PIXEL-BIT
e-ISSN: 2171-7966
REVISTA DE MEDIOS Y EDUCACIÓN
MEDIA & EDUCATION JOURNAL

Augmented reality in STEM learning: developing spatial skills in electrical engineering training

Realidad aumentada en el aprendizaje de materias STEM: desarrollo de habilidades espaciales en la formación en ingeniería eléctrica

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Received: 2025-09-11; **Revised:** 2025-09-22; **Accepted:** 2025-10-29; **Published:** 2026-01-01

ABSTRACT
This research study employs a quantitative approach to examine the impact of augmented reality (AR) on the spatial skills of university students enrolled in electrical engineering programmes. For this purpose, a quasi-experimental study was conducted. The study involved 80 students, who were divided into four homogeneous groups. The groups were subjected to different methodologies. The application of augmented reality (AR) utilises mobile devices (Unity and Vuforia), digital documents, 3D simulations (ANSYS Maxwell) and laboratories. In order to assess spatial skills, standardised assessments such as the Mental Rotation Test (MRT) and Spatial Visualisation Test (SVT) were conducted. In addition, cognitive load was measured using the NASA Task Load Index. Intrinsic motivation was assessed using Keller's ARCS model, while academic performance was determined through theoretical and practical tests on asynchronous induction motors. The results of the study indicate that AR helped develop spatial skills and reduced cognitive load, while maintaining a higher level of attention, relevance, confidence, and satisfaction compared to the other three methodologies used. It was also noted that there was an increase in academic performance. Finally, the study establishes the technical and pedagogical feasibility of AR as an educational resource and identifies its potential for inclusion in STEM education.

RESUMEN
La investigación en este trabajo estudia cuantitativamente el efecto de la realidad aumentada (RA) en las habilidades espaciales de estudiantes universitarios en la formación de ingeniería eléctrica. Con ese fin, se llevó a cabo un estudio cuasi-experimental con 80 estudiantes divididos en cuatro grupos homogéneos y sometidos a diferentes metodologías: RA utilizando dispositivos móviles (Unity y Vuforia), documentos digitales, simulaciones 3D (ANSYS Maxwell) y laboratorios. Para evaluar las habilidades espaciales, se realizaron evaluaciones estandarizadas como Mental Rotation Test (MRT) y Spatial Visualization Test (SVT); la carga cognitiva se midió con NASA Task Load Index; la motivación intrínseca se evaluó utilizando el modelo ARCS de Keller, y el rendimiento académico se determinó mediante pruebas teóricas y prácticas sobre motores de inducción asíncronos. Los resultados del estudio indican que la RA ayudó a desarrollar las habilidades espaciales y redujo la carga cognitiva, al tiempo que mantuvo un mayor nivel de atención, relevancia, confianza y satisfacción en comparación con las otras tres metodologías empleadas. También se identifica un aumento del rendimiento académico. Por último, el estudio establece la viabilidad técnica y pedagógica de la RA como recurso educativo e identifica su potencial para su inclusión en la enseñanza STEM.

KEYWORDS · PALABRAS CLAVES
Augmented reality; spatial ability; cognitive load; engineering; STEM education.
Realidad aumentada; habilidad espacial; carga cognitiva; ingeniería; educación STEM.

1. Introduction

Spatial skills are a vital component of engineering education, as the ability to visualise, evaluate, and mentally manipulate three-dimensional objects is fundamental to understanding technical concepts and solving abstract problems. Electrical engineering, for instance, involves interpreting circuit diagrams, placing devices on control panels, and designing electromechanical systems. All of these activities rely on spatial knowledge and the relevant skills associated with it, such as spatial intelligence (Uttal et al., 2013). These skills have been widely recognised in the literature as predictors of academic and professional success in STEM (science, technology, engineering, and mathematics) fields, as they enable reasoning through informed decision-making and problem-solving using structured reasoning (Sorby, 2009).

Traditionally, training in these skills has been based on two-dimensional methods and computer-aided design (CAD). These methods have limitations in terms of interactivity and immersion, which can hinder the effective integration of complex and abstract information into technical learning experiences (Garzón et al., 2019). In this regard, AR has emerged as an innovative and disruptive technology with significant potential to transform teaching by providing interactive 3D models as part of physical reality, generating value and enhancing learning experiences (Azuma, 1997; del Cerro & Morales, 2021; Asham et al., 2023). In contrast to other digital tools, AR facilitates the creation of active and contextualised learning environments in which students can interact, explore and experiment safely and efficiently, thereby optimising the knowledge acquired through learning experiences (Martín-Gutiérrez et al., 2015).

However, despite the progress made, the literature still presents limitations in research associated with the quantitative comparison of AR with other teaching approaches used in engineering education. These are usually based on digital documents in pdf format supported by audiovisual presentations, simulations and 3D designs, and traditional physical laboratories (Ismail et al., 2019). The literature shows a lack of studies that test how different methodologies affect the development of spatial skills, perceived cognitive load, and intrinsic motivation among students. In order to address this gap, it is necessary to use a quasi-experimental design that allows for the exploration of these variables by applying standardised spatial skills tests, validated cognitive load scales such as the NASA Task Load Index (Hart, 2006), and motivation assessment models (Ma & Lee, 2021).

In line with the above, this study proposes a quantitative and comparative evaluation of the effect of AR in contrast to other teaching methods for the learning and development of spatial skills in electrical engineering students. The study will apply pre-test and post-test assessments of these skills, the cognitive load experienced, and the level of motivation towards learning. Our objective is to generate empirical evidence on the validity of AR as a teaching-learning resource. This evidence will serve as a criterion for its use in engineering education. Furthermore, the results can be extrapolated to other STEM areas where spatial skills are a prerequisite for the training of professionals in the digital age and Industry 4.0.

2. Augmented learning in STEM knowledge areas

AR has established itself as a key technology in the transformation of education in STEM disciplines by providing highly immersive and interactive learning environments. Unlike traditional methods, AR allows three-dimensional digital elements, annotations and interactive simulations to be superimposed on the physical environment, facilitating the understanding of abstract concepts by integrating them into a tangible and manipulable context (Arena et al., 2022). Its ability to combine the physical world with virtual representations enhances the teaching-learning process, as it allows for safe experimentation and the development of complex cognitive skills, promoting meaningful and autonomous learning (Prasetya et al., 2024).

From a cognitive perspective, AR represents an ideal solution for reducing intrinsic cognitive load, as information is distributed across different sensory modalities without overloading working memory, facilitating the acquisition of abstract knowledge (Buchner et al., 2022). This is particularly significant in engineering education, and in particular electrical engineering, given that understanding electrical circuits, control systems and electrical machines depends on simultaneous interaction with graphical, symbolic and mathematical information (García et al. 2023). On the other hand, AR provides students with real-time processed information to detect conceptual errors and optimise the learning experience while reducing teacher supervision (Wu et al., 2022).

Spatial skills are a cognitive ability of fundamental importance in engineering education, as they relate to the ability to interpret electrical diagrams, visualise three-dimensional configurations of control systems (Elford et al., 2022) or understand the layout of electrical components (Papakostas et al., 2021). Spatial skills are not only innate abilities, but can also be improved through practice and experience in environments that allow for the physical manipulation and exploration of three-dimensional models (Bogomolova et al., 2020). The use of augmented environments has grown to such an extent that it has become one of the most beneficial technological contributions to engineering education, as it provides electrical systems that can be visualised, rotated, and held in a physical environment, allowing for the development of a more accurate mental model and reducing conceptual errors (Kim & Irizarry, 2021).

The incorporation of AR into teaching has demonstrated several significant advantages, including knowledge retention, reduced cognitive load, and more accurate spatial problem solving (Yang et al., 2023). Previous studies have shown that students who use AR to learn about electrical circuits, transformers, and power distribution systems perform better on spatial visualisation assessments than students who use traditional methods (Kanivets et al., 2022). In addition, digital representations with physical interactions offer the advantage of reinforcing learning mechanisms and transferring knowledge to the real-world context, where students can develop and apply the technical concepts they have learned (An et al., 2019; Tarasenko et al., 2021; Álvarez-Marín & Velázquez-Iturbide, 2022).

Engineering education has evolved and has been marked by the use of various teaching methodologies which, based on their defining characteristics, have specific applications. Of all of these, the main ones most commonly used in academic training are: pdf resources supported by slide presentations, which allow information to be organised and shared in an accessible way; computer simulations and animated three-dimensional representations that make it possible to show the behaviour of electrical systems in a virtual environment; and laboratories, which facilitate interaction with the material being learned and the possibility of applying knowledge in a practical situation. The wide range of teaching methodologies used in engineering education means that the effectiveness of each of these varies greatly depending on the level of interactivity, accessibility, experimentation and extrapolation to real environments, which has led to the search for new teaching practices such as AR.

Technological teaching resources, which include pdf documents and slide presentations, are widely used thanks to their accessibility, their simplicity in terms of implementation and distribution, and the possibility of keeping all documents constantly updated (Bourbour, 2023). On the other hand, there are limitations in the area of interactivity and three-dimensional representation, which contribute to increasing the difficulties in assimilating complex electrical systems, as well as not favouring the development of spatial skills (Guillén-Gámez et al, 2022). They are also considered passive resources that can lead to poor knowledge retention and affect students' attention levels, especially with technical content (Oguguo et al, 2023).

On the other hand, the use of software simulations and animated 3D designs has proven to be a useful educational resource for modelling and analysing electrical systems in a controlled environment, allowing students to observe the dynamic behaviour of circuits and their components (Bogusevschi et al., 2020). However, their application requires computers and specific software, their use may be limited, and there may be restrictions on their use in certain educational spaces (O'Connor et al, 2021). and although they are advantageous in terms of their graphical representation, effective integration with the real world has not been achieved, which can hinder the transfer of knowledge to practical contexts (Ahn et al., 2020).

Laboratories remain the norm in engineering education as they provide experience of working directly with this type of equipment and devices and also allow practical skills to be developed and applied in specific situations (Kapici et al., 2019). However, laboratories have certain limitations, such as high maintenance costs, limited access, and safety issues associated with testing high-power electrical systems (Thees et al., 2020). Restricted access to laboratories also limits the possibility of repeating practical exercises, which can have a negative impact on the consolidation of learning.

In this regard, AR is presented as an integrative tool that unifies the possibilities of more traditional systems with the immersive and participatory possibilities of digital media. By projecting three-dimensional models into the physical world, students will interact with electrical circuits, electromechanical components, or control systems in a way that reduces barriers to access to this experimental learning (Alzahrani, 2020). AR also offers advantages in terms of flexibility and safety, as it can simulate complex real-world situations without the risk of working with certain electrical equipment in the laboratory.

3. Methodology

The research design is quasi-experimental with a quantitative approach, with the aim of analysing the effect of AR on improving spatial skills and student motivation in teaching electrical engineering content. The performance of AR implementation is compared with that of three other teaching methodologies used in this field: digital documents (pdf and slides), 3D simulations by ANSYS Maxwell, and laboratories. In this regard, the impact of each method on academic performance and the cognitive load perceived by students is also analysed, thus preserving the internal validity of this study by assigning participants to homogeneous groups in terms of variables that could affect performance, due to the difference in the pedagogical methodology applied in each case (Slack & Draugalis Jr, 2001).

The overall objective of this research is to evaluate the effectiveness of using AR on mobile devices for the development of spatial skills in electrical engineering students, compared to other teaching methods. Based on this overall objective, the following specific objectives are determined:

1. Quantify the degree of acquisition of spatial skills by students after the intervention using each of the teaching methodologies.
2. Compare the perceived cognitive load of students in each study group using the NASA Task Load Index (TLX) scale (Hart, 2006).
3. Analyse student motivation and satisfaction using a structured questionnaire based on Keller's ARCS model (Keller, 1987).
4. Determine the relationship between cognitive load, motivation, performance in spatial tests and degree of learning achieved, and extract statistically significant correlations.
5. Evaluate the pedagogical and logistical feasibility of implementing AR in electrical engineering education.

Based on these objectives, the following working hypotheses are formulated:

- H_1: AR on smartphones contributes significantly to improving spatial skills compared to the use of digital documents, 3D simulations and laboratories.
- H_2: The perceived cognitive load will be lower in students who use AR compared to those who use digital documents, 3D simulations and laboratories.
- H_3: The use of AR will lead to higher levels of motivation and satisfaction in the learning process.
- H_4: Perceived cognitive load will be inversely proportional to test performance, such that lower cognitive effort will be associated with higher performance.
- H_5: The large-scale implementation of AR on mobile devices is pedagogically viable and logistically feasible in electrical engineering education, according to the acceptance and ease of curricular integration indices compared to proven methods.

The initial sample for the study consisted of 80 second-year students enrolled in the Chemical Engineering degree programme at the University of Murcia, who were registered for the Electrical and Electronic Engineering course. The students were assigned evenly to four groups of 20 students each (Table 1), ensuring equivalence in terms of age, prior knowledge, and digital tool proficiency. This homogeneity in the composition of the groups allows us to effectively control the influence of variables outside the study, thus ensuring that any differences in results are attributed to the teaching methodology we followed in each of the experimental conditions (Lorenzi-Cioldi, 1998). All groups were taught by the same teaching team, ensuring uniformity in instruction and eliminating biases related to content presentation or teaching style. Thus, the independent variable of the study is also controlled, and the impact of AR on the acquisition of spatial skills, cognitive load, motivation, and learning acquired by students can be objectively evaluated.

Table 1

Distribution of the sample according to the teaching method used.

Group	Teaching method	N
EG	Augmented reality on smartphones (Unity + Vuforia)	20
CG1	Digital documents (pdfs and slide presentations)	20
CG2	3D computer simulations (ANSYS Maxwell)	20
CG3	Traditional physical laboratories	20

Nota: EG = Experimental Group, CG = Control Group.

The intervention was carried out in six one-hour sessions, which were accompanied by theoretical explanations of the operation of the asynchronous induction motor (Chen et al., 2020). These sessions are aligned with the teaching guide for the subject, where three thematic areas related to the electric motor have been selected, addressing operation, connection, and automatic control.

AR has been implemented on smartphones using Unity (version 2023.2.20f1) and Vuforia Engine Package for Unity (version 10.20.3). Unity is a real-time development platform widely used for the development of video games and interactive applications, which allows the creation of immersive 3D experiences. Vuforia Engine Package for Unity, compatible with ARCore and ARKit, enables the creation of AR applications thanks to its advanced tools for image, object and plane recognition. It is incorporated into Unity through the Package Manager or by importing the Unity Asset Package from the Vuforia Engine developer portal, providing flexible and accessible use on Android and iOS devices (Figure 1).

Figure 1

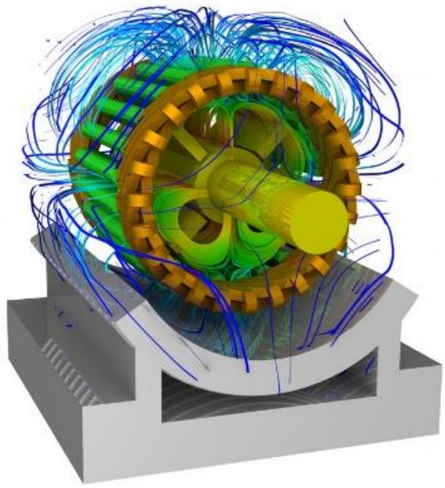
3D model of an asynchronous electric motor in Unity for subsequent integration into AR with the Vuforia Engine.

Source: Own elaboration.

The 3D simulations are carried out using ANSYS Maxwell (version 2024 R1), software for modelling and simulating electromagnetic fields in 2D and 3D, which is widely used in industry for the analysis and design of electric motors, transformers and electromagnetic devices with high simulation fidelity (Figure 2).

Figure 2

Simulation of the electromagnetic field in an asynchronous electric motor with ANSYS Maxwell 2024 R1.



Source: Own elaboration.

To ensure the validity and reliability of the measurements, standardised data collection instruments validated by other research studies are selected. Table 2 shows the collection of instruments used in the research and includes the variables evaluated and their corresponding references.

Table 2

Data collection instruments used in the research.

Instrument	Variable assessed	Reference
Mental Rotation Test (MRT)	Spatial abilities	(Ariali, 2020)
Spatial Visualization Test (SVT)	Mental manipulation of 3D objects	(Branoff, 2000)
NASA Task Load Index (TLX)	Perceived cognitive load	(Hart, 2006)
ARCS questionnaire	Motivation and satisfaction	(Ma & Lee, 2021)
Content test	Written and practical test of electrical concepts	(Cronbach, 1951)

The content test presented and administered by the teaching team aims to assess the theoretical and practical application of the electrical content taught. Given the measurement of internal consistency, Cronbach's alpha coefficient (Cronbach, 1951) was calculated, obtaining a value of .97, i.e., a high reliability that determines the validity of the instrument as a tool for evaluating the content taught. In its design, the items selected are the most representative of the curriculum, thus ensuring content validity and suitability for the academic context. In order to assess the acquisition of knowledge and its application in real contexts, a written and practical test has been designed, consisting of two complementary parts.

The written test includes theoretical questions and applied problems and covers the operation and constituent parts of the motor, the different connection configurations, the calculation of line and phase currents, and the analysis of characteristic curves. It also covers power factor compensation strategies and their optimisation in industrial environments.

The practical test covers the assembly and connection of the motor to the appropriate connection according to the voltage configuration, verification of its operation based on the measurement of voltage, current and power factor at no load, identification of system losses and performance of electrical automatisms: reversal of rotation, direct motor start and star/delta start.

The experimental intervention phase was structured in five stages to ensure comparison between groups and to determine which of the teaching methodologies was having the greatest or least impact on students' spatial skills, cognitive load, motivation and learning (Table 3).

Table 3

Experimental intervention phase.

Stage	Description
Pre-test	Initial assessment of spatial skills and prior knowledge.
Learning sessions	Application of the teaching method assigned to each group (AR, digital documents, 3D simulations or laboratory).
Immediate assessment	Application of the NASA TLX scale at the end of the session to measure perceived cognitive load.
Post-test	Final measurement of spatial skills (MRT/SVT) and motivation (ARCS).
Content test	Theoretical-practical test related to electric motors, validating the transfer of learning.

Data analysis was performed using SPSS (version 28.0.1.1). Descriptive statistics were used to characterise the sample, followed by ANOVA with Tukey's post hoc tests (Brown, 2005) to determine significant differences between groups in spatial skills, cognitive load, motivation, and learning. In addition, Pearson correlations were performed to examine the relationship between cognitive load, motivation, performance on spatial tests, and learning acquired, and ANCOVA covariance analysis (Keselman et al., 1998) was applied to control for the impact of external variables such as familiarity with digital technologies or level of prior knowledge.

4. Results

This section presents the findings obtained after applying the four teaching methods investigated: AR digital documents (pdfs and slide presentations), 3D simulations (ANSYS Maxwell) and laboratories. To provide a comprehensive overview, the characterisation of the sample and the overall statistical analysis (ANOVA, correlations and ANCOVA) are included. The results relating to the development of spatial skills, perceived cognitive load, student motivation and academic performance in the content test are presented in detail below.

4.1. Sample characterisation and overall statistical analysis

4.1.1. Sociodemographic characterisation and prior knowledge

The sample consisted of 80 students enrolled in the Electrical and Electronic Engineering course, distributed equally between the experimental and control groups. Homogeneity was ensured in variables such as age, gender, prior knowledge and use of digital tools.

The age analysis showed an average of 21 years (range: 19-24 years), with no significant differences ($p > .05$) between the groups. In terms of gender distribution, 68.8% were men and 31.2% were women, showing equivalent proportions in each group ($p > .05$).

Regarding prior knowledge of electrical engineering, a written test was administered, showing an average of 6.2 points out of a maximum of 10. Statistical analysis confirmed the absence of significant differences between the groups ($p > .05$), ensuring equivalent initial conditions. Familiarity with digital tools was also measured on a scale of 1 to 5, obtaining an average of 3.8, with no significant differences ($p > .05$). Table 4 presents the detailed values of these variables for each group, showing the homogeneous distribution of the sample, which allows the differences in the results to be attributed exclusively to the teaching methodology used.

Table 4

Sociodemographic characteristics and level of prior knowledge of the sample.

Variable	Category/range	EG	CG1	CG2	CG3	Total
Age (years)	Mean	20.8	21.1	20.9	21	21
	(SD)	(1.3)	(1.5)	(1.2)	(1.4)	(1.3)
	[Min.-Max.]	[19–23]	[19–24]	[19–23]	[19–24]	[19–24]
Gender	Men	13	14	13	15	55
	(%)	(65%)	(70%)	(65%)	(75%)	(68.8%)
	Women	7	6	7	5	25
	(%)	(35%)	(30%)	(35%)	(25%)	(31.2%)
Prior knowledge	Mean (SD)	6.2 (.8)	6.1 (.9)	6.3 (.7)	6.2 (.6)	6.2 (.8)
	[Min.-Max.]	[5–8]	[4–8]	[5–8]	[5–7]	[4–8]
Familiarity with ICT (1–5)	Mean (SD)	3.8 (.4)	3.7 (.5)	3.9 (.4)	3.6 (.5)	3.8 (.5)
	[Min.-Max.]	[3–4]	[3–5]	[3–5]	[3–5]	[3–5]

4.1.2. Comparisons between groups (ANOVA) and post hoc tests

To analyse the impact of the four teaching methods evaluated, a one-way ANOVA was applied, followed by Tukey's post hoc tests to identify significant differences between the groups, where five key variables were evaluated: MRT, SVT, NASA TLX, ARCS and the content test.

The results showed significant differences in all variables ($p < .01$), with effect sizes (η^2) between .18 and .28, indicating a moderate to high impact of the teaching methodology (Table 5).

Table 5

One-way ANOVA and post hoc tests for the main study variables.

Variable	F	*p*	η^2	Principal differences (Tukey)
MRT (post-test)	8.34	< .01	.25	GE > GC1 (*p* < .01), GE > GC3 (*p* < .01), GE > GC2 (*p* < .05)
SVT (post-test)	9.11	< .01	.28	GE > GC1 (*p* < .01), GE > GC3 (*p* < .01), GE > GC2 (*p* < .05)
NASA TLX	7.21	< .01	.22	GE < GC1 (*p* < .01), GE < GC3 (*p* < .01), GE < GC2 (*p* < .05)
ARCS	5.66	< .01	.18	GE > GC1 (*p* < .01), GE > GC3 (*p* < .05), GC2 > GC1 (*p* < .05)
Content test	9.01	< .01	.26	GE > GC1 (*p* < .01), GE > GC3 (*p* < .05), GC2 >GC1 (*p* < .05)

The analyses confirm that EG achieved the best results in MRT, SVT, ARCS, and content testing, significantly outperforming the control groups. Furthermore, EG showed the lowest cognitive load in NASA TLX, indicating that this methodology facilitates learning with less mental effort.

4.1.3. Pearson correlation matrix

To analyse the relationship between the key variables in the study, the Pearson correlation matrix was calculated, which evaluates the association between NASA TLX, ARCS, MRT, SVT and the content test.

As shown in Table 6, there is a negative correlation between NASA TLX and the other variables, indicating that lower cognitive load is associated with higher motivation, better performance in spatial skills, and better results on the content test. In particular, the strongest relationship is with MRT ($r = -.58$, $p < .01$), suggesting that students with lower cognitive effort tend to score higher on spatial skills. On the other hand, ARCS shows a significant positive correlation with MRT ($r = .59$, $p < .01$) and with the content test ($r = .63$, $p < .01$), confirming that higher motivation is associated with better academic performance and spatial skills.

Table 6

Pearson correlations between the main variables in the study.

Variable	NASA TLX	ARCS	MRT	SVT	Content test
NASA TLX	1	-.55**	-.58**	-.50**	-.48**
ARCS	-.55**	1	.59**	.51*	.63**
MRT	-.58**	0.59**	1	.69**	.65**
SVT	-.50**	.51*	.69**	1	.54*
Content Test	-.48**	.63**	.65**	.54*	1

Note: *p < .05, **p < .01 (two-tailed).

4.1.4. Covariance analysis (ANCOVA)

To control for the effect of covariates such as prior knowledge and familiarity with ICT, an ANCOVA was applied, using the teaching method as the independent variable. This analysis made it possible to determine whether differences in student performance persisted after adjusting for these variables, ensuring that the effects observed were attributable to the methodology used and not to external factors.

Table 7 shows the results of the ANCOVA for MRT, where it can be seen that both prior knowledge ($F = 12.05$, $p < .01$, $\eta_p^2 = .14$) and familiarity with ICT ($F = 7.21$, $p < .01$, $\eta_p^2 = .09$) influence performance. However, the teaching method continues to have a significant effect on MRT ($F = 12.42$, $p < .01$, $\eta_p^2 = .33$), indicating that the methodology applied has a considerable impact on the development of spatial skills, even after controlling for these covariates.

Table 7

ANCOVA results for MRT.

Source of variation	SC	gl	CM	F	*p*	η_p^2
Covariate 1	154.27	1	154.27	12.05	< .01	.14
Covariate 2	92.33	1	92.33	7.21	< .01	.09
Teaching method	280.52	3	93.51	12.42	< .01	.33
Error (residual)	571.20	74	7.72			
Total	1098.32	79				

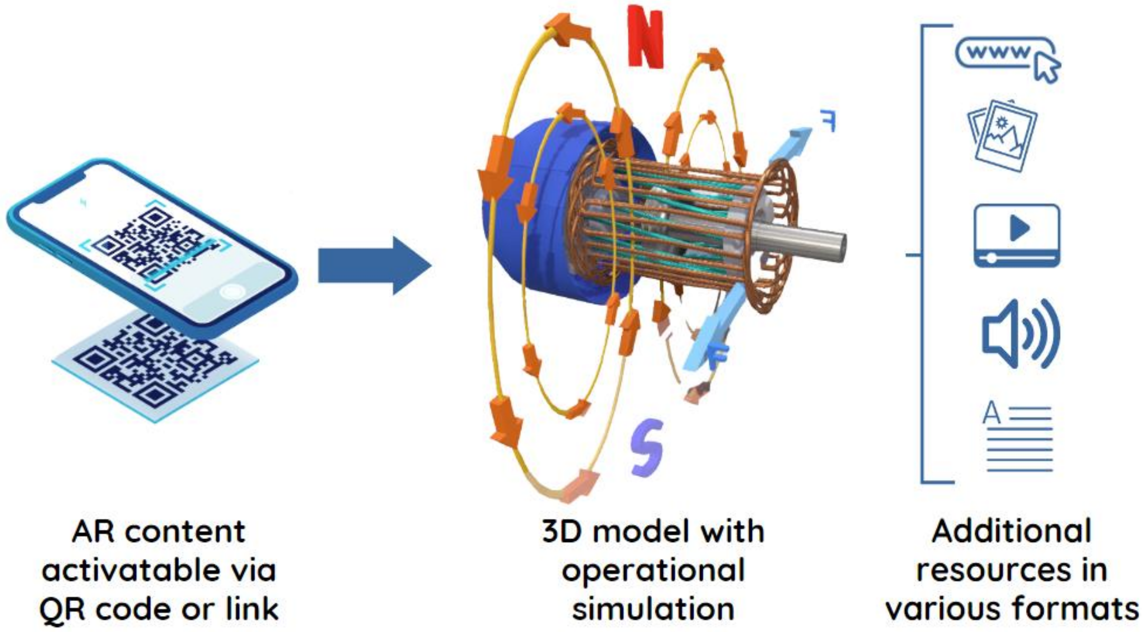
The ANCOVA results confirm that, even when adjusting for initial differences in knowledge and digital familiarity, the ‘teaching method’ factor continues to have a significant effect on MRT scores ($p < .01$, η_p^2=.33), reinforcing the robustness of the findings.

4.2. Visualisation of the AR prototype and physical laboratory

In order to illustrate the integration of AR in the study of the asynchronous induction motor, Figure 3 shows the process of activating and visualising the content in AR. To do this, the user does not need advanced knowledge of AR development, as it is sufficient to access the direct link or scan a QR code. This process is carried out using the Vuforia View app (version 9.23.1) for mobile devices, which employs a spatial recognition system based on artificial vision that eliminates the need for physical markers (markerless AR). This technology allows flat surfaces in the real environment to be identified with the device's camera, thus facilitating intuitive and accessible interaction with the superimposed virtual models.

Figure 3

Process of activating and viewing AR content.

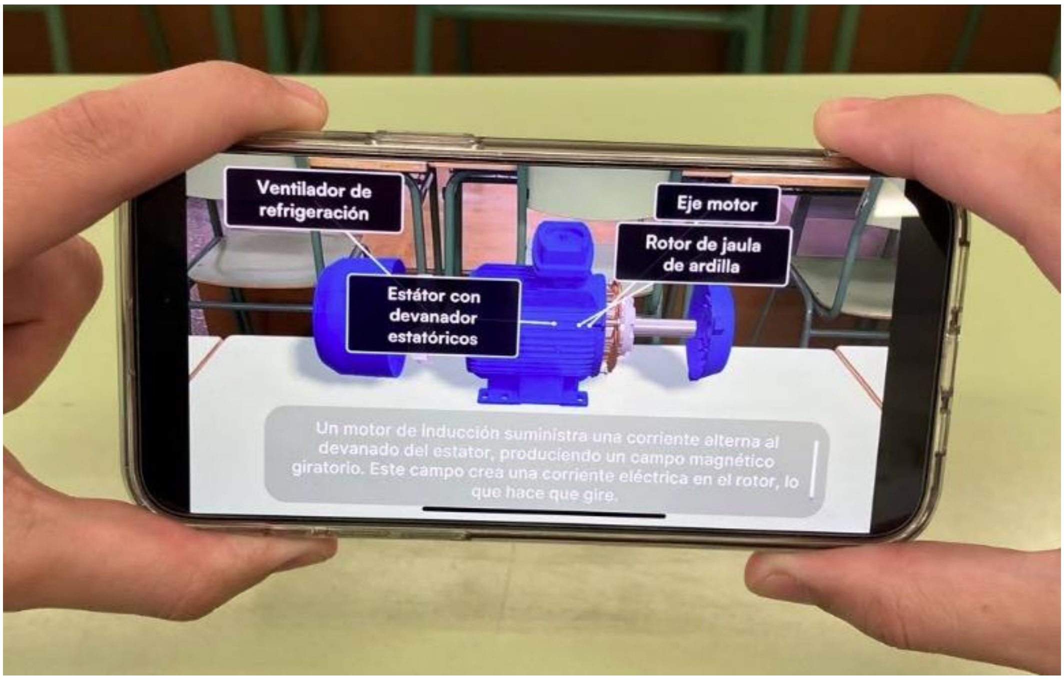


Source: Own elaboration.

Next, Figure 4 shows the augmented content activated on a smartphone developed in Unity (version 2023.2.20f1) using the Vuforia Engine package (version 10.20.3). The model integrates movement, animations, and interactive labels for the main components of the asynchronous induction motor (cooling fan, stator winding, squirrel cage rotor, and shaft), facilitating detailed exploration of its internal structure and operating principle.

Figure 4

3D design of an AR-enabled asynchronous induction motor in Vuforia View, showing the cooling fan, stator winding, squirrel cage rotor and motor shaft.

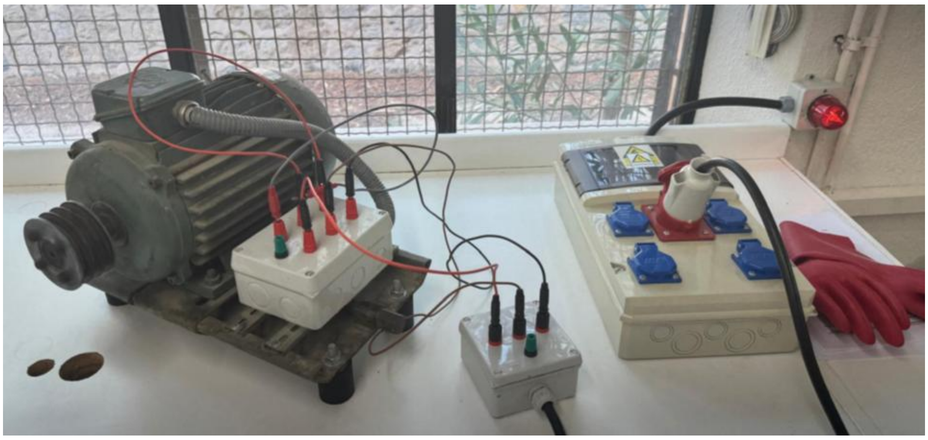


Source: Own elaboration.

Figure 5 shows the asynchronous induction motor in the engineering workshop (CG3), which was used for direct starting practice, in this case star-connected, and for measuring electrical variables (current, voltage, power factor). These practical experiments made it possible to compare, in a real environment, the results obtained with digital and AR methods.

Figure 5

Asynchronous induction motor in the workshop.



Source: Own elaboration.

4.3. Development of spatial skills

The effect of different methods on the acquisition and improvement of spatial skills was evaluated using the MRT and SVT. Table 8 shows the descriptive results (mean and standard deviation) obtained in the post-test for each test, as well as the mean gain values (Δ) compared to the pre-test.

Table 8

Descriptive results in spatial ability tests (MRT and SVT).

Group	MRT Post-test (Mean ± SD)	SVT Post-test (Mean ± SD)	Δ MRT	Δ SVT
EG	29.3 ± 3.1	25.8 ± 2.6	+7.2	+6.8
CG1	23.4 ± 2.9	20.5 ± 3	+4.5	+3.9
CG2	26.1 ± 3	22.7 ± 2.8	+5.9	+4.8
CG3	24.2 ± 2.5	21.1 ± 2.2	+5	+4.1

It was observed that the EG, which used AR on smartphones, achieved significantly higher values in MRT and SVT compared to the control groups. Δ was also higher in the EG, suggesting that the interactivity and immersion provided by AR created an environment conducive to the development of mental rotation and spatial visualisation skills.

ANOVA showed statistically significant differences in the final MRT ($F_{(3.76)} = 8.34$, $p < .01$) and SVT ($F_{(3.76)} = 9.11$, $p < .01$) values. Tukey's post hoc tests confirmed that the most pronounced difference was between the EG and the CG1 and CG3 control groups ($p < .01$). Although the group with 3D simulations using ANSYS Maxwell (CG2) also showed substantial improvements, their results were statistically inferior to those of the EG, although superior to those of CG1 and CG3 ($p < .05$).

4.4. Perceived cognitive load

The effect of different methods Cognitive load was assessed using the NASA TLX scale, administered at the end of each work session (immediate post-test). The factors analysed included mental demand, physical demand, temporal demand, effort, frustration, and perceived performance. Table 9 summarises the average values of the total cognitive load obtained by the participants in each group.

Table 9

Perceived cognitive load according to the NASA TLX scale (immediate post-test).

Group	NASA TLX (Mean ± SD)
EG	39.2 ± 5.8
CG1	47.5 ± 6.2
CG2	42.6 ± 5.5
CG3	45.8 ± 5.9

The ANOVA for perceived cognitive load (NASA TLX) showed significant differences between the groups ($F_{(3.76)} = 7.21$, $p < .01$). The EG reported the lowest levels of cognitive load, ranking below CG1 and CG3 ($p < .01$) and slightly below CG2 ($p < .05$). This finding supports the hypothesis that AR, by offering graphic and informative representations that are highly integrated with the physical environment, facilitates the distribution of cognitive processing and reduces the mental effort required to understand the configuration and operation of the asynchronous induction motor.

4.5. Student motivation

Motivation and perceived satisfaction were assessed using a 1-to-5 Likert scale questionnaire based on Keller's ARCS model (1987), which considers Attention, Relevance, Confidence and Satisfaction as key dimensions of commitment to the learning task. Table 10 details the mean scores for each dimension in the four study groups.

Table 10

Motivation results (ARCS model) in the post-test phase.

Group	Attention (A)	Relevance (R)	Confidence (C)	Satisfaction (S)	ARCS Global
EG	4.32 ± .47	4.2 ± .42	4.18 ± .4	4.35 ± .38	4.26 ± .32
CG1	3.86 ± .51	3.9 ± .56	3.72 ± .48	3.78 ± .50	3.81 ± .46
CG2	4.1 ± .44	4.06 ± .4	4.05 ± .42	4.11 ± .41	4.08 ± .39
CG3	3.94 ± .47	4.01 ± .46	3.96 ± .45	3.92 ± .44	3.96 ± .43

The ANOVA analysis confirmed statistically significant differences in the dimensions of Attention ($F_{(3.76)} = 6.79$, $p < .01$), Relevance ($F_{(3.76)} = 5.66$, $p < .01$), Confidence ($F_{(3.76)} = 5.1$, $p < .05$) and Satisfaction ($F_{(3.76)} = 6.02$, $p < 0.01$). The EG group had the highest scores in all dimensions of the ARCS questionnaire, highlighting the ability of AR to maintain attention, contextualise content in a relevant way and generate confidence in the execution of practical tasks.

4.6. Performance in the content test

Academic performance and the transfer of technical learning about asynchronous induction motors were measured using a content test designed by the teaching team, consisting of theoretical questions and practical application exercises, as detailed in the methodology section. Table 11 shows the overall average score for this test (scale of 0 to 10 points), as well as the proportion of correct answers in the practical exercises on star-delta connection and the calculation of currents and powers.

Table 11

Content test results.

Group	Overall score (0-10)	Correct answers in practical exercises (%)
EG	8.64 ± .77	88.3
CG1	7.38 ± .81	74.5
CG2	8.05 ± .82	81.7
CG3	7.9 ± .7	79.6

The results indicate that EG obtained the highest scores in both the overall rating and the resolution of practical exercises, followed by groups GC2 and CG3. The ANOVA showed significant differences in the final score ($F_{(3.76)} = 9.01$, $p < .01$), with an effect size ($\eta^2 = .26$) suggesting a moderate impact of the AR methodology on academic performance in electrical engineering content. Tukey's post hoc comparisons revealed significant differences between EG and GC1 ($p < .01$), as well as between EG and CG3 ($p < .05$), confirming the superiority of the AR-based method in facilitating theoretical and practical understanding of the asynchronous induction motor.

4.7. Correlational analysis and joint effects

Pearson correlations were explored between cognitive load (NASA TLX), motivation (ARCS), spatial skills performance (MRT, SVT) and content test scores, as previously presented in Table 6. Significant inverse correlations were found between NASA TLX and academic variables (MRT, SVT, ARCS, Grade), as well as positive and statistically relevant correlations between spatial skills and content test scores.

The negative coefficients between NASA TLX and MRT/SVT ($r = -.58$, $r = -.5$) support hypothesis H_4, indicating that lower cognitive load translates into better results on spatial tests, suggesting that students who experience less mental effort have a greater ability to mentally manipulate three-dimensional representations.

Likewise, the negative correlation between NASA TLX and ARCS ($r = -.55$, $p < .01$) supports hypothesis H_2, as it indicates that students with lower cognitive load experience greater motivation in their learning process, reinforcing the idea that AR facilitates learning by better distributing the mental processing load.

On the other hand, the existence of a strong positive correlation between ARCS and the content test ($r = .63$, $p < .01$) validates hypothesis H_3, in that increased motivation directly leads to higher academic performance, i.e., students who are more involved in the teaching activity can achieve more meaningful and effective learning.

Finally, the positive association between MRT/SVT and the content test ($r = .65$ and $r = .54$, respectively) validates hypothesis H_1, such that students with better spatial skills obtain better grades in the final assessment, which highlights the relevance of developing these skills in electrical engineering education.

An ANCOVA was also carried out to control for differences in familiarity with digital tools and prior knowledge (Table 7). The model adjustment did not alter the statistical significance of the teaching method on the outcome variables, which reinforces the findings and confirms that AR is the main determining factor in improving student performance and motivation.

5. Discussion

The findings obtained from this research establish evidence of the effectiveness of AR as a teaching resource for addressing the learning of technical content in electrical engineering, specifically in the development of spatial skills, in reducing cognitive load, and in improving motivation levels among students.

One of the most important findings of this study is the positive effect of AR on the development of spatial skills, which were measured using standardised MRT and SVT tests. An improvement was observed in the EG, which used AR with smartphones to interactively visualise an asynchronous induction motor, compared to the CG in both tests. The differences found are statistically significant, in addition to having relevant effect sizes, which shows that AR generates more suitable conditions for encouraging mental rotation processes, visualisation of three-dimensional representations, and spatial manipulation. This statement is related to the results of Singh et al. (2019), for whom augmented environments in electronics laboratories allow for a significant improvement in students' spatial skills. Along the same lines, research by Thees et al. (2020) indicates that remote laboratories with AR are capable of connecting physical interaction with virtual models, which benefits students' spatial learning of automation and industrial control concepts (Fidan y Tuncel, 2019).

From a cognitive point of view, given that AR showed a clear decrease in the cognitive load perceived by participants, as assessed by the NASA TLX scale, the result validates hypothesis H_2 that underpinned the study, in the same way as Sweller and Chandler's (1991) Cognitive Load Theory, which indicates that good learning design requires minimising extrinsic load in order to make way for germinal load. AR in our research promoted the distribution of information across several sensory channels: visual, spatial, and auditory, to enable parallel processing of knowledge. Kapici et al. (2019) had already detected that AR in the handling of electronic measuring equipment such as oscilloscopes and generators significantly reduces the cognitive load on students. Bogusevschi et al. (2020) also showed that interaction with augmented models leads to an appreciable decrease in mental effort. The effects described by Mejías Borrego and Andújar Márquez (2011) in the case of teaching electromagnetism were similar; they concluded that three-dimensional visualisation favours the construction of mental models and reduces the working memory load. Furthermore, previous research has already demonstrated the potential of augmented environments as cognitive support systems through immediate feedback (del Cerro & Morales 2017).

The correlations and covariance analyses performed in this study also corroborate the existence of a significant inverse relationship between spatial intelligence and cognitive load, as well as a positive correlation between motivation and content testing. Therefore, the results obtained validate hypothesis H_4 and reinforce the assertion that AR not only influences isolated variables, but also has a significant impact on cognitive, motivational, and performance factors. The same type of relationship is in line with the findings of Ibáñez and Delgado-Kloos (2018), who indicate that students with higher intrinsic motivation tend to achieve better concept retention and perform more accurately in practical tasks. Bautista et al. (2025) also concluded that the motivation produced by AR not only contributes to a better predisposition towards learning, but also has quantifiable effects on critical thinking and academic performance (Marini et al., 2022; Yang et al., 2023).

Student motivation measured using Keller's ARCS model also shows positive results. The EG group obtained significantly higher scores in the four dimensions of the model, demonstrating that augmented environments produce an autonomous, immersive, and satisfying learning experience. For their part, An et al. (2019) and Marini et al. (2022) agree that AR fosters interest and a sense of competence by allowing students to actively explore electrical devices. Similarly, Martín-Gutiérrez et al. (2015) stated that AR eliminates the fear of making mistakes when using expensive or dangerous equipment, which leads to greater self-confidence. In the same vein, Yang et al. (2023) highlighted the fact that augmented laboratories allow for autonomous and flexible learning, which generates greater satisfaction with the task and reduces the need for constant teaching guidance.

With regard to the academic test of the content, it was found that the EG performed significantly better than the three CG. This data demonstrates and reaffirms hypothesis H_1, which assumes that AR favours the transfer of knowledge from the theoretical to the practical level, as multiple studies have argued. Morales and del Cerro (2024) indicated in their study that students who used AR in industrial training environments improved their ability to apply technical concepts to real-world problem solving. Along the same lines, Kim and Irizarry (2021) indicate that augmented environments help students perform complex electrical installation procedures by improving accuracy and reducing the error rate, which coincides with the findings obtained in this study on the assembly and analysis of the induction motor in star-delta configuration.

From a methodological perspective, the study demonstrated the pedagogical and technical feasibility of AR on mobile devices, as supported by hypothesis H_5. The implementation of AR with Unity and Vuforia provided accessible, flexible, and low-cost means that point to the scalability of this technology in higher technical education. Asham et al. (2023) propose that the use of mobile technologies can help bridge the gap in access to immersive environments for curriculum integration during university and technical college education. Several studies (Chen et al., 2019; Achachagua & Chinchay, 2022) show that mobile AR applications are capable of replicating laboratory practices with high fidelity, even in distance learning contexts or those with limited laboratory equipment.

6. Conclusions

The research studies the effect of AR on the spatial skills of electrical engineering students and compares its applicability as a learning method with digital documents, three-dimensional simulators, and laboratories. The results show that the implementation of AR through mobile devices has clearly positive effects on STEM learning, specifically in engineering, the representation of spatial objects, and the mental manipulation of three-dimensional objects. Interaction with augmented environments improved students' spatial skills considerably more than CG. In addition, the immersive interactivity of AR is beneficial for cognitive processes related to mental rotation and spatial object representation, as it reduces students' cognitive effort.

From a motivational perspective, students who used AR showed greater attention, relevance, confidence, and satisfaction compared to those who used traditional methods.

Increased perception of learning ability and greater intrinsic motivation had a direct impact on academic performance.

The technical and pedagogical feasibility of AR has also been demonstrated, highlighting its ease of implementation through platforms such as Unity and Vuforia, which are effective, scalable, and economically viable for adoption in university technical curricula. Therefore, AR is considered an educational tool with unique potential to improve spatial skills, reduce cognitive load, and increase motivation, providing tangible benefits for training in electrical engineering and other STEM disciplines.

On the other hand, limitations related to sample size and intervention duration were identified, limiting the possible generalisation of the results. Furthermore, the study was limited to electrical engineering students only, suggesting that further studies are needed to explore the potential of AR in contexts related to STEM education.

Ultimately, future research directions point to the proposal of new studies with larger samples and longer interventions, as well as the exploration of the effect of AR on long-term learning and knowledge retention. Another avenue of research is to replicate the study by integrating other emerging technologies to compare best practices and methodologies in higher education.

Data Availability Statement

The dataset used in this study is available upon reasonable request to the corresponding author.

Ethics approval

Not applicable

Conflicts of interest

The authors declare that they have no conflicts of interest.

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How to cite:

Morales Méndez, G., del Cerro Velázquez, F., & Lozano Avilés, A.B. (2026). Realidad aumentada en el aprendizaje de materias STEM: desarrollo de habilidades espaciales en la formación en ingeniería eléctrica [Augmented reality in STEM learning: developing spatial skills in electrical engineering training]. *Pixel-Bit. Revista de Medios y Educación*, 75, Art. 3. https://doi.org/10.12795/pixelbit.117934