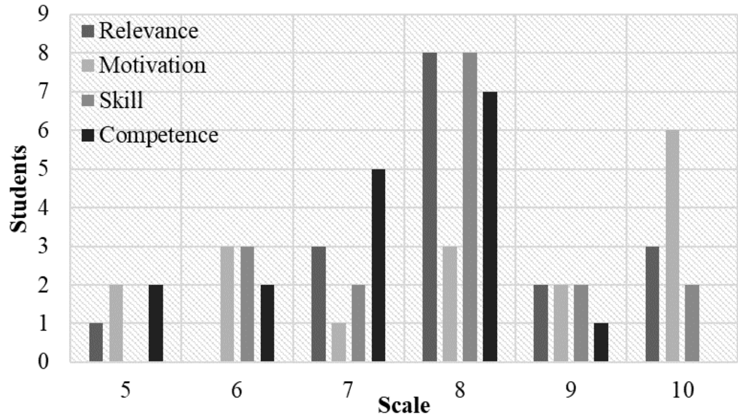
Interestingly, none of the answers were below 5 (Figure 5), and competence did not have punctuations of 10 in the first round. More answers were around 8 on the Likert scale (Figure 5a). This behavior changed in the second round since more students felt motivated and gave the competence construct higher punctuations (Figure 5b). The standard deviations were lower than the case of ART3D, except for the competence (Table 6) of the first round. For the second round, the standard deviations were even lower than in the first round.

Table 6
Total statistics of the instrument results in the Manta case

	Round 1			Round 2		
Variable	Total	Mean	Std. Dev.	Total	Mean	Std. Dev.
Relevance	17	8.118	1.269	17	8.176	0.346
Motivation	17	8.059	1.886	17	8.765	0.315
Skill	17	7.882	1.219	17	8.353	0.320
Competence	17	7.176	1.131	17	7.706	0.318

Descriptive statistics show no difference between the sample means between both Manta rounds. Moreover, the difference in the standard deviation is notable (i.e., round 1 has a more significant dispersion of the students' data concerning their mean for each question than in the second experiment).

a)



b)

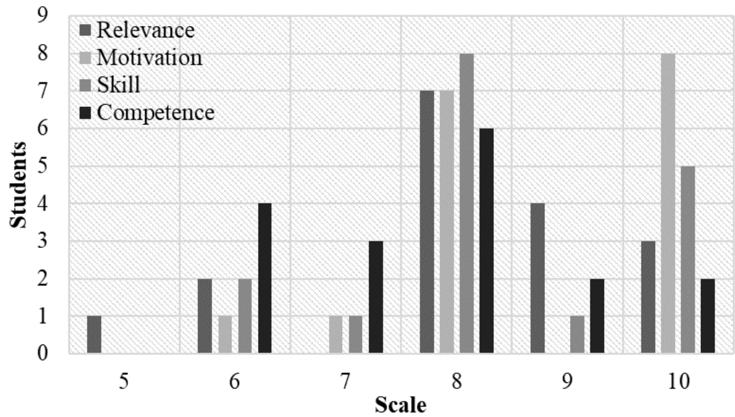


Figure 5
Students' response to the Manta practice survey. a) Round 1, b) Round 2

A test of equal variances was performed to verify if there was a statistically significant difference between the deviations and population variances of rounds 1 and 2. With this, it was verified that with a significance level of 5%, the population variances of rounds 1 and 2 are equal (i.e., there is no significant difference between the variability of the students' data concerning each question mean), as observed in Figure 6.

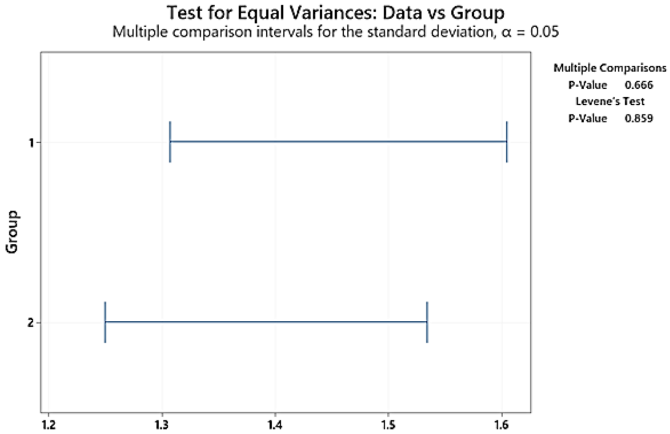


Figure 6
Test for equal variances of rounds 1 and 2 of Manta experiments. If intervals do not overlap, the corresponding standard deviations are significantly different.

In the case of the students of Manta case, with a major in safety engineering, the only relevant correlation found is between the two constructs of self-efficacy (skill and competence) in both rounds, as observed in Table 7.

Table 7
Correlation matrix of the factors involved in engagement in the Manta case

	Round 1			Round 2		
	Relevance	Motivation	Skill	Relevance	Motivation	Skill
Motivation	0.049			0.462		
Skill	0.212	0.438		0.430	0.561	
Competence	0.159	0.083	0.651	0.264	0.360	0.749

In the case of emotions, some positive comments for the first and the second round of the Manta case were:

- *It's amazing to be able to watch how molecules react. When we finished the group task, I felt very excited and happy.*
- *The experiment process is very interesting, motivating me to practice. When we finished the task, I felt very happy.*
- *It's a new feeling, a sense of accomplishment.*
- *It feels like there's so much to come! The mood is good, the feeling is very beneficial to study.*
- *Proud to use VR to complete learning tasks.*

Neutral or negative answers:

- *A little bit of dissatisfaction due to lack of time.*
- *The process of completing the content was difficult.*

- *More shocking, but also more novel. It is the first time to contact VR for me, there are still some shortcomings in the actual operation process; that is, there are too many differences in the practical operation. I hope to get more guidance in the operation process.*

Novelty and happiness were the top emotions mentioned in the first round (Table 8), while these were emotions of likeness and fun in the second round.

Table 8
List of tags assigned to the open question answers in the case of Manta

Tag	Round 1	Round 2	Tag	Round 1
likeness*		5	dissatisfaction	2
fun	1	4	motivated	1
happiness	5	2	amazed	1
accomplishment	1	2	interest	1
novelty	5	1	immerse	1
excitement	2	1	fulfilling	1
relaxed	2	1	shocked	1
entertaining		1		
proud		1		
anything		1		

*Likeness includes good, glad, nice, and great words.

DISCUSSION AND CONCLUSION

XR technologies are necessary for a Smart University (Uskov et al., 2019). It is imperative to instruct faculty in the use and design of this type of resource (Korenova et al., 2019). However, as with any educational innovation, its usefulness in reaching educational objectives should be evaluated. A way of evaluation is student engagement. "Engagement involves students using time and energy to learn materials and skills, demonstrating learning, interacting in a meaningful way with others in the class, and becoming emotionally involved with their learning" (Garris & Fleck, 2022). In this case, we intended to measure how the self-system thinking factors of relevance, motivation, self-efficacy (skills and competence), and emotions relate to the engagement of students who use extended reality resources in science and engineering through an action research approach. The results of the surveys and observations of the experimentation were conducted through qualitative and quantitative methods.

Regarding quantitative methods, descriptive statistics analysis (mean and standard deviation), normality tests, Cronbach's alpha, and correlations were applied to the data of each group. The normality test showed that the two groups did not have a normal distribution. Because of this, the data was analyzed and treated with non-parametric statistics. Other works have suggested that samples in social sciences do not correspond to normal distributions, even when samples are large enough ($n > 30$) (Toraman, 2021). We found significant non-parametric statistical differences (p-value < 0.05) between the courses in Mexico and China (Supplementary Material). The findings proved that each experimental group had different characteristics and contexts and should be analyzed separately.

Cronbach's alpha was calculated for instrument (survey) validity and reliability. The calculated values (0.834 for ART3D, 0.546, and 0.778 for VR Manta) were in the range of similar works (Aliman et al., 2019). As we did in the present work, other studies validated their approaches by quantitative and qualitative data triangulation using mixed methods and following a coherent approach (Arantes do Amaral and Brito, 2018).

The context of different groups in which the instrument was applied significantly differs in terms of the student's learning experience results. Furthermore, the type of program the student studies, the semester or academic year, the discipline, and the country, among others. Besides, it is important to note that the self-system thinking determiners could not be equal regarding their effect on engagement. For example, a perception of relevance can likely override a perceived lack of self-efficacy and a negative emotional response. Thus, correlations of the different factors of self-system thinking would give important hints on student engagement for the two cases, including qualitative data (coded emotions).

In the ART3D case, a high score was given to the motivation, with a lower deviation, and was highly correlated with the relevance of the activity. Also, a correlation was found between the self-efficacy auto-assessment about skills and relevance and the self-efficacy auto-assessment about skills with motivation after the AR activity. Besides, more positive than negative answers were obtained regardless of their career. In other works, it has also been found that self-efficacy is significantly positively correlated with motivation when using AR technology (Kari, 2020).

It is important to note that most students were freshmen at the university. Therefore, it is not ruled out that they later decide to change careers due to the use of these activities. Interestingly, the negative reactions were not due to the activity itself but to the speed with which it was performed. Therefore, in addition to relevance, work must be done so that students can do the activity at their own pace. It is important to plan the execution of XR experiences considering students' pace (Weeks et al., 2021).

The most mentioned emotions were excitement, fun, and satisfaction, indicating that engagement depended both on the relevance of the activity and the satisfaction arising from the emotions generated by the activity. As the students commented, emotions influenced their learning since they better remember what they have learned. However, it was possible to observe that not all the students self-perceive with critical-thinking competence, indicating that the students' emotion may have overwhelmed their reasoning to decide whether the information was relevant or their motivation was genuinely based on the activity. This is understood due to the low correlation between the results of the self-efficacy-competence construct with the rest of the questions. In other works, "interesting", "surprise", "wonder", and "fascinating" positive emotions have been classified as affective triggers had been associated with user autonomy (Alamäki et al., 2021).

In the Manta case, students had a major in safety engineering. The only correlation found was on the self-efficacy assessment critical thinking-competence with skills after the VR activity. This was pronounced in the second round, with lower standard deviations. Emotions were also more positive than negative, and negative answers were also related to time concerns. This result shows a more objective and logical thinking answer versus an emotional and subjective answer in ART3D. Being such a multidisciplinary group could have generated great novelty in this type of experience in the students of group ART3D. In Manta groups, throughout the experimental process, they were very aware of testing an educational innovation initiative; therefore, the emotionality was probably not so recognized, in addition to the size of the sample under study. In this regard, it has also been shown that VR is more related to skill development and user anxiety, affecting student engagement (Tai et al., 2022; Venkatesan et al., 2021).

This study has many limitations, mainly due to the low number of students, the lack of control groups, and the variation in using XR technologies. However, the results of this empirical study, based on student responses, demonstrate that an XR learning resource shows good results in engaging students on a topic and can therefore improve learning, as there is a high correlation between learning and student success (Kunka, 2020). On the other hand, the constructs used may be improved since language can be a determining factor in the results of this work. In a future study, we intend to conduct an in-depth literature review to find instruments tested and validated for student engagement in relevance, motivation, self-efficacy, and emotions or to validate our instrument. In this sense, studies have recommended the use of debriefing after a simulation to increase reflection and integration of virtual experiences (Gordon, 2017), so it is recommended to include in the design the type of activities before answering a survey on the use of XR experiences and prevent responses from being biased by the emotion of the activity.

Despite its potential in education and learning (Sural, 2018; Wahyu et al., 2020; Amprasi et al., 2022), studies have suggested that there are scattered scholarly works and fragmentary insights of XR to be translated into practice, considering its multidisciplinary nature and the need for staff training, guidance, and facilitation as limiting aspects (Chuah, 2018). Studies measuring student engagement with technology-enhanced learning (TEL) have found that motivation and self-efficacy are related to engagement and that there is an emerging literature aiming to explore this relationship to explore new ways to design TEL (Dunn & Kennedy, 2019).

The practical implications of this study rely on the fact that motivation, emotions, or self-efficacy are seldom considered in digital technologies and are hardly related to the student's context (Pumptow & Brahm, 2021). This work contributes with a scale to evaluate students' self-system thinking when working with XR technologies. The instrument can be used for broader applications to other Higher Education Institutions and digital technologies in STEM education. The information collected through the questionnaire is being used to evaluate the teaching effect of the class to provide a better XR experiment experience for future students.

This study showed that engagement-related self-system factors such as relevance, motivation, and self-efficacy were high when an XR was used as an educational strategy. In the case of an AR learning resource, relevance, motivation, and emotions were correlated. In contrast, in the case of a VR learning resource, self-efficacy in skills and critical-thinking competence is related to positive emotions. Even when, in both cases, the emotional response was positive, different contexts had a different effect on the way an XR learning resource engages students in learning. Faculty can implement an AR or VR experiment in their courses depending on time and economic resources to engage students in biology and chemistry topics.

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SUPPLEMENTARY MATERIAL

SURVEY ACTIVITY ART3D CELL AND ORGANELLES

Read carefully and respond according to the relevance, motivation, interest and liking for the activity developed with the Professor. In addition, make a brief self-assessment about your skills and competencies. Thank you very much in advance for sharing this information to see what best practices can give you the best learning experience.

PRIVACY NOTICE: “The information provided will be treated solely for the purposes of educational innovation, as part of the Institute for the Future of Education. The information provided will be treated with absolute privacy and confidentiality. I freely grant my consent to participate in this dynamic, by middle of this form.” For more information, you can go to the Privacy Notice of the Tecnológico de Monterrey at: https://tec.mx/es/aviso-de-privacidad-alumnos
Yes, I agree with everything mentioned.
I disagree with some or all the above.

Q1. Select the semester you are studying.

Q2. Write down the acronyms of your professional career.

Q3. From 1 to 10, with 10 being the best, how relevant did you consider the activity and learning experience for the professional practice of your discipline?

Q4. From 1 to 10, with 10 being the best, what level of motivation did this activity and learning experience generate in you to improve your knowledge and performance for the professional practice of your discipline?

Q5. From 1 to 10, with 10 being the best, at what level of skill do you consider yourself TODAY after having carried out this activity, that is, did you manage to improve your performance or understanding of certain knowledge?
Q6. From 1 to 10, with 10 being the best, how do you self-assess yourself in the competence (knowledge + skills + attitudes + values) to assess the soundness of your own and others' reasoning, based on the identification of fallacies and contradictions that allow you to form a own judgment in the face of a situation or problem, as well as to BASIS own judgments in the face of a situation or problem, through a process of logical reasoning.
Q7. Identify and share in this space what emotion(s) you had during or after the activity/learning experience, as well as the emotion when you achieved certain knowledge.

DETAILS OF VIRTUAL EXPERIMENTS CARRIED OUT IN MANTA

First round

The purpose of the first experiment is to let the students understand the effect of temperature on the rate of chemical reactions. A complex reaction in a mixture of methane and oxygen molecules causes methane combustion. At high temperatures, the reaction mixture spontaneously ignites until equilibrium is reached. From previous experiments on chemical reactions, we know that the rate of chemical reactions accelerates as the temperature increases. This experiment illustrates this phenomenon at the atomic level (Hunt & Taube, 1958). In the experiment, the initial temperature of the reaction system was set as 300 K. The user entered the menu panel, heated the reaction system by manipulating the handle, and gradually increased the system temperature to 2000 K. With increasing temperature, a change in the movement rate of molecules in the reaction system was observed. At 300 K, the atoms in the system move very slowly, and no chemical bonds break. As the temperature rises, the atoms in the system move faster, more chemical bonds break, and the degree of collisions between atoms becomes more intense. If the students can manipulate the handle to increase the temperature of the reaction system and observe changes in the reaction system as the temperature increases, they complete the first experiment.

The second experiment explores how chemical reactions occur at the atomic level. Chemical reactions involve reactive collisions between molecules, causing the formation or breakage of chemical bonds. In practical experiments, we mainly judge whether chemical reactions occur by tracking the changes in the macroscopic properties of the system. Instead, Manta provides the functionality to explore the trajectory of chemical reactions on the atomic level. However, not every collision between atoms is practical, resulting in a chemical reaction (Gochev et al., 1985). Through this experiment, students could observe how the methane combustion chemical process occurs at the atomic level. If the students can observe through Manta that new substances are formed by the collision of atoms in the system, they complete the second experiment.

The third experiment is designed to study the reaction mechanism of methane combustion. The reaction mechanism is used in kinetics to describe the chemical evolution through elementary reactions (Qin et al., 2000). The reaction mechanism includes all the potential intermediates and reactions involved in the process, from reactants to products. In the third VR experiment, students were asked to explore the intermediates and elementary reactions involved in methane combustion. The students can manipulate the temperature to observe more reactions or design specific reactions using the interactive functionality to promote collisions between molecules. In the third experiment, all operations of the student were recorded in the local client, and the students themselves generated a chemical reaction network of methane combustion.

Second round

The first experiment aims to use Manta to understand the chemical structure of complex compounds. Understanding the chemical structure of substances is the basis of chemical learning. However, for complex compounds, it is not easy to fully understand the chemical structure of these complex compounds through traditional visualization tools, such as books, computers, and PPTs. In this experiment, students can closely observe the chemical structure of complex compounds in virtual space through Manta. In Experiment 1, a collection of nine chemicals is included. All students involved in this experiment must observe the nine molecular structures in the virtual space and then match them with the chemical structures shown in the PPT slides.

The second experiment is to judge the bond energies of the chemical bonds within a specific substance. Bond energy is a physical quantity that measures the strength of a chemical bond. It is usually obtained by measuring the dissociation energy through thermochemical or spectrochemical experiments (Sanderson, 1983). In this experiment, we use Manta to apply the same degree of force to the compound’s chemical bonds. The students are asked to rank the bond strength by “feeling” the feedback when dragging the bonds apart.

The third experiment is to observe the decomposition of compounds. Thermal decomposition is the process by which a compound is decomposed by heating (Beyler & Hirschler, 2002). In the system, the initial temperature is set as 1000 K. Students need to operate the handles to heat up the reaction system and observe how the compound decomposes as the temperature rises. At the same time, students are asked to observe what is the first decomposition product during the heating. When the students complete the above operations and identify the first decomposition product, they complete the task of this experiment.

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STATISTICAL ANALYSIS

1. Covariance Matrix

ART3D Case 1

	Q3	*Q4*	*Q5*	*Q6*
Q3	*4.0284*			
Q4	*2.5852*	*2.1307*		
Q5	*2.2642*	*1.9176*	*2.8144*	
Q6	*0.6051*	*0.4091*	*0.7348*	*0.9337*

VR Manta Case 2

First round

	Q3	Q4	Q5	Q6
Q3	1.6103			
Q4	0.1176	3.5588		
Q5	0.3272	1.0074	1.4853	
Q6	0.2279	0.1765	0.8971	1.2794

Second round

	Q3	Q4	Q5	Q6
Q3	2.02941			
Q4	0.85662	1.69118		
Q5	0.80882	0.96324	1.74265	
Q6	0.49265	0.61397	1.29779	1.72059

Q3=Relevance, Q4=motivation, Q5=Skill, Q6=Competence

Regarding covariance, all observed variables have a behavior of positive values on the scale of real numbers.

2. Normality test:

Case 1	Case 2
P-value<0.05	P-value<0.05 (round 1)
	P-value<0.005 (round2)

The two groups do not have a normal distribution. Because of this, the data can be analyzed and treated with non-parametric statistics.

3. Mood´s Test:

The objective was to prove through nonparametric statistics whether there is significant evidence that the medians are statistically different.

Descriptive Statistics

Group	Median	N <= Overall Median	N > Overall Median	95% Median CI
1	10	54	78	(10, 10)
2.1	8	57	11	(8, 8)
2.2	8	50	18	(8, 8)
Overall	9			

Three groups Mood´s Test:

Null hypothesis	H_0: The population medians are all equal
Alternative hypothesis	H_1: The population medians are not all equal

DF	Chi-Square	P-Value
2	41.34	0.000<0.05

Conclusion: at least one group pair (1-2.1; 1-2.2; or 2.1-2.2) populations have different medians.

Group 1 (ART3D) and 2.1 (Manta) Test

Null hypothesis	H_0: The population medians are all equal
Alternative hypothesis	H_1: The population medians are not all equal

DF	Chi-Square	P-Value
1	33.47	0.000<0.05

Conclusion: With a significance level of 5%, it can be concluded that the medians of groups 1 and 2.1, where the Extended Reality experiment was tested (ART3D vs. Manta), are unequal.

Group 2.1 and Group 2.2 (Manta) Test

Null hypothesis	H_0: The population medians are all equal
Alternative hypothesis	H_1: The population medians are not all equal

DF	Chi-Square	P-Value
1	1.67	0.197>0.05

Conclusion: With a significance level of 5%, it can be concluded that the medians of groups 1 and 2, where the Virtual Reality experiment was tested in China, are equal.