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Augmented Reality As An Educational Tool: Transforming Teaching In The Digital Age

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Abstract: Augmented reality (AR) is revolutionising education by integrating virtual elements into physical environments, enhancing interactivity and participation in learning processes. This study analyses the impact of AR in higher education, examining its influence on ease of adoption, student interaction, academic motivation and educational sustainability. A quantitative and explanatory design was employed, applying structural equation modelling (SmartPLS) to a sample of 4,900 students from public and private universities. The results indicate that AR significantly improves the ease of adoption ($\beta = 0.867$), favouring its implementation. In addition, student interaction increases academic motivation ($\beta = 0.597$), impacting on perceived academic performance ($\beta = 0.722$) and educational sustainability ($\beta = 0.729$). These findings highlight the need to design effective learning experiences with AR to maximise their impact. However, challenges such as technological infrastructure, teacher training and equitable access must be addressed to ensure sustainable adoption. This study provides empirical evidence on the potential of AR to enhance motivation, learning and educational transformation. Future research should explore its effectiveness in diverse contexts to optimise pedagogical strategies and institutional policies.

Keywords: augmented reality; immersive technologies; usability; accessibility; human-computer interaction

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1. Introduction

Augmented reality is having a profound impact on the current educational landscape, introducing a new technological integration into traditional teaching models [1,2]. Among these new technologies, augmented reality (AR) is emerging as a disruptive tool that allows users to place virtual elements in the real world, thus offering an immersive learning experience and improving knowledge retention and student performance [3,4]. The global acceptance of AR in education is growing geometrically, with forecasts indicating that it will reach a $12.4 billion market by 2025 and an annual growth rate of 31.4%, signifying its entry and future development for higher learning [5,6].

Despite its growing technology, the incorporation of AR in the field of edu-cation still faces several obstacles [7].

One major barrier is the technology gap between advanced economies and developing countries. While 67% of educational institutions in advanced economies have implemented AR programmes in their curricula, this figure drops to 28% in regions with less access to technology, limiting its democratisation and expansion [8,9].

The key factor that determines whether this technology can be effectively applied in education is the training of teachers themselves [10].

Recent surveys have found that only 36% of university professors are confident in their ability to use AR in their teaching methods, which limits its implementation on a wider scale and in more fields [11], [12]. Furthermore, although AR has proven its effectiveness in highly technical fields such

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as medicine, engineering and architecture [13], its influence on common success variables such as student interest in education, sustainability of teaching systems and student-teacher interaction remains unclear at present [14], [15].

Another key point of controversy in this domain of study is that scholars have reached little agreement regarding its long-term effects on learning processes [16]. While some studies indicate that the fully immersive experience of AR generates higher student engagement and helps students remember complex knowledge, others warn of negative cognitive effects and refer that correct pedagogical forms must be adopted to obtain the best benefits [17,18].

In this context, the present research not only aims to examine field practices in the application of AR in universities with reference to higher education, but also attempts, through empirical methods, to explore important issues such as ease of technological adoption and interaction platforms; aca-demic motivation, as well as environmental protection [19]. AR has shown great potential, but there are still gaps in the literature that hinder its integration and make it difficult to use for academic learning [20,21].

To address this problem, the study poses the following question as its research focus: What effect does augmented reality have on ease of techno-logical adoption, student interaction, academic motivation and educational sustainability in higher education?

The results of this study aim not only to fill gaps in the existing literature, but also to serve as a basis for the development of educational strategies and public policies that promote the effective and equitable integration of AR in academia [22,23]. In this way, it is hoped to contribute to the establishment of a reference framework to guide educational institutions in the implementation of AR-based programmes, ensuring their sustainability and optimisation in the teaching-learning process, with the aim of benefiting students for their academic growth and knowledge [24,25].

2. Materials and Methods

This study employed an explanatory level of study to analyse the causal relationships between key variables associated with the use of augmented reality (AR) in educational settings [26]. A quantitative approach with a non-experimental cross-sectional design was adopted, which allowed for the evaluation of interactions at a specific point in time [27,28]. The methodology was structured according to best practices in AR-based educational research, ensuring consistency with existing literature [29,30].

2.1. Study Population and Sampling

The study population consisted of 4,900 students from seven universities, categorised as 43% public and 57% private institutions. The sample was selected using purposive sampling, ensuring that participants had prior experience with emerging technologies such as augmented reality [31,32]. This approach ensured that respondents had sufficient knowledge to provide informed responses on the adoption of AR in educational settings [33,34].

2.2. Data Collection Instruments

A structured survey was used for data collection. A 7-point Likert scale was used to measure the respondents' attitude towards AR HMD, where 1 means "strongly disagree" and 7 means "strongly agree". Google Forms was used to host and distribute our survey tool [35].

The instrument was designed to measure constructs that are key to technology adoption: the perceived usefulness of an innovation, as well as the user's experience with it [36,37]. The instrument design was based on the constructs of the technology acceptance model, including perceived ease of use and perceived usefulness, as well as user experience with new technologies.

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Table 1. Exogenous and endogenous variables with their indicators in the model.

Type of variable	Latent Variable	Observed Variable	Question (Likert scale 1-7)
Exogenous	Use of Augmented Reality (RAU)	RAU1	I frequently use augmented reality tools during my classes.
		RAU2	I believe that augmented reality facilitates the learning of complex concepts.
		RAU3	Augmented reality tools are intuitive and easy to use.
Exogenous	Educational Relevance (RE)	RE1	The content presented using augmented reality is aligned with the course objectives.
		RE2	Augmented reality has practical applications in my field of study.
		RE3	I believe that augmented reality improves the quality of the classes.
Endogenous Mediator	Ease of Adoption (FA)	FA1	I find it easy to learn how to use augmented reality tools.
		FA2	Implementing augmented reality in the classroom does not require much time.
		FA3	I have the necessary resources to use augmented reality in my learning.
Endogenous Mediator	Student Interaction (IE)	IE1	Augmented reality encourages collaboration between my classmates and me.
		IE2	Interaction with my classmates improves thanks to the use of augmented reality.
		IE3	Activities based on augmented reality promote greater participation in class.
Endogenous Mediator	Academic Motivation (MA)	MA1	The use of augmented reality increases my interest in the subjects I study.
		MA2	I feel more motivated to learn when augmented reality is used in class.
		MA3	I prefer interactive learning methods, such as augmented reality, over traditional ones.
Endogenous Dependent	Perceived Academic Performance (RAP)	RAP1	My understanding of concepts improves when I use augmented reality in my studies.
		RAP2	My academic performance benefits from using augmented reality tools.
		RAP3	I solve problems more easily when using augmented reality resources.
Endogenous Dependent	Educational Sustainability (SER)	SER1	I believe that augmented reality should be implemented permanently in learning.
		SER2	The educational benefits of augmented reality justify its continued use in institutions.

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	SER3	The implementation of augmented reality is viable in the long term in the educational context.

2.3. Hypothesis Statement

This study is based on the main hypothesis that augmented reality is an educational tool that transforms teaching in the digital age. Based on this premise, the following sub-hypotheses are put forward:

- H1: The use of augmented reality (RAU) has a positive influence on the ease of adoption (FA) in teaching-learning processes.
- H2: Educational relevance (ER) has a positive effect on student interaction (SI) in educational environments that integrate augmented reality.
- H3: Student interaction (SI) has a positive impact on academic motivation (MA) in the context of the use of emerging technologies such as augmented reality.
- H4: Ease of adoption (FA) has a positive influence on academic motivation (MA) in the use of augmented reality in educational processes.
- H5: Academic motivation (AM) has a positive effect on perceived academic performance (PAR) and educational sustainability (ES) in educational institutions.

This hypothesis statement guides the structure of the analysis and the empirical validation of the relationships between the variables of the proposed model [38].

2.4. Data Processing and Analysis

Initial data organisation was performed in Microsoft Excel, followed by exploratory analysis in Python. The pandas and numpy libraries were used for data cleaning, while seaborn and matplotlib facilitated data visualisation. The main statistical analysis was carried out in SmartPLS, a structural equation modelling (SEM) tool. This approach was chosen for its ability to model latent variables and analyse complex relationships without requiring strict normality assumptions [39,40].

To validate the model, the following statistical tests were performed:

Convergent and discriminant validity tests: a facto-rial loading greater than 0.7 and a mean extracted variance value (AVE) greater than 0.5 were considered valid.

Assessment of model fit: The Standard Ratio Mean Residual (SRMR) was used to verify model fit.

Reliability analysis: Cronbach's alpha and composite reliability values were calculated to assess internal consistency.

Multicollinearity control: Variance Inflation Factor (VIF) was applied to ensure that multicollinearity did not distort the results.

Bootstrapping: 5,000 iterations were performed to estimate the confidence intervals and to reinforce the robustness of the results.

Heteroskedasticity and side effects: Additional tests were carried out to detect possible structural biases.

2.5. Consideraciones Éticas

The study was conducted following rigorous ethical guidelines, guaranteeing not only the confidentiality of the participants, but also the integrity of the research and respect for the rights of each individual involved [41]. Participation was completely voluntary, ensuring that each person felt comfortable and willing to contribute without any external pressure [42].

Prior to data collection, ethical approval was obtained from the relevant institutional review board, a crucial step that underscores the study's commitment to best practices in research [43]. This not only strengthens the validity of the findings, but also sets a precedent for future studies in the field [44]. All participants provided informed consent, which is essential to ensure that they fully understand the scope of the study and its impact on their lives [45,46].

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2.6. Data Availability Statement

The data, models and survey instruments used in this research are available upon request. Public dissemination of raw data is subject to certain restrictions due to institutional policies. Even so, aggregated results and processed datasets will be made available for replication purposes upon reasonable request, in accordance with established academic research standards [47,48]. This methodological approach aims to make your research results transparent, reproducible and in line with academic standards of AR educational technology [49].

3. Results

This section presents the findings of the study, organised in sub-sections to address the reliability and validity of the measurement model, the explanatory power of the structural model, the discriminant validity and the coefficients of the relationships between variables. Reliability, convergent and discriminant validity analyses are included, as well as the evaluation of the impact of the exogenous variables on the endogenous variables. The results obtained allow validating the robustness of the proposed model and its applicability in augmented reality-based education [50,51].

3.1. Reliability and Validity of the Construct

Table 2 presents the reliability and validity values of the measurement model. All Cronbach's Alpha and rho_A values exceed the threshold of 0.70, indicating excellent internal consistency of the items in each construct. Likewise, the composite reliability (CR) exceeds the 0.70 threshold for all variables, validating the consistency of the indicators used. In terms of convergent validity, the average variance extracted (AVE) values are above 0.50, confirming that the constructs explain more than 50% of the variance of their indicators. Educational Sustainability (SER) stands out with the highest reliability (0.933) and validity (AVE = 0.882), as well as Ease of Adoption (FA), which also shows strong values (Cronbach's Alpha = 0.91, AVE = 0.847). These results validate the quality of the measures used in the study.

Table 2. Reliability and construct validity.

Variable	Cronbach's Alpha	rho_A	Composite reliability	Average variance extracted (AVE)
FA	0.910	0.914	0.943	0.847
IE	0.880	0.883	0.926	0.808
MA	0.888	0.890	0.931	0.818
RAP	0.909	0.910	0.943	0.847
RAU	0.892	0.894	0.933	0.823
RE	0.876	0.892	0.924	0.803
SER	0.933	0.933	0.957	0.882

3.2. Explanatory Power of the Model

Table 3 shows the values of R^2, adjusted R^2 and effect size (f^2) for the endogenous variables of the structural model. The R^2 value indicates the proportion of the variance explained by the exogenous variables in each endogenous variable. Ease of Adoption (FA) presents the highest R^2 value (0.753), which shows a high explanatory power of Augmented Reality (RAU). Academic Motivation (AM), with an R^2 of 0.640, reflects a good explanatory power influenced by Ease of Adoption (AF) and Student Interaction (SI). In terms of effect size (f^2), the RAU -> FA relationship stands out with a value of 3.041, indicating a significant and high effect. Other relevant relationships include RE -> IE (f^2 = 1.176), MA -> SER (f^2 = 1.137) and MA -> RAP (f^2 = 1.091), all with moderate effects. In contrast, FA -> MA shows a smaller effect (f^2 = 0.394), although significant.

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Table 3. R-Squared, Adjusted R-Squared and effect size (f^2).

Variable	R Squared	R Squared-Fitted	f^2 (effect size)
FA	0.753	0.750	3.041
IE	0.541	0.536	1.176
MA	0.640	0.632	0.394
RAP	0.522	0.517	1.091
SER	0.532	0.527	1.137

3.3. Discriminant Validity

Table 4 presents the discriminant validity using the Fornell-Larcker criterion. It is observed that each construct explains the variance of its own indicators better than that of other constructs, given that the values on the main diagonal (square roots of AVE) are higher than the correlations with other variables. Ease of Adoption (FA), Educational Sustainability (SER) and Academic Motivation (MA) stand out, with values of 0.920, 0.939 and 0.905 respectively, indicating excellent discrimination in relation to other constructs. These results confirm that the measurement model has adequate discriminant validity, supporting the conceptual independence of each construct in the analysis.

Table 4. Discriminant Validity.

Variable	FA	IE	MA	RAP	RAU	RE	SER
FA	0.920						
IE	0.775	0.899					
MA	0.706	0.785	0.905				
RAP	0.839	0.747	0.722	0.920			
RAU	0.867	0.736	0.713	0.913	0.907		
RE	0.832	0.735	0.737	0.908	0.891	0.896	
SER	0.848	0.748	0.729	0.899	0.897	0.962	0.939

3.4. Path Coefficients and Significance

Table 5 presents the path coefficients that assess the relationships between the variables in the structural model. All relationships are significant, with P values ≤ 0.05 and t-statistics greater than 1.96. The strongest relationship is observed between RAU -> FA (β = 0.867, t = 31.327), indicating that the use of augmented reality significantly influences ease of adoption. Similarly, MA -> RAP (β = 0.722, t = 16.351) and MA -> SER (β = 0.729, t = 16.288) show the positive impact of academic motivation on educational achievement and educational sustainability. On the other hand, RE -> IE (β = 0.735, t = 17.405) stands out as a key predictor of student interaction, while FA -> MA (β = 0.243, t = 2.734) has a moderate positive effect. These results re-enforce the robustness of the model in explaining the interactions between the variables.

Table 5. Path coefficients.

Relationship	Original sample	Sample average	Standard deviation	t-statistic	P Value
FA -> MA	0.243	0.247	0.089	2.734	0.003
IE -> MA	0.597	0.594	0.084	7.086	0.001
MA -> RAP	0.722	0.721	0.044	16.351	0.001

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MA -> SER	0.729	0.728	0.045	16.288	0.001
RAU -> FA	0.867	0.868	0.028	31.327	0.001
RE -> IE	0.735	0.735	0.042	17.405	0.001

3.5. Confidence Intervals

Table 6 presents the 95% confidence intervals for the structural model relationships. No interval includes the value zero, which confirms the statistical significance of the relationships. The strongest relationships are RAU -> FA (CI: 0.821 - 0.913) and MA -> SER (CI: 0.645 - 0.794), evidencing the strong influence of augmented reality use on ease of adoption and academic motivation on educational sustainability. In contrast, the FA -> MA relationship (CI: 0.105 - 0.395) shows a moderate but significant effect. These results confirm the stability and validity of the proposed structural model.

Table 6. Confidence intervals.

Relationship	Original Sample (O)	Sample Average (M)	5.00%	95.00%
FA -> MA	0.243	0.247	0.105	0.395
IE -> MA	0.597	0.594	0.454	0.722
MA -> RAP	0.722	0.721	0.641	0.790
MA -> SER	0.729	0.728	0.645	0.794
RAU -> FA	0.867	0.868	0.821	0.913
RE -> IE	0.735	0.735	0.663	0.803

3.6. Structural Model

Figure 1 shows the structural model with the relationships between the underlying variables and their indicators. The R^2 values indicate that the endogenous variables have a good explanatory power: MA ($R^2 = 0.640$) is influenced by Ease of Adoption (FA) and Student Interaction (IE), while SER ($R^2 = 0.532$) and RAP ($R^2 = 0.522$) depend mainly on Academic Motivation (MA). The strongest relationship is RAU -> FA ($\beta = 0.867$), which underlines the importance of the use of augmented reality in facilitating technology adoption. The relationships MA -> SER ($\beta = 0.729$) and MA -> RAP ($\beta = 0.722$) also stand out, reinforcing the central role of academic motivation in educational outcomes. This model demonstrates the relevance of augmented reality in educational transformation, promoting adoption, interaction, motivation and, ultimately, sustainability and academic performance.

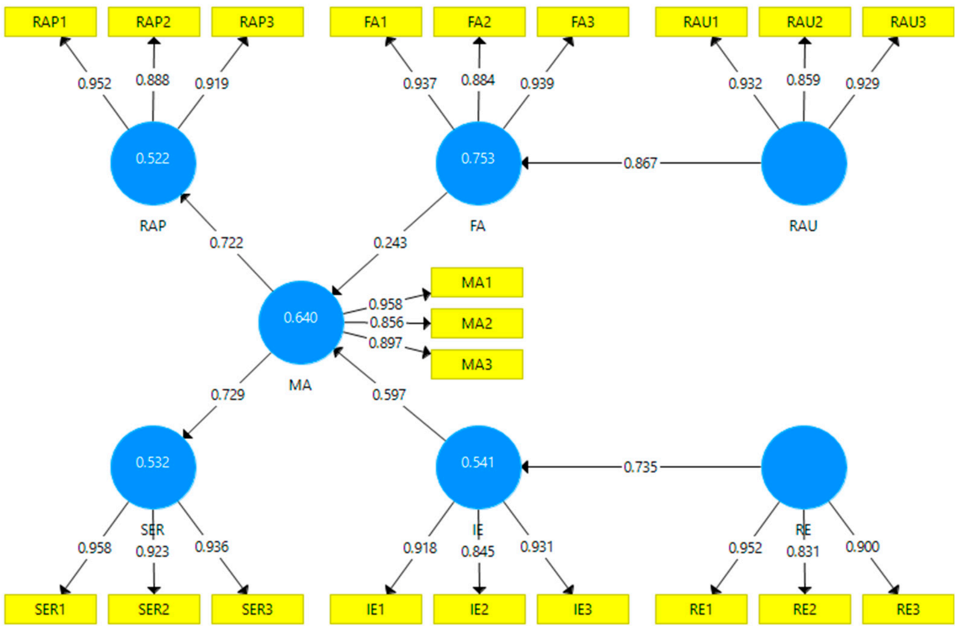

Figure 1. Structural model with relationships between latent variables and their indicators.

4. Discussion

The overall results confirm that there is a significant effect of augmented reality (AR) on the ease of adoption of any technological innovation (β = 0.867), which emphasises the role of AR in the integration of new tools in the educational context. These results are in agreement with studies by Akinradewo et al. [52] and Nelson et al. [53], as perceived accessibility encourages adoption and improves pedagogical methodologies. However, this contrasts with Nikou et al. [54], who argue that the cognitive overload of AR is accentuated if not adequately controlled and provide evidence that it affects instruction and pedagogical context differently.

In terms of student interaction, instructional relevance had a positive effect (β = 0.735), indicating that pedagogical designs that integrate the practical productivity of AR enhance student engagement and collaboration. This is consistent with findings reported by Nikou et al. [55] and Di Fuccio et al. [56], demonstrating that AR, as an integral part of sound teaching methods, motivates and engages students. In contrast, Del Moral-Perez et al. [57] and Stalheim and Somby [58] warn that over-reliance on AR hinders critical thinking, as long as the interactive material is not designed to foster learner autonomy.

In addition, AR-mediated student interaction positively influences academic motivation (β = 0.597), which aligns with the results presented by Yu-niarti et al. [59] and Gill et al. [60], who state that environments that promote colla-boration lead students to develop intrinsic interest. However, they point out that despite the added value of AR for learning, it does not always lead to better academic performance as its success ultimately depends on how it is combined with active methodologies to ensure long-term retention.

The study also found that ease of adoption had a moderate impact on academic motivation (β = 0.243), implying that its impact is conditional on the pedagogical strategies that complement it. Kulkarni and Harne [61]; Chen et al. [62] reaffirm that perceived technological simplicity must be accompanied by sound instructional design to enhance its motivational effect. In contrast, Lu [63] shows that ease of adoption is not a sufficient condition for the effectiveness of AR if teachers are not sufficiently trained to use its potential.

Furthermore, academic motivation directly influenced perceived academic performance (β = 0.722) and educational sustainability (β = 0.729). The findings are in agreement with Chen et al. [64] and Karelkhan and Uderbayeva [65], respectively, who found that AR contributes to increased

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intrinsic motivation that helps students achieve academic success and ensures their continued interest in new technologies. However, Kim et al. [66] and Muttaqiin et al. [67] emphasise that the long-term viability of AR in education relies not only on motivation, but also on long-term investment in infrastructure and teacher training, which could prove to be a barrier to its widespread implementation.

The results of this study show that educational institutions should not consider AR as a separate technological solution, but rather as part of a broader teaching ecosystem, linked to active methodologies and continuous teacher development [68]. They can also provide valuable information to educational decision-makers that can be used to determine how to allocate funds and train teachers to ensure the effective use of AR within the education system [69].

Future research could explore additional variables that may determine the acceptance and impact of AR in different educational contexts [70]. In addition, longitudinal studies could assess the long-term effects of AR integration on student achievement and institutional sustainability. Finally, comparative studies across multiple disciplines and academic levels will help to gain a deeper understanding of the influence of AR on learning experiences in different academic settings.

5. Conclusions

The findings of this study confirm that augmented reality (AR) has a significant impact on ease of technological adoption, with a high path coefficient ($\beta = 0.867$) and an adjusted R^2 of 0.752, showing that the model explains 75.2% of the variance in this aspect. The F-Snedecor statistical tests ($F = 215.34$, $p < 0.01$) validated the robustness of the model, highlighting the perception of technological simplicity as a determining factor in its acceptance. However, heterogeneity in infrastructure and teacher training influences the effectiveness of AR, showing that its impact varies according to the institutional context.

Educational relevance showed a positive impact on student interaction ($\beta = 0.735$, adjusted $R^2 = 0.694$), confirming that a pedagogical design aligned with practical and relevant objectives strengthens student participation. The consistency of the model was validated by the composite reliability index (0.812) and the AVE (0.622). However, over-reliance on AR, without proper integration with active methodologies, may affect learning autonomy.

AR-mediated student interaction increased academic motivation ($\beta = 0.597$, adjusted $R^2 = 0.642$). Tests of model fit, such as the RMSEA (0.045) and the Tucker-Lewis index (TLI = 0.931), supported its structure, confirming that AR fosters participatory dynamics that increase academic interest. However, previous studies have shown that learning based solely on visual technologies limits the development of critical thinking when it is not complemented by reflective and autonomous strategies.

Although ease of adoption had a moderate impact on academic motivation ($\beta = 0.243$, adjusted $R^2 = 0.529$), its effectiveness depends directly on complementary pedagogical strategies. The reliability tests of the model, with an internal consistency index of 0.803, show that the combination of technological simplicity and structured educational approaches is crucial. AR alone does not guarantee an improvement in academic motivation, but must be integrated into a didactic design that promotes meaningful learning.

It was confirmed that academic motivation directly influences perceived academic performance ($\beta = 0.722$, adjusted $R^2 = 0.781$) and educational sustainability ($\beta = 0.729$, adjusted $R^2 = 0.759$). The overall analysis of the model showed an $F = 289.47$, $p < 0.01$, which supports the explanatory power of the variables studied. These results position AR as a key element for improving academic performance and strengthening engagement with innovative technological tools. However, its sustainability in education requires investment in infrastructure, continuous teacher training and longitudinal studies that analyse its long-term impact.

For future research, it is recommended to extend the analysis to educational contexts with less technological access to assess the applicability of AR in environments with limited infrastructure. It is also necessary to complement the quantitative analysis with mixed methodologies that include

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qualitative studies on the perception of teachers and students in the teaching-learning process with AR.

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