Computers & Education: X Reality 3 (2023) 100036

Contents lists available at ScienceDirect

Computers & Education: X Reality

journal homepage: www.journals.elsevier.com/computers-and-education-x-reality

Evaluation of eXtended reality (XR) technology on motivation for learning physics among students in mexican schools

Brandon Antonio Cárdenas-Sainz [a,*], María Lucía Barrón-Estrada [a], Ramón Zatarain-Cabada [a], Maria Elena Chavez-Echeagaray [b]

[a] Tecnológico Nacional De México – Instituto Tecnológico De Culiacán, Sinaloa, Mexico
[b] Arizona State University, Tempe, USA

A R T I C L E I N F O

Keywords:
Extended reality
Virtual reality
Augmented reality
Learning motivation
Physics education
ARCS motivation theory

A B S T R A C T

Developing countries, including Mexico, face the challenge of integrating technology to enhance education and improve learning outcomes. Despite evidence in many settings of the benefits of using virtual reality (VR) and augmented reality (AR) as learning tools, their potential use is still understudied in many developing regions. The objective of the present study is to evaluate the impact of a web-based eXtended Reality (XR) learning tool, PhysXR, among college-level students enrolled in a Mexican University. PhysXR is a web-based learning application designed to present users with information focused on Newtonian mechanics. This tool presents users with interactive experiences ranging from VR to AR environments and supports a physics simulator for experiments on physical phenomena of dynamics and kinematics. Overall, learning methodologies implemented using PhysXR follow the competency-based learning model implemented in Mexican Education Institutions, and include *Learn by Doing* and *Problem Based Learning* (PBL). In order to evaluate the PhysXR tool, 99 students were recruited and randomized to either experimental (VR and AR conditions using PhysXR) or control groups. Outcomes included student's learning and motivation, assessed using the John Keller's Attention, Relevance, Confidence and Satisfaction (ARCS) learning motivation model. Results from this study indicate that the use of the PhysXR tool, both VR and AR approaches, generates a significant improvement in learning gains and motivation compared with traditional methods, highlighting the potential of cross-platform capabilities that web-based XR technology could offer, as well as the use of real time physics simulations for learning.

1. Introduction

The Mexican education system faces several challenges since the last decade, underscoring the need for changes and reforms to effectively improve the quality of education. Following the current standards presented by the Organization for Economic Co-operation and Development (OECD), the competency-based educational (CBE) model has been gradually implemented in Mexico from basic to higher education institutions since 2004 (Levano et al., 2019). According to the Programme of International Student Assessment (PISA), the CBE model is oriented towards the autonomous and independent development of students' skills, aptitudes, and knowledge, increasing their competences for both professional and everyday life. The model also differs from traditional approaches since it shifts the evaluation focus from credits and grades, and instead measures learning by time and mastery of competences and skills (Santiago et al., 2012). CBE presents an exploratory, constructive, active, contextual, and reflexive approach, as such, there is a need to offer educational experiences to motivate and develop learning. Currently, several methodologies and paradigms of learning design (e.g., learning by doing, problem-based learning, project-based learning, cooperative learning) are being used by instructors according to the subject or field of interest (Dragoo & Barrows, 2016; Sälzer & Roczen, 2018).

The science, technology, engineering, and mathematics (STEM) field of education in Mexico has been studying these educational methodologies and the feasibility of their implementation among students with diverse demographics. The instruction of STEM topics is faced with particular challenges in the Mexican setting, including the availability of specialized human capital for teaching specific subjects, as well as the call for digital transformation, which is present in the actual educational

* Corresponding author. Departamento de Posgrado, Tecnologico Nacional De México, Campus Culiacán, Juan de Dios Batiz No. 310 pte, Col. Guadalupe, Mexico.
E-mail addresses: brandon.cs@culiacan.tecnm.mx (B.A. Cárdenas-Sainz), lucia.be@culiacan.tecnm.mx (M.L. Barrón-Estrada), ramon.zc@culiacan.tecnm.mx (R. Zatarain-Cabada), helenchavez@asu.edu (M.E. Chavez-Echeagaray).

https://doi.org/10.1016/j.cexr.2023.100036
Received 5 December 2022; Received in revised form 23 July 2023; Accepted 6 August 2023
Available online 12 August 2023

system with the development of the 4.0 education model (Lopez-Garcia et al., 2019). Under these circumstances, STEM education must confront several changes to transform learning as an adaptable activity, tailored in pace and speed to the needs of each student. This includes using digital learning approaches that provide constant feedback, analyzing information and data from the learning progress of an individual, and training instructors and managers for the use of digital procedures in schools (O'sullivan & Burce, 2014, pp. 22–23). Still, other issues that STEM education should consider are the aspects of stimulation and motivation that learning tools and its content should provide for students.

As stated by Zaikin et al. (2017), education 4.0 model in CBE is likely to introduce changes in the educational procedures at higher education, changing the roles and relationships between all participants in the learning process, and potentially losing relevant aspects such as inspiration and motivation. Learning activities require students to be actively engaged and in contact with an agent that motivates them; therefore, it is necessary to consider aspects related to motivation in the development of tools, instruments and digital content used for learning. STEM scholars have addressed some of these challenges in disciplines such as mathematics and physics, as these learning fields present complex and abstract concepts that students may find difficult to understand and comprehend, especially when these are not appropriately presented (Fidan & Tuncel, 2019). This suboptimal presentation has several consequences on the student's interest towards learning, and when added to the lack of stimulation and the monotony of learning activities can lead to a decrease in students' motivation and concentration.

The diverse challenges in STEM education have resulted in a growing trend towards the integration of emerging technologies such as extended reality (XR), which aims to improve the educational experience by including more interactive and intuitive learning environments in instructional curricula. XR refers to an umbrella term that encompasses all the technologies that create digital elements and environments and interact partially or completely with the existing real environment. These include augmented reality (AR) technologies, which consist in real-world centric experiences overlaid with digital information, and virtual reality (VR), which provides immersive digital experiences totally isolated from reality. XR is also a concept that introduces a new design paradigm, where immersive applications provide adaptable experiences based on the features and capabilities of a device and platform. This suggests that interactive digital content can be generalized and distributed across the web to enhance communication and sharing of information and knowledge. Both AR and VR approaches have become popular in education for their capabilities to enhance the presentation and visualization of learning material, while offering various levels of immersion and interaction through virtual components. Several studies have demonstrated that the integration of these new technologies can improve many aspects of learning, including engagement, satisfaction, motivation, and knowledge retention (Di Serio et al., 2013; Harris & Reid, 2005; Hussein & Nätterdal, 2015; Ibáñez & Delgado-Kloos, 2018; Kavanagh et al., 2017; Ratclife et al., 2021). Nonetheless, few attempts have been made to design XR applications with online learning courses in mind. This newer approach implies a process of development isolated from conventional schemes, which are fixed on explicit native AR and VR applications. Another issue is that most of the studies assessing these tools have been carried out in developed settings, and there is limited information regarding the use of XR in the context of CBE and education 4.0 in developing settings, including Mexico.

Currently, most Mexican schools using the CBE model stablished by the Ministry of Public Education (SEP) are in the public sector, and many of these schools face considerable resource limitations. These schools, from elementary to higher education, often lack the necessary areas or tools to adequately undertake learning methodologies focused on improving students' competencies at an exploratory and self-taught level (Tromp & Datzberger, 2021). This leads to a lack of learning motivation, especially in the case of complex or abstract STEM subjects such as physics, as students struggle and are less willing to develop and improve their competencies and skills (Chomphuphra et al., 2019). This lack of encouraging incentives may be due to factors including the absence of a motivating agent (e.g., a human teacher or a proper tutoring system), the lack of a suitable learning space (e.g., a laboratory) for learning activities that require exploration and experimentation, or to the use of inadequate tools and methodologies that could be perceived as monotonous, outdated, and irrelevant(Antón-Sancho et al., 2021). In light of these issues, educational technology researchers in Mexico suggest that there is a latent potential in using emerging digital technologies such as XR to stimulate students' curiosity to experiment and explore, and that it is therefore necessary to consider the needs of Mexican students, as well as their perceptions regarding the use of digital approaches for educational and training purposes. Several projects and applications of VR and AR for learning have been developed in the last decade, however in Mexico, the lack of funding, support, as well as the effects caused by the latest educational reforms have drastically slowed down their adoption and has further limited the possibilities for greater traction among both teachers and academic institutions (González Calleros et al., 2022).

After recognizing the impending need to address motivation for STEM education in Mexico, we designed the present study to evaluate the implementation of XR technology and assess the effect of an immersive style (AR and VR) in terms of the motivation and learning performance of students during the learning process. The study was set in the context of a physics course, in order to showcase the visual and interactive capabilities of XR technology to support students in a subject traditionally perceived as difficult. Our approach uses a web-based XR learning application that presents learning content in virtual environments for both AR and VR technologies. The content can be accessed using any device, from personal computers to mobile devices with web and internet capabilities and with compatible peripherals, making it a multiplatform application.

2. Related work

As many researchers and educators around the world are actively developing didactic applications in combination with digital content to enhance the quality of learning, the current literature on the use of immersive XR technologies in STEM education has become more comprehensive and mature. Recent precedents of implementations in STEM domains include mathematics (Ahmad & Junaini, 2020; Lai & Cheong, 2022a), physics (Alnagrat et al., 2021; Lai & Cheong, 2022b), and chemistry (Mazzuco et al., 2022; Reeves et al., 2021). Results from these previous studies generally show that XR strategies such as AR and VR can improve learning outcomes and motivation.

In a study conducted by Johnson-Glenberg et al. (2021), the authors analyze the effects of embodied learning in STEM experiences by comparing platforms with different levels of immersion and interactivity, including a non-immersive VR environment and an immersive 3D environment. The results revealed that the effect of the platform was significantly mediated by presence, agency, and engagement. The authors underscore the importance of designing VR content with higher agency and interactive capabilities, and also advise to avoid passive learning.

Lee et al. (2022) investigated a XR classroom setup for STEM education among undergraduate aerospace and mechanical engineering students. The researchers designed AR and VR courses to analyze collaborative, interactive and immersive capabilities, and their effects on learning. In a quantitative survey, the results showed an increase in students' self-efficacy and academic performance when using these tools. Limitations stemming from this approach include cost, scalability, and management complexity of team-based activities.

Mystakidis and Christopoulos (2022) assessed the perceptions of VR escape room games for STEM education. According to this study, escape rooms have the potential to develop competencies in problem solving, as these present approaches based in exploration and interaction, while stimulating creativity and cognitive skills. The results also suggest that students and teachers are willing to use student-centered blended learning scenarios, as these present an innovative and active approach, befitting motivation, and engagement in STEM education for the industry 4.0 era.

Additional examples include the work of Smith et al. (2023) who present a VR plotting system for STEM education, using examples from math, physics and chemistry to enable students, teachers, and researchers to create stereoscopic VR visualizations in a web-based application for smartphones. A pilot test indicated that students and teachers perceived the app as easy to use and engaging. Alkhabra et al. (2023) also presented a study using an experimental approach to enhance learning retention and critical thinking using AR. The authors analyze the interaction between AR design and the development of critical and practical skills on high school students. Results from this study revelated that AR implementation has a significant impact on overall critical thinking with a low cognitive load. The authors suggest that future research should be focused on quantifying learning outcomes by sociocultural context and on revealing the educational benefits of AR in active learning.

Despite the positive impact of XR integration in STEM curricula showcased in these previous studies, the use of XR technologies in teaching and learning still poses many significant challenges. Some of these are acknowledged in the current literature, and include: the availability and adoption of XR capable devices, the qualification of teachers in the use of techno-pedagogical approaches, and the specific development of digital learning content that could fully exploit the potential of XR (Luo et al., 2021). Likewise, it is understood that these shortcomings arise from the social, economic, and cultural context in which these approaches are applied, as well as generational differences in the perceptions and acceptance towards the use of technology for learning.

2.1. Current state of digital technologies for education in Mexico

In the context of Mexico and its CBE model, much emphasis is placed on innovative learning methods and tools to provide students with the capabilities to develop and gain better skills and competencies for real-world scenarios (R. Tromp, 2018). However, Mexico faces unstable and limited public investment in education, as well as a lack of government policies and reforms to contribute towards the development of technological innovation (Sánchez-Juárez & García-Almada, 2016). These limitations were broadly highlighted during the COVID-19 pandemic, a time that required a rapid shift from traditional to alternative education strategies which exploited distance learning via the internet. This resulted in a need to adopt digital methodologies and tools for educational purposes. Some examples include the use of video streaming and videoconferencing services, virtual classrooms, and the use of massive open online courses (MOOCs) (Aguilera-Hermida et al., 2021), which were successfully embraced during this period of educational crisis, emphasizing that Mexican institutes favored the use of digital technologies tools for diffusion and communication. However, there was very little exploration and adoption of XR technologies to support the development of knowledge, skills, and competencies of Mexican students (González Calleros et al., 2022) and no further efforts were made to systematically improve the overall educational experience, nor to enhance the way that students can interact and experiment with digital learning content.

Still, there are recent attempts to apply XR technologies in the Mexican school curricula, which include the work of Olivas Castellanos et al., (2022) which presents a VR laboratory approach for remote education. Similarly, Rocha Estrada et al., (2021) present an assessment of acceptance and user experience of a web-based virtual campus approach due to the COVID-19 policies introduced in Mexico. The implementation of AR for STEM education has also been explored in the work of Ibáñez et al. (2020) showcasing a comparative analysis of the learning performance and motivation among high school students from private and public institutions when using AR for learning geometry. The use of AR for data analysis and problem solving for engineering students in a Mexican university was also implemented by Zamora-Antuñano et al. (2022); results from this study showcased improvements in academic performance and a positive interest towards using AR tools for academic training purposes. Last, the integration of AR for remote training in the education and industrial sector proposed by López-Hernández et al. (2022) presented a use case scenario in a northwestern region of Mexico with a deficient infrastructure of information and communication technology (ICT). The results in this study showed that AR capabilities allow productive and representative results considering the limitations in economic resources.

As evidenced by the literature above, there is an interest in carrying out educational methodologies that stimulate the motivation and willingness from students to improve their competencies, without forgetting that the current state of education in Mexico lacks the necessary initiatives to undertake large projects involving educational development (Silva Rodríguez de San Miguel, 2019), especially education in STEM domains, which require a high degree of involvement with digital information technologies.

2.2. Research questions

To the best of our knowledge, there is currently no information regarding the motivational effects of using XR technologies among Mexican University-level students compared with traditional teaching methodologies. One key component in our study design is the implementation of two distinct XR approaches, namely VR and AR, which should shed information regarding the student experience when using applications that vary in terms of presentation and interactivity. Through this approach, we aim to assess the overall experience of using AR and VR approaches, including the type of interactive interface (touchscreen gestures in AR, using a peripheric with buttons and joysticks in VR), the way the educational environment is presented (digital overlay on the real world in AR, a fully virtual environment in VR), and the type of device and platform on which the application runs (AR on mobile devices, VR on desktop devices). The information will help to thoroughly evaluate the experience of using XR for learning proposals and how these are perceived by Mexican school students.

In this study we aimed to evaluate the use of AR and VR (both with similar instructional sequences, learning content and topics), compared to a conventional methodology for learning Physics content. The study was designed to randomly allocate students to either the experimental group (XR technologies) or the control group (conventional methodology), to adequately compare against the current standard for learning physics in this context and population. Physics was considered an ideal topic for the development of this study since it is one of the STEM subjects in which the capabilities of XR technologies can be demonstrated in depth. Physics is a subject which presents several abstract concepts, whose representation can be enhanced through XR in a spatial and temporal manner. In addition, XR makes it possible to carry out experimental physics activities interactively, simultaneously favoring different forms of information presentation (auditory, visual, kinesthetic). Last, this system can provide interactive 3D audiovisual didactic material, which can be exploited by the users through a simulation system for physical phenomena. Overall, this paper aims to answer the following questions by exploring the use of interactive XR technologies compared with traditional methods for learning:

RQ1. Are there any significant differences in learning performance between each group (AR group, VR group, and control group) for learning physics?

RQ2. Are there any significant differences between the motivational scores in each group (AR group, VR group, and control group) when learning physics?

RQ3. Is there a correlation between learning gains and motivational factors when using XR technologies for physics education?

RQ4. How do XR usage relate to motivational factors?

Through these research questions, we attempt to evaluate the differences of learning performance for each possible use case of XR technology by device capabilities (AR for mobile devices, VR for desktop and headsets peripherals), and compare them to the current methods used for learning in the context of Mexican schools. Given that education in Mexico has low capital and investment in technology for education, it is necessary to show the advantages and disadvantages when using such technological approaches, while detecting which aspects of an XR design model significantly impact the learning gains and motivation of students.

3. Learning application

PhysXR is a web-based learning application that provides interactive experiences in VR and AR environments. It uses a simulator for experiments of physical phenomena such as dynamics and kinematics. PhysXR shows students various topics related to physical phenomena through demonstrations and interactive exercises in XR.

The learning application was designed by following the guidelines of the official education program followed by Mexican schools to teach physics. This official program uses the CBE model, which defines key objectives, activities, and abilities that students must develop and perform. The topics presented in PhysXR apply “learn-by-doing” and problem-based learning (PBL) methodologies, which are divided into two sections. The first section is dedicated to kinematics topics (see Fig. 1) and includes: introduction to concepts such as of velocity, uniform rectilinear motion, uniformly varied rectilinear motion, and vertical free fall motion. The second section covers dynamics topics (see Fig. 2) and includes: introduction to the basic concepts of dynamics (force, mass, gravity, etc.) along with an induction to Newton’s three laws of motion (law of inertia, fundamental law of dynamics, and law of action and reaction).

When the students are finished with the demonstrations, the application presents visual interfaces that allow them to have control over the physics simulator, to complete a series of experimental exercises. Students must interact and configurate the properties of an object to find the correct answer to a question. The system tracks the elapsed time and number of errors that the student made before finding the correct answer.

3.1. Technical features of the system

PhysXR is a cross-platform web-based application, which uses the WebXR API to provide VR and AR experiences on the web in an adaptive way, depending on the capabilities of the device (see Table 1) and the used platform, Windows, Linux, MacOS, or Android.

When accessing the learning application from a device that does not support VR or AR capabilities, e.g., a desktop PC, PhysXR displays the interactive content in a 3D virtual environment where students can interact with the interfaces using the keyboard and mouse (see Fig. 3a). If a mobile device is used, the device’s gyroscopic sensors and cameras provide students with AR experiences (see Fig. 3b).

4. Experimental study

This study considered that the stimulation of motivation towards the use of digital tools for education is an important aspect during design and development, which is associated with several variables that affect learning and its effectiveness. Although there are different theories that attempt to explain the behavioral aspects of human motivation, only a few consider its implications in the learning process. One of the models oriented to this end is the John Keller’s (Keller, 1987) Attention, Relevance, Confidence, and Attention (ARCS) model. According to Keller, the ARCS model provides a solution of four variables that could be used as indicators in instructional design assessment (see Table 2), allowing to verify the characteristics and purpose of a learning tool: learning interest, learning design and method, learning behavior, and learning satisfaction. It also suggests that individual behavior depends on the expectations of success, and the achievements while doing a determined task. The ARCS model has been extensively used in computer-based learning environments as portrayed by the current literature in learning (Li & Keller, 2018).

To evaluate these variables when using the PhysXR application, a randomized study was conducted among undergraduate students enrolled in remote classes during the fall semester (October–November) 2021. The study setup included a pretest-posttest quantitative experimental design composed of two experimental conditions (AR, VR), and a control group. In each experimental condition, the students used PhysXR in interactive environments, through exercises and demonstrations using a PBL methodology. For each of the topics presented, students initially interacted with the application through demonstrations with the physics simulator, and then went on to answer an exercise section, where students were required to solve problems related to the presented topic.

The main distinctions between the experimental conditions lie in the device used and its capabilities for visualization and interaction with the digital elements shown in the experimental process. In order to minimize differences in the educational content, both AR and VR conditions presented similar instructional sequences, similar elements and similar topics compared to a conventional learning methodology as a control group, which was conducted through a conventional lecture and PBL methodology. In general, CBE is considered as a student-centered approach, designed to promote questions and participation during instructional exercises, which increases motivation with the interaction between students while the tutor acts as a facilitator. For the control group, the instructor explains the content during a remote class using slides, and then the students perform a set of graphical and textual exercises. This is for the purpose of testing whether the use of XR technologies has a significant impact on student motivation and learning gains, when compared to a more conventional teaching methodology with similar content and goals.

Fig. 1. Learning activities in kinematics included in PhysXR.

Fig. 2. Learning activities in dynamics included in PhysXR.

Table 1
Comparison between PhysXR modes.

	PhysXR Desktop mode	PhysXR Mobile mode
Compatible devices	Compatible with VR devices (headsets, controls) and conventional PC peripherals (keyboard and mouse)	Compatible with AR supported devices (needs a camera and gyroscope access)
Compatible platforms	Windows, Linux, Mac OS.	Android
Type of extended reality environment	Virtual interactive environment	Augmented interactive environment
Unique features	More immersive interactions over elements (such as grabbing, picking, throwing) via VR joysticks.	Real-time location and mapping to relate virtual elements and distance measurements over the real world.

4.1. Participants

This study recruited undergraduate participants enrolled in the Physics I course at the Instituto Tecnológico Culiacán in Sinaloa, Mexico. A total of 117 students met the inclusion criteria, however 18 participants were eliminated from the analysis since they did not complete the requirements and thus had missing data. The final sample consisted of 99 students, 87 male and 12 female, between the ages of 18–24 years. A device availability survey was applied during the screening period to distribute participants in each study group. Demographic characteristics were evenly distributed among the three study groups: those who participated from mobile devices (using the AR mode), from desktop personal computers (using VR mode), and the third group that used slides and documents (control group).

4.2. Measurement instruments

A pre-test and post-test were used to assess learning gains, and the Instructional Materials Motivation Survey (IMMS) & Course Interest Survey (CIS) instruments from Keller's ARCS evaluation model (Keller, 1995) to measure motivation. The PhysXR's log file was also used to obtain data from students while using the learning application. Details of each instrument are presented below.

4.2.1. Pre-test and post-test

Pre-test and post-test were designed to evaluate students' performance and retention on dynamics and kinematics topics. Both instruments were composed of 10 multiple-choice questions and were validated by physics teachers.

4.2.2. IMMS & CIS motivation surveys

Motivational surveys composed of questions according to the ARCS evaluative model of motivation towards the use of instructional material by Keller (Li & Keller, 2018) were applied using the IMMS and CIS instruments, which measure the motivational factors of attention, relevance, control, and satisfaction. The IMMS instrument is composed of 36 questions presented on a 5-point Likert scale of satisfaction. The CIS instrument contains 34 questions that measure the motivational factors of the ARCS model.

4.2.3. PhysX's log file

For all participants who interacted with the PhysXR educational application a log file composed of two main factors was created. The

Table 2
ARCS variables for instructional design.

Element	Variables	Purpose
A Attention	Learning interest	1. Analyze the impact of XR technology on learner interest. 2. Identify aspects that stimulate learning with XR technology. 3. Observe effects in student attention towards learning physics with XR technology.
R Relevance	Learning design and method	1. Analyze how students consider the use of XR technology as relevant for learning physics. 2. Identify if the learning content presented with XR technology is appropriate for learning.
C Confidence	Learning behavior	1. Analyze if the perceived ease of use impacts confidence when using XR technologies. 2. Observe the learners' confidence when learning physics with XR technologies.
S Satisfaction	Learning satisfaction	1. Assess the effects in the student's perceived satisfaction when using XR for learning physics.

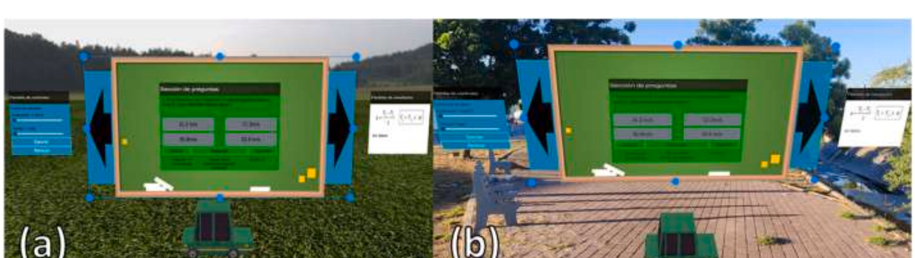

Fig. 3. Interactive interfaces presented in PhysXR: (a) Desktop VR mode (b) Mobile AR mode.

factors are: (1) the number of errors per topic, as well as the total sum of errors during their participation; (2) the time needed by the student to complete each topic and exercise and the total time using the learning application.

4.3. Procedure

All subjects included in the study participated through remote sessions via videoconferences and chat using online communication and collaboration platforms during physics classes. Fig. 4 shows the flow of the procedure executed during the three sessions.

In the Session 1, previous to the intervention, students were asked to complete a 20-min, 10-multiple-choice pre-test on kinematics and dynamics concepts to ascertain prior knowledge; students also responded a 10-min device availability survey to distribute participants in each experimental condition according to their personal electronic devices available. Both, the pre-test and the survey were conducted confidentially over the Internet.

One week following the initial preparation and assignment session, students undertook Session 2. In this session, students were divided based on the group (control or experimental). Students in the control group, attended a 10-min introductory lecture on the activities to be performed, while students allocated to the AR and VR groups received a 10-min introductory tutorial on how to use the PhysXR educational application on desktop and mobile devices. After the introduction, all groups continued with the 30-min intervention session. During the intervention process, students were presented with four topics related to kinematics and four topics on dynamics. In the AR and VR condition group, each topic offered a series of illustrative and interactive demonstrations implementing the physics simulator, to provide the student with an induction on the necessary concepts to perform a series of activities with questions at the end of each topic. Similarly, the didactic content was shown to the control group, but in the format of digital documents and slides.

One week after the intervention, session 3 was executed where each student answered the 20-mintue 10-mutilple-choice post-test evaluation to measure the retention and academic performance. Students in the AR and VR condition groups answered the IMMS motivational survey, while the CIS instrument was applied to those in the control group.

5. Data analysis and results

In the following section, we present the results of each of the research questions specified in this paper. These questions analyze the use of XR technologies and their impact on improving learning and student motivation through ARCS factors. In order to do so, we undertake a series of analysis of variance (ANOVA) for the differences among means, which provide a statistical inference of any difference between the means (or average) obtained in the AR, VR and control groups, and correlational tests to measure dependence between sets of data related to the effects of motivation on students. More details of each analysis method and results obtained are presented below.

5.1. Testing of assumptions of normality, homogeneity, and reliability

In order to carry out the analysis of the results obtained in this study, a Shapiro-Wilk test was performed to confirm the assumption of normality from the data obtained in the pretest in the AR, VR, and control groups. The results obtained in the AR group ($N = 33$, $w = 0.203$, $M = 6.575$, $SD = 2.136$), VR group ($N = 33$, $w = 0.091$, $M = 6.393$, $SD = 2.121$) and control group ($N = 33$, $w = 0.124$, $M = 6.212$, $SD = 2.642$) suggest that students' knowledge prior to the intervention could be described as a regularly distributed population. Thus, confirming the use of parametric tests for the procedure of this analysis. To assess homogeneity, the results of a Levene's test statistic $F\ (1{,}99) = 1.063$, p-value= < 0.350) are shown as non-significant, indicating that the assumption of homogeneity of variance is met. Further analysis over the pretest data with a one-way ANOVA ($F\ (1{,}99) = 0.204$, p-value= < 0.816) indicate no significative differences between groups, meaning that students had similar knowledge before the intervention with the PhysXR learning application. Also, to assess reliability and consistency for the results obtained for the IMMS and CIS instruments used to measure motivation, a Cronbach Alfa coefficient was calculated for each variable specified in the ARCS model, which should be greater than $\alpha > 0.6$ to indicate an acceptable level of reliability of the results that comprise the measured motivation in students. Table 3 shows a comparison of the obtained Cronbach Alpha values for the AR, VR, and control group, indicating satisfactory levels of reliability.

5.2. RQ1: Are there any significant differences in learning performance between each group (AR group, VR group, and control group) for learning physics?

A mixed design ANOVA analysis was performed to compare the conditions and observe changes in learning gains. In this case, the

Table 3
Cronbach's alpha results for each ARCS variable.

Variable	CIS Cronbach alpha (Control)	IMMS Cronbach alpha (AR)	IMMS Cronbach alpha (VR)
Attention	0.734	0.790	0.866
Relevance	0.767	0.813	0.816
Confidence	0.352	0.664	0.637
Satisfaction	0.739	0.744	0.892
Overall	0.863	0.923	0.932

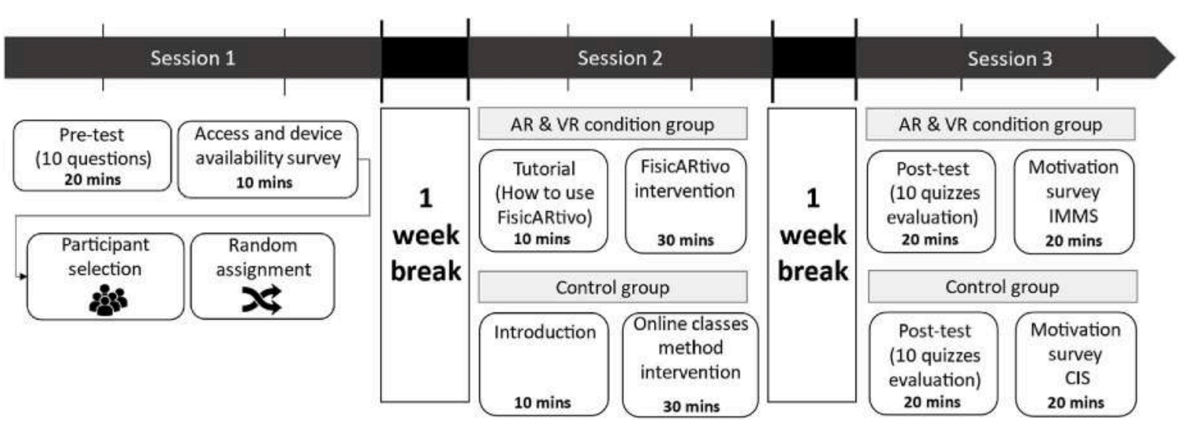

Fig. 4. Study procedure flow chart.

interaction of 2 factors is presented: assessment time (pre-test and post-test) and the type of experimental condition (AR, VR, and control group). This analysis method allows to compare the mean differences between the experimental groups and understand the effects between these two factors on the dependent variable (learning gains), considering that this study have measured learning rate in two separated time points and the subjects have been assigned in three groups.

The results of this analysis (see Table 4) reveal a significantly and independently difference between the pre-test and pos-test results (F (1,99) = 18.869, p-value= < 0.000, $\eta^2 = 0.164$), which is the expected when comparing the averages obtained during the pre-test and post-test in each of the conditions (Fig. 5).

Analyzing the interaction of assessment time between experimental groups reveal a statistical significance difference (F (1,99) = 3.973, p-value = 0.022, $\eta^2 = 0.076$). These results suggest that a statistically significant and independent difference between learning gains between AR, VR, and control group was present, indicating that the students using AR had the best outcomes, followed by the group using VR (Fig. 5).

5.3. *RQ2: Are there any significant differences between the motivational scores in each group (AR group, VR group, and control group) when learning physics?*

A one-way ANOVA analysis was conducted to compare the results of the ARCS factors (Attention, Relevance, Confidence, and Satisfaction) between conditions among study groups, in order to determine any statistically significant differences between the means of each experimental and control group. Except for the attention factor, the results in Table 5 show that the difference between the three conditions (AR, VR, and control group) was statistically significant at an alpha of 0.05. Also, in order to individually identify which of these three conditions show statistically significant difference in each of the ARCS factors of motivation, a post-hoc test was performed with Tukey's HSD (Honestly-Significant-Difference) method (see Table 6) performing multiple comparisons between conditions. Considering that the assumption of homogeneity of variance has been met, the Tukey HSD test allows to perform pairwise comparisons between groups to find more individual details about the dependent variables, setting a studentized rank distribution that stablishes a threshold. Differences above this threshold are considered significant differences. Those below are considered non-significant differences.

According to the ANOVA results, no statistically significant differences were found between the three conditions in the **attention factor**, showing p-values >0.05. The means values for attention were 3.345 ± 0.316 in the AR condition, 3.338 ± 0.485 for VR and 3.383 ± 0.538 for the control group. It is worth mentioning that the AR and VR conditions were designed to teach the same educational content in PhysXR but with certain differences in presentation and interaction interfaces; the control group condition presented the same PhysXR content, but using a presentation-based method shown online, so this result suggests that the impact towards the attention factor could be given by the educational content itself.

Table 4
Learning gains comparisons by condition.

Group	Time	Mean	SD	Confidence interval at 95% Min	Max
AR	PRE-TEST	6.576	.403	5.777	7.375
	POST-TEST	7.939	.376	7.193	8.686
VR	PRE-TEST	6.394	.403	5.595	7.193
	POST-TEST	7.273	.376	6.526	8.019
Control	PRE-TEST	6.212	.403	5.413	7.011
	POST-TEST	6.333	.376	5.587	7.080

Effect	SS	df	MS	*F* value	*p*-value	η^2
time	30.727	1	30.727	18.869	<0.000	.164
time * group	12.939	2	6.470	3.973	0.022	.076

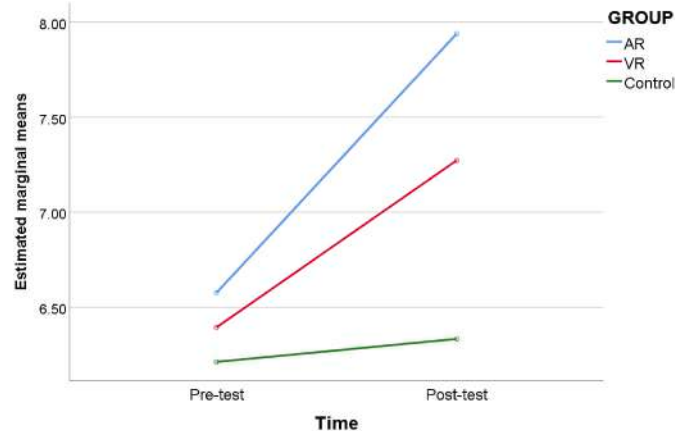

Fig. 5. Pre-test & Post-test means comparisons by condition.

Table 5
ARCS factors comparisons between conditions.

Dependent variable		SS	df	MS	*F* value	Sig.
ATTENTION	Between groups	.037	2	.019	.089	.915
	Within groups	19.991	96	.208		
	Total	20.028	98			
RELEVANCE	Between groups	9.827	2	4.913	**18.686**	**.000**
	Within groups	25.243	96	.263		
	Total	35.070	98			
CONFIDENCE	Between groups	2.785	2	1.392	**7.836**	**.001**
	Within groups	17.058	96	.178		
	Total	19.842	98			
SATISFACTION	Between groups	12.088	2	6.044	**19.238**	**.000**
	Within groups	30.160	96	.314		
	Total	42.247	98			

The measurements showed a statistically significant difference in the **relevance factor** (F (1,33) = 18.686, p-value <0.01). The means values for relevance were 4.214 ± 0.486 in the AR condition, 3.879 ± 0.524 for VR and 3.444 ± 0.528 for the control group. In the *post hoc* Tukey HSD tests, statistically significant differences were found in the three groups of this study (p-values <0.05), indicating that each type of experimental condition (AR and VR) had a positive impact in the perceived relevance of students during this study intervention.

A statistically significant difference between experimental condition was also identified in the **confidence factor** (F (1,33) = 7.836, p-value = 0.01) between conditions. The median values for confidence were 3.650 ± 0.421 in the AR condition, 3.301 ± 0.361 for VR and 3.288 ± 0.475 for the control group. The *post hoc* Tukey HSD tests showed statistically significant differences between the AR condition when compared to the VR and control group (p-values <0.01). However, no statistically significant difference was found between the VR condition and the control group, (p-value >0.05). These results could indicate that there is a correlation between these two conditions. Such correlation may be associated to the use of desktop computers to undertake the experimental activities by both the VR and control group, a device familiar to the students.

5.4. *RQ3: Is there a correlation between learning gains and motivational factors when using XR technologies for physics education?*

To analyze the effect of each motivation factor on the learning gain of students, a Pearson correlation was applied to obtain correlation coefficients between the ARCS motivational components and the normalized learning gains (Posttest- Pretest)/(100% - Pretest) between each of the conditions. The results presented in Table 7 show that no statistically

Table 6
HSD Tukey post-hoc comparison analysis.

Dependent variable	Group (I)	Group (J)	Average difference (I-J)	SD	Sig.	95% confidence interval	
						Min	Max
ATTENTION	Control	AR	0.037	0.112	0.942	−0.230	0.305
		VR	0.044	0.112	0.918	−0.223	0.312
	AR	Control	−0.037	0.112	0.942	−0.305	0.230
		VR	0.007	0.112	0.998	−0.260	0.274
	VR	Control	−0.044	0.112	0.918	−0.312	0.223
		AR	−0.007	0.112	0.998	−0.274	0.260
RELEVANCE	Control	AR	−.770*	0.126	0.000	−1.070	−0.469
		VR	−.434*	0.126	0.002	−0.735	−0.134
	AR	Control	.770*	0.126	0.000	0.469	1.070
		VR	.335*	0.126	0.025	0.035	0.636
	VR	Control	.434*	0.126	0.002	0.134	0.735
		AR	−.335*	0.126	0.025	−0.636	−0.035
CONFIDENCE	Control	AR	−.362*	0.104	0.002	−0.609	−0.115
		VR	−0.013	0.104	0.992	−0.260	0.234
	AR	Control	.362*	0.104	0.002	0.115	0.609
		VR	.349*	0.104	0.003	0.102	0.596
	VR	Control	0.013	0.104	0.992	−0.234	0.260
		AR	−.349*	0.104	0.003	−0.596	−0.102
SATISFACTION	Control	AR	−.833*	0.138	0.000	−1.162	−0.505
		VR	−.586*	0.138	0.000	−0.914	−0.257
	AR	Control	.833*	0.138	0.000	0.505	1.162
		VR	0.247	0.138	0.177	−0.081	0.576
	VR	Control	.586*	0.138	0.000	0.257	0.914
		AR	−0.247	0.138	0.177	−0.576	0.081

*. The mean difference is significant at the 0.05 level.

The **satisfaction factor** presented a statistically significant difference between conditions ($F(1,33) = 19.238$, p-value <0.01). The median and deviation ratio for satisfaction were 4.328 ± 0.557 in the AR condition, 4.081 ± 0.627 for VR and 3.495 ± 0.490 for the control group. The *post hoc* Tukey HSD tests showed a statistically significant difference between the control group when compared with AR and VR conditions (p-values <0.01). There was no statistically significant difference in the satisfaction factor when comparing the AR to VR groups (p-value >0.05), this may be related to the fact that the AR and VR conditions were conducted under the same educational tool, PhysXR, and both groups shared similar interactive activities, with the difference being the use of AR or the application of interactive VR environments.

significant correlations were identified between learning gains and ARCS motivational factors in the control group.

In the AR condition (see Table 8) a statistically significant correlation was observed between the learning gains and the attention factor ($r = 0.408$, $n = 33$, $p = 0.018$). There is also a statistically significant correlation with the confidence factor ($r = 0.417$, $n = 33$, $p = 0.016$) indicating that students who had higher levels of attention and confidence obtained greater learning gains compared with students who presented lower levels of attention and confidence.

A significant correlation was identified between learning gain and confidence in the results of the VR condition ($r = -0.480$, $n = 33$, $p = 0.005$) presented in Table 9. In this case, an inverse Pearson correlation is observed, indicating that students who presented a high level of confidence lowered their learning gain levels.

5.5. RQ4: How do XR usage relate to motivational factors?

The following are the results of an independent sample *t*-test between the 2 experimental conditions of AR and VR, where the differences in usage time and errors between conditions are analyzed.

Table 10 shows a no statistically significant difference in the usage time factor between the two conditions ($t = -1.693$, $p = 0.095$). On the other hand, the error factor shows a statistically significant difference between conditions ($t = -2.097$, $p = 0.040$). Thereafter, a Pearson correlation analysis was performed to find out the possible correlations of the factors of use in PhysXR between the ARCS motivation factors.

According to Table 11, no statistically significant correlations were found between time and motivation among students who participated in the AR condition. The error factor, on the other hand, showed significant inverse correlations between attention ($r = -0.395$, $n = 33$, $p = 0.023$). and confidence ($r = -0.752$, $n = 33$, $p < 0.01$). This indicates that the higher students' confidence and attention, the lower the number of errors when performing activities in PhysXR. On the other hand, when applying the same Pearson correlation analysis in the VR condition, no statistically significant correlations were found (see Table 12).

Table 7
Control group condition - correlations between learning gains and ARCS factors.

Measure	Motivation Factor	r	df	p-value
Learning gains	Attention	−0.141	33	0.434
	Relevance	−0.122	33	0.500
	Confidence	−0.007	33	0.968
	Satisfaction	−0.167	33	0.353

Table 8
AR condition - correlations between learning gains and ARCS factors.

Measure	Motivation Factor	r	df	p-value
Learning gains	Attention	0.408[a]	33	0.018
	Relevance	0.190	33	0.289
	Confidence	0.417[a]	33	0.016
	Satisfaction	0.246	33	0.168

[a] The correlation is significant at level 0.05 (bilateral).

Table 9
VR condition - correlations between learning gains and ARCS factors.

Measure	Motivation Factor	r	df	p-value
Learning gains	Attention	−0.142	33	0.430
	Relevance	−0.222	33	0.214
	Confidence	−0.480[a]	33	0.005
	Satisfaction	0.002	33	0.989

[a] The correlation is significant at level 0.01 (bilateral).

Table 10
AR and VR conditions - comparisons between PhysXR use factors.

Measure	Group	Mean	Average difference	SD	t	Sig. (bilateral)
Time	AR	0:19:30	−0:03:36	0:05:35	−1.69	0.095
	VR	0:23:06		0:10:54		
Errors	AR	11.63	−3.61	6.47	−2.09	0.040*
	VR	15.24		7.45		

Table 11
AR condition - correlations between use and ARCS factors.

Measure	Motivation Factor	r	df	p-value
Time	Attention	−0.057	33	0.754
	Relevance	0.137	33	0.447
	Confidence	0.111	33	0.539
	Satisfaction	0.075	33	0.676
Errors	Attention	−0.395*	33	0.023
	Relevance	−0.229	33	0.200
	Confidence	−0.752**	33	0.000
	Satisfaction	−0.279	33	0.115

*. The correlation is significant at level 0.05 (bilateral).

**. The correlation is significant at level 0.01 (bilateral).

6. Discussion

For this study, we designed a learning application, PhysXR, with XR capabilities, which was used for teaching Newtonian mechanics. Through the versatility of AR and VR presentation capabilities, PhysXR can exploit benefits of both approaches. First, the use of an AR approach allows this application to show the simulation of physical phenomena with superposed virtual elements in the real world. While in VR, it represents the learning content over a virtual, immersive learning environment. By using our experimental design, its AR capabilities were compared with its VR equivalent and a control group, using the ARCS theoretical model along with a quantitative, statistical analysis to assess learning gains and impact in motivation. To ensure a fair comparison between experimental conditions, all conditions shared similar learning contents, teachers, and number of students with a similar academic performance.

6.1. Reflections on findings by research question

Regarding our first research question (RQ1**: Are there any significant differences in learning performance between each group (AR group, VR group, and control group) for learning physics?**), the results indicate that students that used the AR capabilities of PhysXR presented the highest statistically significant increase on learning gains. The AR and VR experimental conditions showed more learning gains in comparison with the control group. This result is attributed to the influence of XR technologies as a medium to tech and learn material related to Newtonian Mechanics. Several works in the past (Cai et al., 2013; Parong & Mayer, 2018; Pirker et al., 2017; Tsichouridis et al., 2020) presented similar results in their interventions, thus, proving that students can learn physics topics using XR technologies.

Concerning the second research question (RQ2**: Are there any significant differences between the motivational scores in each group (AR group, VR group, and control group) when learning physics?**), the results show that the AR condition had a positive impact in the perceived relevance, confidence, and overall satisfaction of students in comparison to VR and the control group. While the interest levels presented in the three conditions were similar, these similarities could be caused by the learning content itself, which was the same in the three conditions. As these results indicate, the possibilities of implementing XR in other physics subjects need to be further explored, as the learning content could pose the need to use different forms of material and concept representation, especially when considering factors like interactivity and 3D data visualization that could affect student' perception such as motivation when using XR for learning. Previous research studies have focused on different instances of XR technology for learning: from AR books presenting augmented figures, to indoors virtual learning laboratories using VR and even outdoors approaches that use AR with geolocation to show virtual elements that are correlated to wide spaces in the real world as part of the learning setting (Pacheco et al., 2014; Pirker et al., 2018). It is important to mention that PhysXR, designed as a web-based XR learning tool, presents its learning material in a variety of scenarios, considering the characteristics of the platform or device on which its used, with each one providing different features and capabilities.

The results for the third research question (RQ3**: Is there a correlation between learning gains and motivational factors when using XR technologies for physics education?**) indicate several correlations between the learning gains and the ARCS factors of motivation when using XR technologies. Participants allocated to the AR condition had a statistically significant correlation in attention and confidence and their learning gains, showcasing that students with a high level of motivation, driven by attention and confidence, had a positive impact in their performance. This evidence strongly suggests that the approaches using AR positively impact motivation for learning physics. However, in our results we found that in the VR condition the confidence factor had an inverse correlation to learning gains. This result could be explained by the participation of some students with overconfidence in performing the activities in the VR condition, and consequently impacting negatively on their learning gains. There is also the possibility that students reduced their seriousness when performing the experimental activities, since most of the participants in the VR condition didn't have access to a peripherical such as a VR headset to fully benefit from the immersive features this approach offers; instead, they participated by viewing a virtual environment from their monitor while using a conventional keyboard and mouse as a means of interaction. Further analysis is needed to obtain more precise conclusions on this topic.

For answering our fourth research question (RQ4**: How do XR usage relate to motivational factors?**), we analyzed the use factors (time & errors) and their possible correlation to motivation. In the AR condition, the results show that the errors factor had a negative statistical correlation to attention and confidence, indicating that students with high levels of attention and confidence showed a statistically significant decrease in their errors. On the VR condition no statistically significant correlations were found; while these results suggest that students that used AR had an impact in their motivation and therefore performed better and made fewer mistakes, this raises the need for further analysis

Table 12
VR condition - correlations between use and ARCS factors.

Measure	Motivation Factor	r	df	p-value
Time	Attention	−0.088	33	0.754
	Relevance	0.002	33	0.447
	Confidence	0.149	33	0.539
	Satisfaction	−0.004	33	0.676
Errors	Attention	0.056	33	0.758
	Relevance	0.025	33	0.891
	Confidence	0.159	33	0.376
	Satisfaction	0.227	33	0.203

to identify other factors related to student perceptions, as well as the students emotional state while using XR learning applications such as PhysXR, which could also be associated with diverse usage outcomes.

By obtaining positive results in each hypothesis regarding learning and motivation through the use of AR, this study confirms that our approaches improve students' understanding of Newtonian mechanics topics while enhancing motivation, confidence, and learning satisfaction to ultimately increase their learning gains and performance. These results are consistent with theories such as experientialism (Kolb & Kolb, 2022) and the principles of "learning by doing" (Anzai & Simon, 1979) which describe that learning comes from direct experience, as opposed to methodologies that focus on learning only by reading or listening to instructions or lectures. An experiential methodology implies that the learner acquires knowledge and skills directly through active action, which involves sensory or kinesthetic contact with the learning environment. In an XR experience, the learner can surround him or herself with a variety of conditions that can set up appropriate scenarios for the exploration of a topic. Further, there are several motivation theories that consider the intrinsic and extrinsic factors that drive an individual to reach a goal or to fulfill an expectation in learning activities. Such theories state that an optimum level of arousal in emotions and cognitive state are prominent to enhance academic performance and motivation. In this study we present an XR environment that applied the ARCS model to assess motivation. According to Keller (1987), students can be motivated directly by grabbing their attention through a stimulating and attractive medium or didactic material, being important to sustaining their curiosity in the learning process, and results from our study indicate that XR might serve as this stimulating material.

6.2. Theoretical and practical implications

The presented research aims to create XR experiences focused on developing physics learning by offering interactive learning content and real-time physics simulations, while being accessible with a wide variety of devices and platforms via web-based services for multiplatform compatibility.

We proposed a strong emphasis in AR for mobile devices using web-based technologies, where the user can interact with virtual elements in the real world regardless of the platform, being able to experiment with physics phenomena and the physical properties of objects, while also using easy and intuitive GUI elements to navigate through the learning content. Moreover, we presented an approach for the implementation of virtual environments in desktop devices, as these lack the portability and hardware standardization to execute AR content in comparison to their mobile counterpart. In this case scenario, we proposed to use VR-oriented peripherals but also, the use of more conventional human-machine interfaces, such as the keyboard and mouse to navigate web-based virtual learning environments.

Regarding the implementation of XR technology for physics learning in the context of Mexican school system, results show that students prefer to use the PhysXR AR mode, which could be due to the accessibility and familiarity of interacting with smartphone applications thanks to the touchpad and gyroscope controls. Students were more motivated to use a XR learning application from a smartphone device, preferring an easy and portable way to use and learn content, which is different from using a headset (VR headset) or a desktop device (PC). This shows that familiarity, mobility, portability, and comfort offered by XR were the most influential factors in motivating Mexican students in learning. It is important to state that the limited availability and accessibility of specialized VR devices, especially due to their cost, hinders their adoption compared with tools that boast AR design philosophies.

Based on the data presented, we would suggest that initial experiences of Mexican students with XR technologies should be based on AR concepts. The immersive application achieved through AR can serve as a starting point so that students gradually adapt to the use of digital technologies for education, which may initially be perceived as complex. This approach would allow students to become familiar with the usefulness and benefits that more immersive XR experiences, such as VR-based implementations, can offer. Additionally, we suggest that immersive applications should be offered through the web and be compatible with mobile devices, in order to increase the uptake of these technologies in Mexico. We consider that distribution of educational material through online platforms can lay the foundations for the embracement of these technologies in current academic curricula, especially considering that most of the educational programs in academic institutes in Mexico follow a competency-based educational model. It's important to note that CBE is related to the development of various STEM education skills that require students to know and be competent in the use of digital information and communication tools, as well as the use of Internet technologies, which have become necessary in the current job market.

This study shows that Mexican students are willing to use XR tools for educational and training purposes; however, we face the challenge of spreading this interest in a progressive and general way in the educational curriculum of Mexican schools. For these tools to successfully become part of the education landscape in Mexico, these should favor accessibility, ease of use, as well as offer interactive experiences that do not have a high degree of impact on the cognitive load of students. Our study showcases the benefits of interactive digital environments accessible via the internet, highlighting their accessibility through any mobile or desktop device, which can overcome some of the key limitations for the acceptance and implementation of XR in Mexican schools. Given the current situation in Mexico, education through digital tools and platforms must overcome several misconceptions in order to be properly incorporated into the current educational curriculum. This is especially relevant when it comes to subjects that have been traditionally taught through methodologies that rarely use digital approaches, either because these have been considered unnecessary by teachers or because these are perceived as very complex to implement. Therefore, further research is needed to show the advantages of these technologies in the current context of education in Mexico and to know the perceptions of teachers and academic institutions towards the adaptation of these technologies in today's curricula.

6.3. Limitations and future work

To the best of our knowledge, this study is the first to present a web-based learning application that implements XR technology such as AR and VR towards physics learning activities using real-time physics simulation. Furthermore, this is the first to report the effects of web-based XR learning applications on students' motivation and learning, through the comparison of AR and VR case scenarios; where each offers a different visual presentation of the learning content, as well as different forms of interactivity depending on the platform or hardware used.

However, there are some limitations that must be appraised when considering our approaches in Newtonian mechanics education. The first limitation is that the access to internet connection is necessary due the fact that PhysXR is a web-based learning tool. Devices with missing sensors or lacking compatibility due to obsolescence are also some limitations to take into consideration. Another limitation is that PhysXR covers limited topics of dynamic and kinematics. It is important to provide teachers with the technical knowledge to author and develop new learning content for Newtonian mechanics, as making the adaptation of these physics' concepts to use digital media technologies requires substantial time to master. Another limitation in this study stems from the lack of access to VR headsets since students did not have these at home. This implies that the VR condition group experienced PhysXR learning content in a virtual environment from a conventional display, thus, diminishing the immersive factor that VR offers when using VR headsets.

The novelty effect should also be considered among the limitations of this study, and results must be appraised in view of this factor which is associated with attitudes towards learning. In this sense, exposure to these new technologies in the education context might also be related to motivation, therefore it is important to perform future studies among students who have been previously exposed to XR interventions in order to control for the novelty effect and determine whether the intervention and its content are associated with improvements in cognitive gains and attitude towards learning, rather than just the novelty of the tool.

There are several interesting perspectives to explore in future work in this field. This includes providing the necessary tools for teachers to author XR learning content related to physics topics, as well as undertake studies to identify the characteristics needed in XR development to provide motivation in other physics-related topics. This includes further investigation of student's perceptions and their emotional state when learning. Similarly, more in-depth research is also needed regarding perceived immersion toward XR, especially when using VR headsets or other immersive XR devices to obtain more detailed data on students' immersion when using these technologies for learning.

6.4. Conclusions

This work analyzed the impact of XR technologies in education, with a focus on Newtonian mechanics. A learning application called PhysXR has been developed as an alternative method to help to understand physical phenomena and its mathematical abstractions in an interactive environment with real-time physics simulation, including several multimedia contents for learning and 3D model demonstrations. This study carried out the use of statistical significance tests and correlations analysis, and it comprehensively validated the positive impact of the XR implementations presented in PhysXR within the Mexican educational context.

According to the results obtained in this study, the use of these technologies has a statistically significant positive impact in motivation while improving students' learning gains. With PhysXR, students can develop their self-learning skills and improve their understanding of the mathematical abstractions used in Newtonian mechanics topics such as kinematics and dynamics. These results are aligned with the findings of other studies which evaluate XR technologies such as AR and VR for educative and motivational purposes (Alkhabra et al., 2023; Johnson--Glenberg et al., 2021; Lee et al., 2022; Midak et al., 2021; Mystakidis & Christopoulos, 2022; Smith et al., 2023).

Contributions derived from this study include evidence that XR learning tools are suitable for teaching Newtonian mechanics, and the finding that XR implementations that can be used on mobile devices and provide features such as accessibility, portability, and ease of use are most preferred by Mexican students. The development of PhysXR as a web-based application allows executing its functions as a multiplatform learning application, being able to display AR content on mobile devices and VR content in desktop computers, providing students with real-time physics simulations in interactive environments with different levels of immersion. In comparison to more conventional methods of teaching physics phenomena (Dünser et al., 2012), the use of XR technologies enhances the representation and visualization with more dynamic and interactive approaches, enriching students' self-taught experiences.

Statement on open data and ethics

This study received ethics approval from the Tecnologico Nacional De México – Campus Culiacán. Informed consent was obtained from all participants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work described in this paper is fully supported by TecNM grant number 13883.22-P and 16917.23-P in Mexico.

7. Acronyms

ANOVA Analysis of variance
API Application Programming Interface
AR Augmented Reality
ARCS model Attention, Relevance, Confidence, and satisfaction model
CBE Competency Based Education
CIS Course Interest Survey
GUI Graphical User Interface
IMMS Instructional Materials Motivation Survey
OECD Organization for Economic Co-operation and Development
PBL Problem Based Learning
PISA Programme of International Student Assessment
SD Standard deviation
SEP Secretaria de Educación Pública
SS Sum of squares
STEM Science, Technology, engineering, and Mathematics
Tukey HSD Tukey's honest significance test
VR Virtual Reality
XR Extended Reality

References

Aguilera-Hermida, A. P., Quiroga-Garza, A., Gómez-Mendoza, S., Del Río Villanueva, C. A., Avolio Alecchi, B., & Avci, D. (2021). Comparison of students' use and acceptance of emergency online learning due to COVID-19 in the USA, Mexico, Peru, and Turkey. *Education and Information Technologies, 26*(6), 6823–6845. https://doi.org/10.1007/s10639-021-10473-8

Ahmad, N. I. N., & Junaini, S. N. (2020). Augmented reality for learning mathematics: A systematic literature review. *International Journal of Emerging Technologies in Learning, 15*(16), 106–122. https://doi.org/10.3991/ijet.v15i16.14961

Alkhabra, Y. A., Ibrahem, U. M., & Alkhabra, S. A. (2023). Augmented reality technology in enhancing learning retention and critical thinking according to STEAM program. *Humanities and Social Sciences Communications, 10*(1), 1–10. https://doi.org/10.1057/s41599-023-01650-w

Alnagrat, A. J. A., Ismail, R. C., & Idrus, S. Z. S. (2021). Extended reality (XR) in virtual laboratories: A review of challenges and future training directions. *Journal of Physics: Conference Series, 1874*(1). https://doi.org/10.1088/1742-6596/1874/1/012031

Antón-Sancho, Á., Vergara, D., Lamas-álvarez, V. E., & Fernández-Arias, P. (2021). Digital content creation tools: American university teachers' perception. *Applied Sciences, 11*(24). https://doi.org/10.3390/app112411649

Anzai, Y., & Simon, H. A. (1979). The theory of learning by doing. *Psychological Review, 86*(2), 124–140. https://doi.org/10.1037/0033-295X.86.2.124

Cai, S., Chiang, F. K., & Wang, X. (2013). Using the augmented reality 3D technique for a convex imaging experiment in a physics course. *International Journal of Engineering Education, 29*(4), 856–865.

Chomphuphra, P., Chaipidech, P., & Yuenyong, C. (2019). Trends and research issues of STEM education: A review of academic publications from 2007 to 2017. *Journal of Physics: Conference Series, 1340*(1), Article 12069.

Di Serio, Á., Ibáñez, M. B., & Kloos, C. D. (2013). Impact of an augmented reality system on students' motivation for a visual art course. *Computers in Education, 68*, 586–596. https://doi.org/10.1016/j.compedu.2012.03.002

Dragoo, A., & Barrows, R. (2016). Implementing competency-based education: Challenges, strategies, and a decision-making framework. *The Journal of Continuing Higher Education, 64*(2), 73–83.

Dünser, A., Walker, L., Horner, H., & Bentall, D. (2012). Creating interactive physics education books with augmented reality. In *Proceedings of the 24th Australian computer-human interaction conference* (pp. 107–114). https://doi.org/10.1145/2414536.2414554. OzCHI 2012.

Fidan, M., & Tuncel, M. (2019). Integrating augmented reality into problem based learning: The effects on learning achievement and attitude in physics education. *Computers in Education, 142*, Article 103635. https://doi.org/10.1016/j.compedu.2019.103635

González Calleros, C. B., Guerrero García, J., Navarro Rangel, Y., González Calleros, J. M., & Collazos Ordoñez, C. A. (2022). Digital competencies of higher education institutions in Mexico: A systematic literature review. In Ł. Tomczyk, & L. Fedeli (Eds.), *Lecture notes in educational technology* (pp. 313–343). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-1738-7_17.

Harris, K., & Reid, D. (2005). The influence of virtual reality play on children'S motivation. *Canadian Journal of Occupational Therapy, 72*(1), 21–29. https://doi.org/10.1177/000841740507200107

Hussein, M., & Nätterdal, C. (2015). *The benefits of virtual reality in education: A comparison study*. University of Gothenburg, Chalmers University of Technology. June, 15 https://gupea.ub.gu.se/bitstream/2077/39977/1/gupea_2077_39977_1.pdf.

Ibáñez, M. B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers in Education, 123*, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Ibáñez, M. B., Uriarte Portillo, A., Zatarain Cabada, R., & Barrón, M. L. (2020). Impact of augmented reality technology on academic achievement and motivation of students from public and private Mexican schools. A case study in a middle-school geometry course. *Computers in Education, 145*, Article 103734. https://doi.org/10.1016/j.compedu.2019.103734

Johnson-Glenberg, M. C., Bartolomea, H., & Kalina, E. (2021). Platform is not destiny: Embodied learning effects comparing 2D desktop to 3D virtual reality STEM experiences. *Journal of Computer Assisted Learning, 37*(5), 1263–1284. https://doi.org/10.1111/jcal.12567

Kavanagh, S., Luxton-Reilly, A., Wuensche, B., & Plimmer, B. (2017). A systematic review of virtual reality in education. *Themes in Science and Technology Education, 10*(2), 85–119.

Keller, J. M. (1987). Development and use of the ARCS model of instructional design. *Journal of Instructional Development, 10*(3), 2–10. https://doi.org/10.1007/BF02905780

Keller, J. M. (1995). Motivation in cyber learning environments. *International Journal of Educational Telecommunications, 1*(1), 7–30.

Kolb, A. Y., & Kolb, D. A. (2022). Experiential learning theory as a guide for experiential educators in higher education. *Experiential Learning and Teaching in Higher Education, 1*(1), 38. https://doi.org/10.46787/elthe.v1i1.3362

Lai, J. W., & Cheong, K. H. (2022a). Adoption of virtual and augmented reality for mathematics education: A scoping review. *IEEE Access, 10*, 13693–13703. https://doi.org/10.1109/ACCESS.2022.3145991

Lai, J. W., & Cheong, K. H. (2022b). Educational opportunities and challenges in augmented reality: Featuring implementations in physics education. *IEEE Access, 10*, 43143–43158. https://doi.org/10.1109/ACCESS.2022.3166478

Lee, T., Wen, Y., Chan, M. Y., Azam, A. B., Looi, C. K., Taib, S., Ooi, C. H., Huang, L. H., Xie, Y., & Cai, Y. (2022). Investigation of virtual & augmented reality classroom learning environments in university STEM education. *Interactive Learning Environments*, 1–41. https://doi.org/10.1080/10494820.2022.2155838. February 2024.

Levano, L., Sanchez, S., Guillén, P., Tello, S., Herrera, N., & Collantes, Z. (2019). Digital competences and education. *Propositos y Representaciones, 7*(2), 569–588. https://bit.ly/3jDkaQ0.

Li, K., & Keller, J. M. (2018). Use of the ARCS model in education: A literature review. *Computers in Education, 122*, 54–62. https://doi.org/10.1016/j.compedu.2018.03.019

Lopez-Garcia, T. J., Alvarez-Cedillo, J. A., Sanchez, T. A., & Vicario-Solorzano, C. M. (2019). Review of trends in the educational model of distance education in Mexico, towards an education 4.0. *Computer Reviews Journal, 3*, 111–121.

López-Hernández, J. G., Valdes- Hernández, R. C., Lopez-Rodríguez, R., Quiroz-Sánchez, J. C., Ramírez-Franco, O., Hernández-Ramos, D., & Lopez-Badilla, G. (2022). The augmented reality technology. An experimental application in the educational and industrial sector of baja California, Mexico. *Studies in Systems, Decision and Control, 435*, 183–232. https://doi.org/10.1007/978-3-031-00856-6_10. Springer.

Luo, H., Li, G., Feng, Q., Yang, Y., & Zuo, M. (2021). Virtual reality in K-12 and higher education: A systematic review of the literature from 2000 to 2019. *Journal of Computer Assisted Learning, 37*(3), 887–901. https://doi.org/10.1111/jcal.12538

Mazzuco, A., Krassmann, A. L., Reategui, E., & Gomes, R. S. (2022). A systematic review of augmented reality in chemistry education. *The Review of Education, 10*(1), e3325. https://doi.org/10.1002/rev3.3325

Midak, L. Y., Kravets, I. V., Kuzyshyn, O. V., Baziuk, L. V., Buzhdyhan, K. V., & Pahomov, J. D. (2021). Augmented reality as a part of STEM lessons. *Journal of Physics: Conference Series, 1946*(1). https://doi.org/10.1088/1742-6596/1946/1/012009

Mystakidis, S., & Christopoulos, A. (2022). Teacher perceptions on virtual reality escape rooms for STEM education. *Information, 13*(3), 1–13. https://doi.org/10.3390/info13030136

Olivas Castellanos, E. C., De Gunther, L., Vazquez Paz, F. M., Lerma Ramos, M. T., & Rivera Garrido, O. D. (2022). The Sciences through Pixels: Virtual Reality as an innovation in the learning outcome in higher education in northwestern Mexico: Virtual Reality as an innovation in the learning outcome in higher education in northwestern Mexico. In *Proceedings of the 2022 6th international conference on education and E-learning* (pp. 275–280).

O'sullivan, N., & Burce, A. (2014). *Teaching and learning in competency-based education*. The Fifth International Conference on E-Learning (ELearning-2014).

Pacheco, D., Wierenga, S., Omedas, P., Wilbricht, S., Knoch, H., & Verschure, P. F. M. J. (2014). Spatializing experience: A framework for the geolocalization, visualization and exploration of historical data using VR/AR technologies. In *ACM international conference proceeding series*. https://doi.org/10.1145/2617841.2617842, 2014-April.

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

Pirker, J., Lesjak, I., & Guetl, C. (2017). Maroon VR: A room-scale physics laboratory experience. In *Proceedings - IEEE 17th international conference on advanced learning technologies* (pp. 482–484). ICALT. https://doi.org/10.1109/ICALT.2017.92, 2017.

Pirker, J., Lesjak, I., Parger, M., & Gütl, C. (2018). An educational physics laboratory in mobile versus room scale virtual reality - a comparative study. *Lecture Notes in Networks and Systems, 22*, 1029–1043. https://doi.org/10.1007/978-3-319-64352-6_95

Ratclife, J., Soave, F., Bryan-Kinns, N., Tokarchuk, L., & Farkhatdinov, I. (2021). Extended reality (xr) remote research: A survey of drawbacks and opportunities. In *Conference on human factors in computing systems - proceedings*. https://doi.org/10.1145/3411764.3445170

Reeves, S. M., Crippen, K. J., & McCray, E. D. (2021). The varied experience of undergraduate students learning chemistry in virtual reality laboratories. *Computers in Education, 175*, Article 104320. https://doi.org/10.1016/j.compedu.2021.104320

Rocha Estrada, F. J., Ruiz Ramírez, J. A., George-Reyes, C. E., & Glasserman-Morales, L. D. (2021). Students, experience using a web-based virtual reality tool. 2021. In *Machine learning-driven digital technologies for educational innovation workshop*. https://doi.org/10.1109/IEEECONF53024.2021.9733763, 1–5.

Sälzer, C., & Roczen, N. (2018). Assessing global competence in PISA 2018: Challenges and approaches to capturing a complex construct. *International Journal of Development Education and Global Learning, 10*(1), 5–20. https://doi.org/10.18546/ijdegl.10.1.02

Sánchez-Juárez, I., & García-Almada, R. (2016). Public debt, public investment and economic growth in Mexico. *International Journal of Financial Studies, 4*(2). https://doi.org/10.3390/ijfs4020006

Santiago, P., McGregor, I., Nusche, D., Ravela, P., & Toledo, D. (2012). *OECD reviews of evaluation and assessment in education: Mexico*. OECD Publishing.

Silva Rodríguez de San Miguel, J. A. (2019). Adoption of virtual education in Mexico. *Espacios, 40*(21).

Smith, J. R., Snapp, B., Madar, S., Brown, J. R., Fowler, J., Andersen, M., Porter, C. D., & Orban, C. (2023). A smartphone-based virtual reality plotting system for STEM education. *Primus, 33*(1), 1–15. https://doi.org/10.1080/10511970.2021.2006378

Tromp, R. (2018). Global policies, local meanings: The re-contextualization of competency-based education reforms in Mexico. *Global Education Policy and International Development: New Agendas, Issues and Policies*, 161.

Tromp, R. E., & Datzberger, S. (2021). Global education policies versus local realities. Insights from Uganda and Mexico. *Compare: A Journal of Comparative and International Education, 51*(3), 356–374. https://doi.org/10.1080/03057925.2019.1616163

Tsichouridis, C., Batsila, M., Vavougios, D., & Ioannidis, G. (2020). Virtual and augmented reality in science teaching and learning. *Advances in Intelligent Systems and Computing, 1134*, 193–205. https://doi.org/10.1007/978-3-030-40274-7_20. AISC(October.

Zaikin, O., Malinowska, M., Bakhtadze, N., & Zyławski, A. (2017). Motivation and social aspects of competence-based learning process. *Procedia Computer Science, 112*, 1092–1101. https://doi.org/10.1016/j.procs.2017.08.131

Zamora-Antuñano, M. A., Barros-Baertl, R., Tovar-Luna, B., González-Gutiérrez, C. A., Mendez-Lozano, N. E., & Cruz-Perez, M.Á. (2022). The Use of Augmented Reality to Strengthen Competence in Data Analysis and Problem Solving in Engineering Students at the Universidad del Valle de México. *Education Sciences, 12*(11). https://doi.org/10.3390/educsci12110755