Augmented reality in teaching instrumentation in STEM subjects: immersive learning through PEARL in higher education

Realidad aumentada en la enseñanza de la instrumentación en materias STEM: aprendizaje inmersivo mediante PEARL en educación superior

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Abstract
The ability to comprehend and competently utilise instrumentation constitutes a foundational skill for students, particularly within the disciplines of science, technology, engineering, and mathematics (STEM). Nevertheless, restricted access to laboratories, the complexity of handling real equipment, and the need for expert supervision present considerable obstacles to safe and effective learning. In this context, PEARL (Paderborner Elektrotechnik Augmented Reality Labor) emerges as an innovative educational application that uses augmented reality (AR). This platform facilitates immersive interaction with tools such as oscilloscopes, function generators, and multimeters, thereby augmenting physical environments with additional information to simulate operations and procedures in real time. The present study employs a quasi-experimental approach, incorporating both control and experimental groups, in order to analyse the impact of the phenomenon under investigation on learning. The findings indicate substantial enhancements in technical proficiency and self-assurance among the cohort that utilised AR, along with elevated ratings concerning usability and user experience. These findings serve to reinforce the effectiveness of PEARL as a resource for the teaching of electronic instrumentation in higher education, helping to mitigate the limitations of traditional laboratories and promoting active, accessible, and safe learning methodologies.
Keywords: augmented reality, STEM education, electronic instrumentation, immersive learning, virtual laboratories.

Resumen
La comprensión y el manejo de la instrumentación es una habilidad fundamental para los estudiantes, especialmente en los campos de ciencia, tecnología, ingeniería y matemáticas (STEM). No obstante, el acceso restringido a laboratorios, la complejidad en el manejo de equipos reales y la exigencia de una supervisión experta presentan obstáculos considerables para un aprendizaje seguro y efectivo. En este marco, PEARL (Paderborner Elektrotechnik Augmented Reality Labor) emerge como una aplicación formativa innovadora que utiliza la realidad aumentada (RA). Esta plataforma permite a los usuarios interactuar de manera inmersiva con herramientas como osciloscopios, generadores de funciones, y multímetros, enriqueciendo los ambientes físicos con información aumentada para simular

operaciones y procedimientos en tiempo real. Este estudio analiza su impacto en el aprendizaje a través de un enfoque cuasi-experimental que incluye grupos de control y experimental. Los resultados muestran mejoras significativas en el rendimiento técnico y en la autoconfianza del grupo que utilizó RA, así como una valoración alta en términos de uso y experiencia de uso. Estos hallazgos refuerzan la efectividad de PEARL como recurso para la enseñanza de la instrumentación electrónica en educación superior, ayudando a mitigar las limitaciones de los laboratorios tradicionales y promoviendo metodologías de aprendizaje activas, accesibles y seguras.
Palabras clave: realidad aumentada, educación STEM, instrumentación electrónica, aprendizaje inmersivo, laboratorios virtuales.

1. Introduction

A cornerstone of university education is developing practical skills in STEM subjects (Science, Technology, Engineering and Mathematics). This is particularly important in subjects that require the manipulation and understanding of electronic instrumentation. This equipment is fundamental to acquiring skills in the measurement, analysis and interpretation of electrical and electronic signals, as well as topics related to circuit assembly and verification. Examples include oscilloscopes, function generators, multimeters and protoboards (Nursita & Hadi, 2021; Kanivets et al., 2022). However, despite the academic importance of teaching practical skills in electronic instrumentation, there are notable structural, logistical and pedagogical limitations.

Firstly, access to physical laboratories is often limited by the availability of materials, maintenance costs and the need for specialised supervision, reducing the number of practical hours available per student (Sandoval-Pérez et al., 2022; Singh & Ahmad, 2024). Limitations also arise from the high demand for equipment, hazards related to improper handling and the inability to repeat experiments outside the laboratory indefinitely (Meskhi et al., 2019; Pordanjani & Salehi, 2025). These factors result in many students failing to achieve a minimum level of proficiency by the end of their courses.

From this perspective, immersive technologies, particularly Augmented Reality (AR), have emerged as a highly promising tool for adapting technical instruction in higher education (Cheng & Tsai, 2013; Akçayır & Akçayır, 2017; Yoon et al., 2017). AR enables interactive virtual elements to be overlaid onto the physical environment in real time, creating a hybrid environment. In this setting, users can manipulate or visualise objects or phenomena that would be restricted in a traditional laboratory due to safety, cost or availability constraints (Bacca et al., 2014; Ibáñez & Delgado-Kloos, 2018). AR increases accessibility to practical experiences and enhances active learning, self-efficacy and student motivation (Garzón et al., 2019; Al-Ansi et al., 2023).

Numerous studies have demonstrated the benefits of AR in STEM education, identifying improvements in performance and learning retention, as well as its link with the development of procedural skills (Di Serio et al., 2013; del Cerro & Morales, 2021; Tene et al., 2024). In electronic instrumentation, the Augmented Reality for Electronics Learning (AUREL) study showed that using virtual device models followed by augmented contextual guides allows students to learn and apply complex concepts more quickly and accurately (Ang & Lim, 2019). However, many previous implementations have suffered from technical limitations associated with marker-based dependency, unnatural interaction or poor integration of automatic assessment systems.

To address these limitations, the Paderborner Elektrotechnik AR Labor (PEARL) educational solution for standalone headsets, such as the Meta Quest 3, has been developed. It enables direct (gestural) interaction with simulated electronic instrumentation without the need for markers, providing immediate feedback and integrated assessments. The training environment includes modules covering the use of an oscilloscope, function generator, multimeter and protoboard, enabling practical sessions that realistically reproduce the activities of a physical laboratory in terms of visuals, interaction, technology and functionality.

This study aims to evaluate the impact of PEARL on the technical performance, self-efficacy and motivation of university students on basic electronics courses. A quasi-experimental study was designed with two non-equivalent groups (experimental and control) and pre- and post-test measures. Two working hypotheses were formulated:
H_1: The experimental group using PEARL will demonstrate statistically significant improvements in technical knowledge acquisition compared to the control group.
H_2: Using PEARL will increase perceived self-efficacy and motivation for practical learning in electronic instrumentation.

Empirical validation of this proposal provides scientific evidence of the potential of AR as a training tool in higher technical education. Furthermore, it contributes to the evidence base for pedagogical guidelines on integrating AR into STEM curricula with the aim of improving the quality, accessibility and efficacy of learning in technical environments.

2. Theoretical framework

2.1. Augmented reality in education

Augmented reality (AR) technology enhances the user's physical environment by overlaying digital content, such as 3D models, images, data or audio, in real time (Azuma, 1997; Carmigniani & Furht, 2011). By contrast, virtual reality (VR) replaces the physical world with an entirely digital one; AR, however, uses the physical world as a reference point, enriching it with digital information. This makes AR especially useful in educational contexts that involve interaction with physical reality (Wu et al., 2013; Yoon et al., 2017).

Technological advancements in computer vision, depth sensors and graphics processing have led to the development of educational AR platforms. Initially, these focused on personal computers (PCs) and webcams, incorporating marker-based tracking systems (Billinghurst & Kato, 2002; Pérez-López & Contero, 2013). Currently, markerless tracking systems are utilised on mobile devices and standalone headsets such as the Meta Quest 3, which integrate gesture tracking without requiring additional equipment (Syberfeldt et al., 2017; Morales & del Cerro, 2025).

Specialised literature provides evidence that AR significantly enhances education, particularly in technical learning involving a substantial visual component and high procedural complexity. Various studies have shown that using AR increases students' intrinsic and extrinsic motivation by providing more immersive, interactive and contextualised learning experiences, thereby promoting sustained interest in the content (Radu, 2014; Palacios-Rodríguez et al., 2024; Bautista et al., 2025). This increase in motivation may also stem from a greater willingness to tackle complex tasks and improved perseverance when facing technical challenges.

Furthermore, AR improves knowledge retention and transfer by enabling the consolidation of information over the medium and long term, and its application to other scenarios, problems, or challenges. This can include the development of visuospatial skills, for example. Cheng & Tsai (2013) and Ibáñez et al. (2014) confirm that manipulating virtual representations embedded in a physical space combined with observing real-time dynamic phenomena favours the encoding of information and its subsequent retrieval. This benefit has also been demonstrated in studies such as those by Morales-Méndez and Lozano-Avilés (2025), which show that using AR to teach volumetric geometry significantly improves students' spatial intelligence. This is because technologies that integrate spatial representation can foster cognitive skills that can be transferred to various STEM disciplines.

In the context of procedural competencies, AR enables technical operations to be simulated with a high level of visual and functional accuracy, thereby facilitating the development of operational skills in a safe environment prior to handling real equipment (Martín-Gutiérrez et al., 2010; Fonseca et al., 2015; Del Moral-Pérez et al., 2025). For example, Chaljub-Hasbún et al. (2025) assessed the use of a VR resource for teaching the oscilloscope, noting improvements in students' understanding of its functions and confidence in using it independently.

Furthermore, AR can be characterised by its integration of immediate feedback mechanisms and unlimited repetition of activities without cost or logistical constraints, thus directly promoting autonomous and self-regulated learning (Akçayır & Akçayır, 2017; Garzón et al., 2019). These attributes are highly relevant in STEM discipline training, where autonomous problem solving, time management and self-assessment are considered key professional competencies in highly specialised environments.

2.2. AR applications in STEM education

AR has great potential for teaching in STEM fields, as it allows theoretical and practical content to be integrated within the same learning environment (Bacca et al., 2014; Ibáñez & Delgado-Kloos, 2018). The ability of AR to render abstract or invisible phenomena, such as electromagnetic fields or signal propagation, into observable representations helps to break down the cognitive barriers frequently encountered in technical instruction (Salmi et al., 2017; Garzón et al., 2019).

In electrical and electronic engineering, resources such as AUREL have been developed. This tool integrates virtual schematics and components onto a real workbench to support circuit assembly (Ang & Lim, 2019). Other resources include multimeter simulators that emulate taking virtual measurements alongside instructions on real-life operation (Nursita & Hadi, 2021), and oscilloscope simulators that perform measurements without risking equipment damage (Singh & Ahmad, 2024).

Findings from Garzón et al.'s (2019) review indicate that such solutions lead to a greater understanding of concepts, fewer procedural errors and increased student autonomy. However, limitations remain, including the absence of natural gestural interaction, the need for specific hardware and the lack of dedicated assessment systems (Bacca et al., 2014; Ibáñez et al., 2018).

2.3. AR use cases in electronic instrumentation

As electronic instrumentation involves complex procedural skills such as equipment configuration, understanding measurements and detecting connection errors, this area is considered well-suited to AR applications. Gutiérrez and Fernández (2014) demonstrated that using augmented oscilloscopes improves understanding of advanced functions and facilitates the transfer of skills to physical environments.

Similarly, AR has been shown to be beneficial in electronic prototyping, reducing the likelihood of wiring errors by providing augmented projections of connections and components (Fonseca et al., 2015; Alptekin & Temmen, 2018). AR has also been applied to the soldering process through augmented environments that enable safe training prior to actual manipulation (Yunus et al., 2025).

In this regard, PEARL,developed by the University of Paderborn with support from the Foundation for Innovation in University Teaching and involving software development engineers, developers and didactic experts, is a clear example. PEARL is characterised by its foundation in natural gestural interaction without the need for physical controllers, its completely markerless operation, its multiple modules (oscilloscope, function generator, multimeter and protoboard) and its assessment system which provides constant feedback.

As summarised in Table 1, a comparison with other systems documented in the literature reveals that PEARL is unique in combining natural gestural control, marker independence, high visual and functional fidelity, and multiple modules within the same headset. This, in turn, reinforces its potential as a training tool for electronic instrumentation in higher education.

Table 1

Technical comparison of AR-based systems for electronic instrumentation

Software	Interaction type	Marker dependency	Primary device	Integrated assessment	Visual fidelity	Functional fidelity	Available modules
AUREL (Ang & Lim., 2019)	Controllers and limited gestural	Yes, marker-based	PC + external camera	No	High	Medium	Basic oscilloscope, virtual multimeter
AR multimeter simulator (Alan, 2022)	Touchscreen + mobile AR	No, markerless	Tablet/ smartphone	Partial	Partial	High	Multimeter
AR oscilloscope (Singh & Ahmad, 2024)	Physical controllers	No, markerless	Semi-standalone AR headset	No	High	High	Digital oscilloscope
AR prototyping environment (Alptekin &	Gestural with haptic gloves	Yes, marker-based	PC + camera + haptic gloves	Partial	High	High	Protoboard, discrete components

Temmen, 2018)							
PEARL (Paderborn University, 2025)	Direct hand-based gestural	No, markerless	Standalone headset (Meta Quest 3)	Yes	Very high	Very high	Oscilloscope, function generator, multimeter, protoboard with virtual components

2.4. Pedagogical foundations of AR

The use of AR as an educational resource in training contexts is rooted in well-established learning theories in the field of educational research. According to the constructivist view of education, as articulated by Zajda (2021), knowledge is not passively transmitted, but actively constructed through interaction with the environment. This implies that complex concepts are best assimilated through practical, hands-on experience. This concept is aligned with the theory of situated learning (Lave & Wenger, 2001), which emphasises the importance of meaningful contexts for acquiring skills, as well as with Kolb's (2013) experiential learning model. This model posits that significant learning is based on an integrated cycle of experience, reflective observation, abstract conceptualisation and active experimentation.

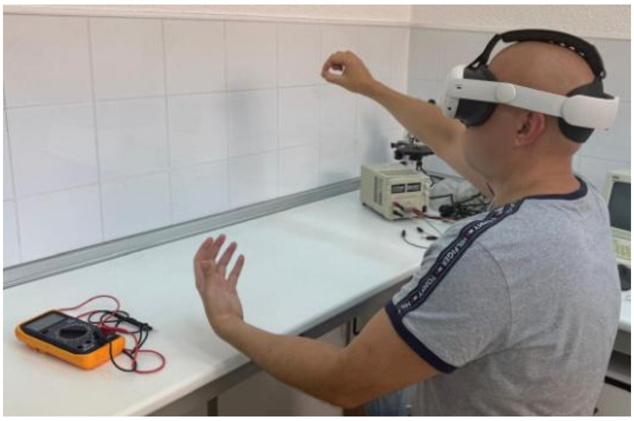
In the context of electronic instrumentation, AR enables strategies such as guided discovery and multimedia learning (De Jong & Lazonder, 2005) to be applied. These strategies encourage autonomous exploration within a supportive framework. AR also enables problem-based learning (PBL) (Hmelo-Silver, 2004) to be implemented, whereby students are presented with technical challenges to be solved creatively. AR enables contextual information and interactive processes to be superimposed onto physical environments. This enables students to virtually operate equipment such as oscilloscopes and function generators while receiving instantaneous feedback. Students can repeat the practice without the temporal or logistical constraints of a physical laboratory, and this mode of interaction fosters self-regulated learning (Zimmerman, 2002) and learning from errors (Keith & Frese, 2005). Mistakes become opportunities for improvement without the risk of damaging real physical equipment. These attributes are particularly crucial in fields that demand high-precision technical competencies, where practice is a determining factor in task proficiency.

There is growing empirical evidence that, when contextualised within a methodological design aligned with the curriculum and supported by advanced immersive technologies such as PEARL, AR enhances academic performance and intrinsic motivation (Di Serio et al., 2013; Garzón et al., 2019; Tene et al., 2024), as well as promoting long-term retention and the transfer of acquired knowledge to future situations. AR thus becomes a strategy for improving the quality and longevity of learning in specialised technical fields. This is particularly true of STEM disciplines, which require the simultaneous integration of theoretical knowledge and procedural skills.

3. Design and architecture of PEARL

PEARL is an AR application designed for standalone headsets, such as the Meta Quest 3. It is intended to optimise the teaching and learning of electronic instrumentation in higher education, particularly within engineering and science degree programmes. According to Azuma (1997) and Bacca et al. (2014), AR in educational contexts can overcome the limitations of physical laboratories, including restricted access to equipment, high maintenance costs and the requirement for supervisory teaching staff. Similarly, research by Ibáñez and Delgado-Kloos (2018) and Estrada et al. (2022) suggests that these technologies can reduce the risks associated with handling real equipment in laboratories. When running PEARL on headsets such as the Meta Quest 3 (Figure 1), users interact with augmented laboratories in which virtual elements that simulate electronic devices are superimposed. This allows for effective interaction utilising both physical and virtual spaces (López et al., 2024).

Figure 1
User interacting with PEARL in an augmented laboratory via a Meta Quest 3, showing superimposed virtual elements



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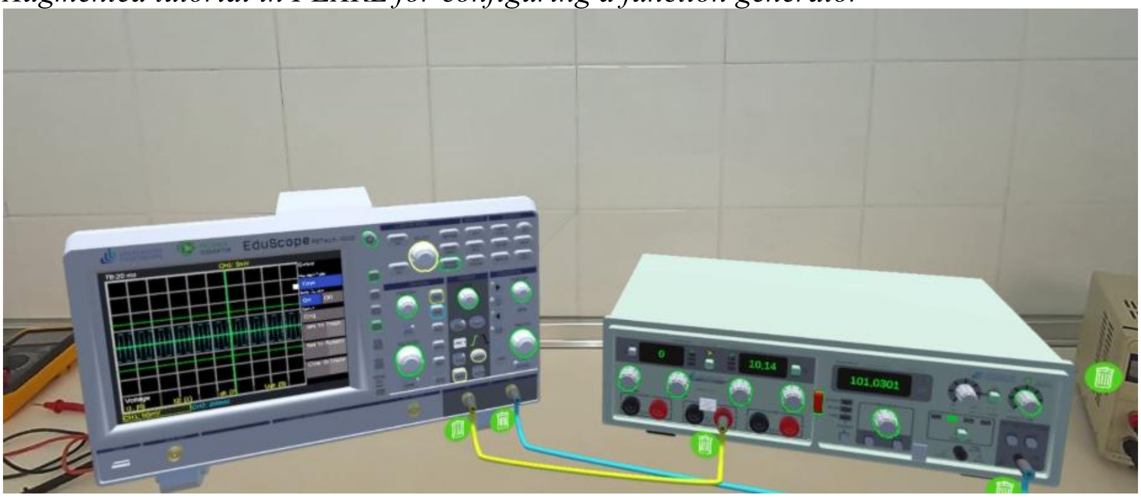
PEARL's functional design generates a high-fidelity augmented laboratory environment in which students can interact with essential instruments such as oscilloscopes, function generators, digital multimeters and protoboards. Each element has been 3D modelled with a high level of geometric precision and includes a physically coherent simulation, resulting in a true-to-life reproduction of the equipment's actual behaviour. Hand-tracking technology allows users to manipulate instruments with their hands and fingers, enabling natural interactions such as pressing or turning buttons, adjusting controls and moving or resizing devices freely within the augmented space. As affirmed by Singh & Ahmad (2024), this alternative eliminates the need for physical controllers and promotes intuitive and ergonomic forms of interaction. Similarly, research by Salmi et al. (2017) and Estrada et al. (2022) corroborates that this approach fosters immersion and the transfer of practical skills to real-world situations — a crucial characteristic in the training of engineers and scientists, as predicted by Mekni & Lemieux (2014). Figure 2 shows the initial interface of the introductory module. This was designed using the usability heuristics established by Nielsen (1994) to improve navigation and reduce cognitive load during the initial learning process.

Figure 2
PEARL start-up interface for selecting electronic instrumentation modules

Source: created by the authors

In terms of its technical architecture, PEARL leverages the Meta Quest 3's graphical capabilities to provide a high-performance, immersive environment, ensuring fluid interaction even in graphically intensive contexts. Stereoscopic rendering, for example, enables refresh rates in excess of 72 Hz. As indicated by Salmi et al. (2017) and Estrada et al. (2022), this plays an important role in reducing visual fatigue, resulting in less cybersickness and enabling prolonged use without negatively impacting the learning experience. Figure 3 illustrates this technical capability through an augmented tutorial for configuring a function generator. It guides students through the parameter setup process step-by-step, in line with Akçayır and Akçayır's (2017) recommendations on the importance of guided instruction in AR contexts.

Figure 3
Augmented tutorial in PEARL for configuring a function generator



Source: created by the authors

Regarding assessment management, PEARL has an internal database which stores the number of errors and successes achieved by the user during practical exercises. Execution times and interaction paths are not recorded in this database. Instead, these are captured via the telemetry and motion capture systems integrated into the Oculus Insight API and the Meta Interaction SDK (Boulo et al., 2024). These systems enable precise measurement of action sequences, task duration and spatial manipulation patterns for subsequent statistical analysis.

4. Methodology

This study uses a quasi-experimental design with non-equivalent groups and a pre-test/post-test measurement scheme to evaluate the impact of PEARL on electronic instrumentation learning. The sample comprised 40 students enrolled on the Electrical and Electronic Engineering course as part of the Chemical Engineering degree at the University of Murcia. According to the academic schedule, these students were organised into two groups for practical sessions: an experimental group (EG) and a control group (CG). None of the participants had prior experience of handling laboratory equipment such as oscilloscopes or function generators, ensuring a homogeneous baseline. The two intact class groups were pre-assigned to different time slots by the Registrar's Office. Condition assignment (EG/CG) was determined by logistical criteria (laboratory availability and scheduling), rather than randomisation. The same instructor, curriculum, temporal load and equivalent spaces and laboratories were used for both groups.

The intervention was conducted over four consecutive one-hour sessions. The pre-test, which included a technical knowledge test and psychometric scales to assess self-efficacy and motivation towards practical learning, was administered during the first half of the first session. The intervention phase spanned from the second half of the first session through to the third session. The EG used PEARL via Meta Quest 3 standalone headsets in a completely markerless AR environment, while the CG performed equivalent practicals in a traditional physical laboratory with the same real equipment. In both conditions, the activities aligned with curricular objectives and were supervised by the same instructor to ensure consistent instruction. The fourth session was dedicated to the post-test and final questionnaires. Data collection was carried out using three primary instruments.

First, the Technical Knowledge Test in Electronic Instrumentation (TKT-EI) (see Appendix I) was designed to assess the conceptual and procedural mastery of STEM university students in the use of oscilloscopes, function generators, multimeters and protoboards. The instrument consists of 20 multiple-choice questions with four response options (a–d), only one of which is correct. It includes both theoretical questions and practical problems. Content validity was established through the judgement of three electrical and electronic engineering professors. Internal consistency, as measured by Cronbach's α in an earlier pilot study, was found to be 0.87, indicating high reliability. This value was derived from an independent pilot study involving students from the same curriculum, who were given the test collectively the week before the intervention. This pilot verified item clarity, and minor wording adjustments were made where necessary.

Secondly, the Self-Efficacy Scale in Electronic Instrumentation (SE-EI) (see Appendix II) was designed. Comprising 12 items on a 5-point Likert scale (1 = strongly disagree; 5

= strongly agree), it focuses on students' perceived competence in handling electronic instrumentation, their ability to interpret measurements, and their capacity for resolving technical issues. The items were developed based on a review of self-efficacy literature (Pajares, 1996; Bandura, 2006) and adapted for STEM learning environments, specifically the context of electronic instrumentation. Content validity was established through expert judgement (n = 3) and the internal consistency obtained in a pilot study yielded a Cronbach's α of 0.84, indicating high reliability.

Finally, the Motivation Scale for Practical Learning in Electronic Instrumentation (MPL-EI) (see Appendix III) was administered. Consisting of 10 items in a 5-point Likert format (1 = strongly disagree; 5 = strongly agree), this scale is designed to measure students' interest, involvement and disposition towards laboratory practicals in electronic instrumentation. It was designed based on Keller's (2009) ARCS (Attention, Relevance, Confidence, Satisfaction) motivation model and previous studies on motivation in STEM education with immersive technologies (Di Serio et al., 2013; Garzón et al., 2019). Content validity was verified by a panel of three experts in engineering and technology didactics. The scale's internal consistency was 0.82, indicating adequate reliability for research purposes. This coefficient was estimated in a pilot study using a similar sample and administration procedure, and the comprehension and ordering of the items were reviewed before final implementation.

Data analysis included descriptive statistics (means, standard deviations and frequency distributions) and inferential analysis. Paired-samples t-tests were applied to compare pre-test and post-test results within each group, and independent-samples t-tests were used to contrast differences in gains achieved between groups. Additionally, a repeated measures analysis of variance (ANOVA) was performed to examine the interaction effect between time and experimental condition. The effect size was calculated using Cohen's d (1988) and interpreted according to the established criteria in the literature. The statistical significance level was set at $p < .05$ for all tests. The statistical analyses were conducted using IBM SPSS Statistics (v. 29) software, in accordance with the guidelines for quantitative educational research in technological environments (Creswell & Guetterman, 2024).

5. Results

The results are presented in accordance with international recommendations for the communication of quantitative research findings, incorporating descriptive statistics with 95% confidence intervals ($CI_{95\%}$), inferential analyses with verification of assumptions, and estimations of effect size with $CI_{95\%}$. The findings are then interpreted (Lakens, 2013; Cumming, 2014). Graphical representations are included to allow inspection of both data variability and individual participant trajectories.

To reduce the probability of incorrectly rejecting the null hypothesis in the context of multiple comparisons, the false discovery rate (FDR) control procedure proposed by Benjamini and Hochberg (1995) was applied. Effect sizes are expressed as d Cohen (1988) for independent comparisons, dz for paired comparisons, and η^2 for analysis of variance with repeated measures, employing, where appropriate, the Hedges correction to reduce bias in small samples (Morris & DeShon, 2002).

5.1. Technical performance (TKT-EI test)

Table 2 summarises the descriptive statistics for technical performance (TKT-EI test) by group and assessment time (pre-test and post-test), including sample size (N), mean ($\bar{x}$), standard deviation (SD), minimum and maximum values, standard error of the mean (SEM) and $CI_{95\%}$.

Table 2

Descriptive statistics for technical performance (TKT-EI) by group

Group	N	Time	$\bar{x}$	SD	Mín	Max	SEM	$IC_{95\%}$
EG	20	Pretest	8,35	1,94	5	12	0,43	[7,45; 9,25]
EG	20	Postest	14,10	2,15	10	18	0,48	[13,12; 15,08]
CG	20	Pretest	8,20	1,88	5	12	0,42	[7,33; 9,07]
CG	20	Postest	12,25	2,40	8	17	0,54	[11,18; 13,32]

The initial measurement (pre-test) revealed substantive equivalence between the EG ($\bar{x}$ = 8.35, SD = 1.94, $CI_{95\%}$ [7.45; 9.25]) and the control CG ($\bar{x}$ = 8.20, SD = 1.88, $CI_{95\%}$ [7.33; 9.07]), indicating comparable baseline conditions.

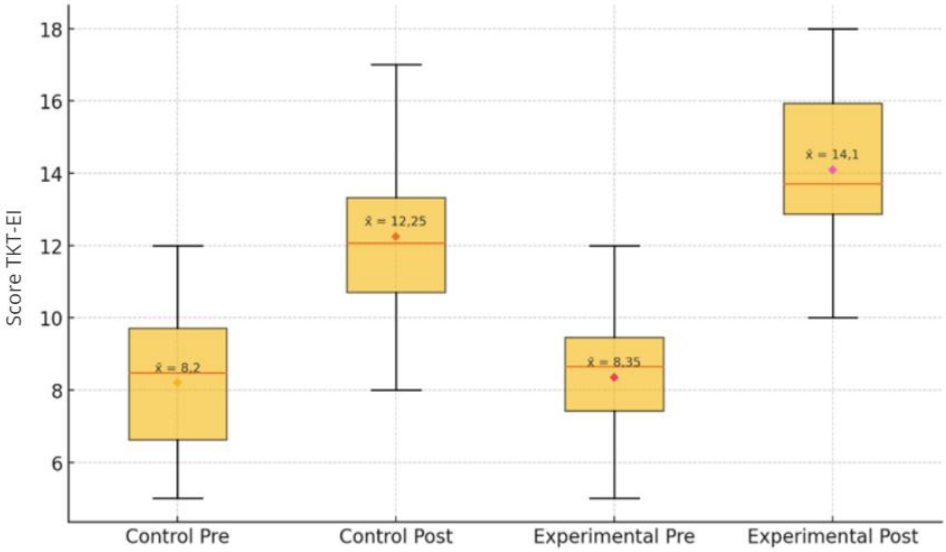
Following the intervention, a notable increase was observed in both groups. However, the magnitude of change was greater in the EG ($\bar{x}$ = 14.10, DT = 2.15, $CI_{95\%}$ [13.12; 15.08]) than in the CG ($\bar{x}$ = 12.25, DT = 2.40, $CI_{95\%}$ [11.18; 13.32]). This difference suggests an additional positive effect of using PEARL to enhance technical performance.

Shapiro–Wilk normality tests applied to the pre-post differences showed no statistically significant deviations ($p > .10$), indicating that the normal distribution assumption was met. Homogeneity of variances in the post-test was confirmed using Levene's test ($F(1,38) = 1.12$, $p = .296$). To verify the stability of the results, the contrasts were repeated using Yuen's t-test with 20% trimming and non-parametric tests (Wilcoxon/Mann–Whitney), yielding patterns of results congruent with those of the parametric analyses.

Figure 4 shows the distribution of scores for each group and assessment time using box plots. In the EG, the post-test shows a clear shift towards higher scores and reduced dispersion, indicating simultaneous improvements in precision and responses. Furthermore, a generalised performance increase is reflected by the increase in the median compared to the pretest. No extreme outliers were identified, suggesting that the improvement was consistent among most participants.

Figure 4

Pretest–posttest box plots by group



Source: created by the authors

5.2. Inferential analysis of performance

El análisis inferencial reveló que, en el GE, la puntuación media en la prueba PCT-IE aumentó de forma significativa del pretest al postest ($t(19) = 12{,}42$, $p < .001$), con un tamaño del efecto muy elevado d_z= 2,78, $IC_{95\%}$ [1,92, 3,60]). El grupo GC también mostró una mejora estadísticamente significativa ($t(19) = 8{,}15$, $p < .001$), aunque con una magnitud inferior (d_z= 1,82, $IC_{95\%}$ [1,13, 2,47]) (Tabla 3). Los resultados se mantuvieron al replicar los análisis mediante la *t* de Yuen con recorte al 20 % y pruebas no paramétricas de Wilcoxon, evidenciando la consistencia en los hallazgos.

The inferential analysis revealed that the mean score on the TKT-EI test increased significantly from pretest to posttest in the EG (t(19) = 12.42, p < .001), with a very large effect size (d = 2.78, $CI_{95\%}$ [1.92, 3.60]). The CG also showed a statistically significant improvement (t(19) = 8.15, p < .001), albeit of smaller magnitude (d = 1.82, $CI_{95\%}$ [1.13, 2.47]) (Table 3). These results were replicated using Yuen's t-test (20% trimming) and Wilcoxon non-parametric tests, demonstrating the consistency of the findings.

Table 3

Results of the paired-samples t-tests (pretest–posttest) for each group

Group	N	$\bar{x}_{Pretest}$	$SD_{Pretest}$	$\bar{x}_{Postest}$	$SD_{Postest}$	*t*	df	*p*	d_z	$CI_{95\%}$ d_z
EG	20	8,35	1,94	14,10	2,15	12,42	19	<.001	2,78	[1,92; 3,60]
CG	20	8,20	1,88	12,25	2,40	8,15	19	<.001	1,82	[1,13; 2,47]

In the intergroup comparison of post-test scores (Table 4), the EG performed significantly better than the CG (t(38) = 2.64, p = .012), with a large effect size (d = 0.83, $CI_{95\%}$ [0.18, 1.45]) and a nearly identical Hedges' g value (g = 0.81, $CI_{95\%}$ [0.17, 1.42]).

Table 4
Results of the intergroup comparison at posttest

Comparison	$\bar{x}_{EG}$	SD_{EG}	$\bar{x}_{CG}$	SD_{CG}	*t*	df	*p*	*d*	$CI_{95\%}$ *d*	*g*	$CI_{95\%}$ *g*
GE/GC	14,1	2,15	12,25	2,40	2,64	38	.012	0,83	[0,18; 1,45]	0,81	[0,17; 1,42]

A repeated measures ANOVA (2×2 mixed design) revealed a significant group-by-time interaction ($F(1, 38) = 8.41$, $p = .006$, $\eta_p^2 = 0.181$, $CI_{95\%}$ [0.022, 0.371]), suggesting that the improvement between the pre- and post-tests was more pronounced in the group that used PEARL. Furthermore, a statistically significant main effect of time was observed ($F(1, 38) = 162.90$, $p < .001$), while the main effect of group at pre-test did not reach significance ($p = .761$), which supports baseline equivalence between the two groups. To control for potential initial imbalances, an ANCOVA was performed using the pre-test score as a covariate. This yielded a similarly significant effect of group on the post-test ($F(1, 37) = 6.92$, $p = .012$).

5.3. Self-efficacy and motivation

The descriptive and inferential results for the SE-EI (self-efficacy) and MPL-EI (motivation) scales are presented in Table 5. For self-efficacy, the EG showed a significant increase from the pretest ($\bar{x}$ = 3.10, SD = 0.45) to the posttest ($\bar{x}$ = 3.95, SD = 0.50), with a mean difference of 0.85 points ($CI_{95\%}$ [0.64; 1.06], $t(19) = 9.28$, $p < .001$, d = 2.08, $CI_{95\%}$ [1.31; 2.81]). The CG also improved, albeit to a lesser extent ($\bar{x}$ = 3,05, SD = 0,48 to $\bar{x}$ = 3,40, SD = 0,52; $\Delta\bar{x}$ = 0,35, $CI_{95\%}$ [0,01; 0,69], $t(19) = 2,18$, $p = .041$, d_z = 0,49, $CI_{95\%}$ [0,02, 0,94]).

Table 5
Descriptive and inferential statistics for self-efficacy (SE-EI) and motivation (MPL-EI) by group

Variable	Group	Pretest $\bar{x}$ (SD)	Postest $\bar{x}$ (SD)	$\Delta\bar{x}$	$CI_{95\%}$ $\Delta\bar{x}$	*t*	df	*p*	*dz*	$CI_{95\%}$ *dz*
Self-efficacy	EG	3,10 (0,45)	3,95 (0,50)	0,85	[0,64; 1,06]	9,28	19	<.001	2,08	[1,31; 2,81]
Self-efficacy	CG	3,05 (0,48)	3,40 (0,52)	0,35	[0,01; 0,69]	2,18	19	.041	0,49	[0,02; 0,94]
Motivation	EG	3,60 (0,40)	4,30 (0,42)	0,70	[0,51; 0,89]	8,43	19	<.001	1,88	[1,14; 2,60]
Motivation	CG	3,55 (0,38)	3,80 (0,40)	0,25	[0,00; 0,50]	2,09	19	.05	0,47	[0,00; 0,92]

In terms of motivation, the EG advanced from an average of 3.60 (SD = 0.40) to an average of 4.30 (SD = 0.42), with a change in average of 0.70 ($CI_{95\%}$ [0.51; 0.89], $t(19) = 8.43$, $p < .001$, d = 1.88, $CI_{95\%}$ [1.14; 2.60]). Meanwhile, the CG experienced a smaller increase (from $\bar{x}$ = 3.55, SD = 0.38 to $\bar{x}$ = 3.80, SD = 0.40; $\Delta\bar{x}$ = 0.25, $CI_{95\%}$ [0.00; 0.50], $t(19) = 2.09$, $p = .05$, dz = 0.47, $CI_{95\%}$ [0.00; 0.92]).

In the intergroup post-test comparisons, the differences favoured the EG in both self-efficacy and motivation, with large and moderate effect sizes, respectively. As the scales are Likert-based, convergence of the findings was verified using non-parametric Mann–Whitney U tests, yielding patterns consistent with the parametric analyses.

Table 6 shows that the improvement in technical performance (ΔTKT-EI) positively and significantly correlated with the increase in self-efficacy (ΔSE-EI): r = 0.56, $CI_{95\%}$ [0.17;

0.79], p = 0.009. Conversely, the correlation with the change in motivation (ΔMPL-EI) was positive but not significant (r = 0.29, $CI_{95\%}$ [−0.16; 0.64], p = 0.206).

Table 6.

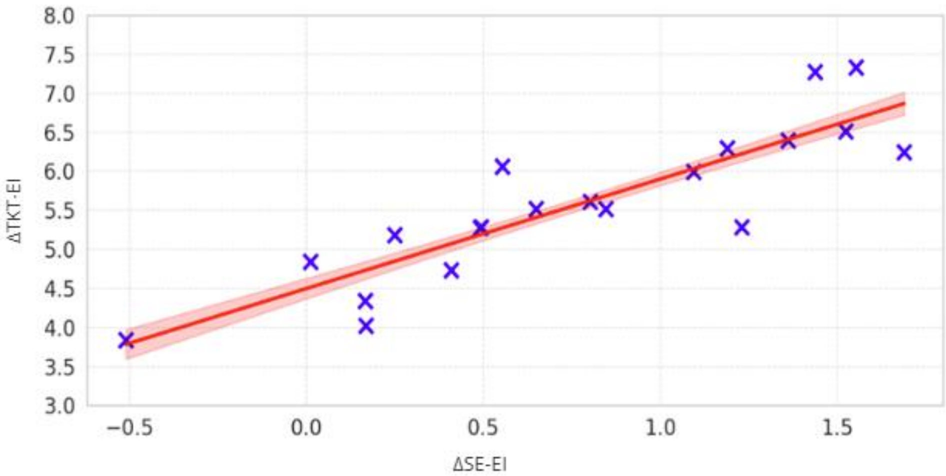
correlations between self-efficacy, motivation, and technical performance

Variables	*r*	$CI_{95\%}$	*p*
ΔPCT-IE vs. ΔEAIE	0,56	[0,17; 0,79]	.009
ΔPCT-IE vs. ΔEMAP-IE	0,29	[−0,16; 0,64]	.206

Figure 5 illustrates these relationships graphically, depicting the association between ΔSE-EI and ΔTKT-EI using a scatter plot with a regression line and $CI_{95\%}$ prediction bands. Linear regression analysis indicated that this relationship can be described by the equation ΔTKT-EI = 2.14 + 2.06 · ΔSE-EI, with an R^2 value of 0.224. This suggests that approximately 22.4% of the variability in technical performance improvement is explained by an increase in self-efficacy, indicating a moderately strong positive relationship.

Figure 5

Scatter plot of ΔSE-EI vs. ΔTKT-EI with $CI_{95\%}$. band



Source: created by the authors

6. Discussion

The results obtained indicate that implementing PEARL is an effective strategy for optimising learning in higher technical education, particularly with regard to electronic instrumentation. Descriptive and inferential analyses demonstrate that the EG achieved significant improvements in technical performance (TKT-EI) and self-efficacy measures, notably outperforming the CG. These findings are consistent with those reported by Bacca et al. (2014) and Ibáñez & Delgado-Kloos (2018) and suggest that interacting with virtualised devices in an immersive way, with the support of interactive guides and immediate feedback, improves the understanding of technical concepts and procedures, increases motivation and reduces the cognitive load associated with initially using real equipment (García et al., 2023; Cabero-Almenara et al., 2025).

The observed improvement is consistent with previous findings in the AR educational literature in STEM environments (Ibáñez & Delgado-Kloos, 2018), which demonstrate improvements in conceptual understanding, content retention and the ability to apply competencies when working with real instrumentation. Estrada et al. (2022) emphasise that integrating AR with object recognition and adaptive content systems facilitates personalised training, an approach also present in PEARL through the automatic generation of equipment and activation of specific training tutorials. This approach is an improvement on solutions based exclusively on markers (Azuma, 1997) as it enables direct interaction with real equipment without the need for additional anchoring elements, thus making the experience more natural and didactic.

From a methodological perspective, the present investigation adopted recommendations for quantitative, technology-based studies (Lakens, 2013; Cumming, 2014), including estimation of effect size magnitude and contextualised interpretation. The magnitude of the observed effects suggests that PEARL has a significant impact on students' technical competence rather than yielding marginal improvements. This may be explained by the active, exploratory and self-regulated nature of the AR training experience, as demonstrated in previous research (Ibáñez & Delgado-Kloos, 2018; Morales & Lozano, 2025).

PEARL innovatively combines three key dimensions: (i) technological precision, through real-time hand recognition and object manipulation; (ii) immersive realism, thanks to interactive 3D models that simulate real equipment; and (iii) didactic flexibility, since the system can be used in uncontrolled environments, reducing dependence on physical laboratories and their associated infrastructure costs. This architecture addresses limitations identified in previous literature reviews (Bacca et al., 2014; del Cerro & Morales, 2018; Ibáñez & Delgado-Kloos, 2018) and provides a foundation for a more flexible, accessible model for teaching electronic instrumentation at university level.

PEARL's integration as an educational tool is based on principles of manipulative learning, aligning with approaches such as learning by doing and challenge-based learning. This allows theoretical knowledge to be applied in a safe, controlled environment, thereby consolidating technical skills and competencies. As highlighted by Estrada et al. (2022), this approach increases active student involvement, encourages the deliberate repetition of procedures to reinforce skill development and allows experimentation without the risk of damaging equipment or endangering personnel.

Despite the achievements of this research, it is important to note certain limitations. While the sample size was sufficient to detect significant effects, it was limited and may not be representative of the broader student population's heterogeneity. Similarly, the tests were conducted under controlled lighting and spatial layout conditions, as extreme variations in these elements could affect the quality of the immersive experience and consequently the success of object recognition. Finally, the medium- to long-term effects on learning retention and the transfer of acquired competencies to the use of real equipment should be verified. These aspects constitute areas for future research into the efficacy of PEARL.

7. Conclusions

The present study has demonstrated that AR environments, and the PEARL system in particular, are an effective pedagogical strategy for optimising learning in electronic instrumentation for STEM degree programmes at higher education level. Significant improvements in technical performance, self-efficacy and motivation were observed among students using PEARL, compared to those conducting practices solely in a conventional physical laboratory.

Furthermore, inferential analysis revealed large effect sizes across the three evaluated dimensions. This suggests that the PEARL system has a considerable impact on the acquisition and consolidation of procedural STEM competencies, rather than producing marginal improvements. This impact is associated with the system's ability to provide highly immersive visual and functional experiences featuring natural gestural interaction, immediate feedback and the option to repeat practicals without logistical constraints or risk to personnel or equipment.

In pedagogical terms, the architecture and instructional design employed by PEARL represent a considerable advancement toward the principles of experiential learning, facilitating active student involvement, self-regulated learning, and the transfer of knowledge to real-world practice. Moreover, its design eliminates dependencies on additional hardware and markers, thereby increasing its portability and versatility, and overcomes the limitations identified in previous AR implementations for electronic instrumentation.

These findings suggest that the PEARL system is a tool with high potential for the digital transformation of electronic instrumentation education. It serves to improve the accessibility, quality, and efficacy of practical learning in STEM fields and contributes to developing the technical competencies required for professional practice in engineering and science.

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Appendix I

Technical Knowledge Test in Electronic Instrumentation (TKT-EI)

Item	Question	Response options	Correct response	Technical justification
1	In a digital oscilloscope, what parameter must be adjusted to prevent aliasing when viewing high-frequency signals?	a) Vertical scale b) Time base c) AC coupling d) Bandwidth limit	b	Adjusting the time base increases the effective sample rate, preventing undersampling and signal distortion.
2	The "AC coupling" control on an oscilloscope is used to:	a) Filter DC components b) Filter AC components c) Increase vertical resolution d) Reduce thermal noise	a	AC coupling inserts a series capacitor that blocks the DC component, allowing only AC variations to be seen.
3	If a function generator is set to 1 kHz and 4 Vpp, what does "Vpp" mean?	a) Average voltage b) RMS voltage c) Peak-to-peak voltage d) Positive peak voltage	c	Vpp corresponds to the voltage difference between the positive maximum and the negative maximum of the signal.
4	What is the purpose of the trigger control on an oscilloscope?	a) Stabilize the signal's display b) Expand the bandwidth c) Filter unwanted harmonics d) Increase the sample rate	a	The trigger synchronizes the screen sweep with a specific point on the signal, preventing the display from "rolling."
5	On a digital multimeter, the 200 Ω range indicates:	a) Maximum precision for low resistances b) Lower measurement limit c) Overload protection d) High-precision autoranging	a	On low ranges, the resolution is higher for small values, optimizing precision for low resistances.
6	What happens if an oscilloscope with AC coupling is connected to a pure DC signal?	a) The signal is amplified b) The DC component is blocked c) The signal is inverted d) A vertical shift occurs	b	The AC coupling capacitor prevents DC current from passing, resulting in a flat line.
7	On a function generator, the offset control allows you to:	a) Change the waveform shape b) Shift the signal relative to the reference level c) Reduce high-frequency noise d) Increase the peak-to-peak amplitude	b	The offset adds or subtracts a DC value from the AC signal, modifying its vertical position.
8	On a protoboard, the central rows of five perforations are connected:	a) Horizontally b) Vertically by columns c) Diagonally d) Only by the outer rows	b	Each column of five holes is electrically connected to facilitate component mounting.
9	An oscilloscope with a 20 MHz bandwidth can adequately measure signals:	a) Up to 10 MHz b) Up to 15 MHz c) Up to 20 MHz d) Up to 25 MHz	c	The bandwidth specifies the maximum frequency at which the equipment maintains amplitude without significant attenuation.
10	The RMS value of a pure sine wave is calculated as:	a) Peak value × 0,5 b) Peak value / √2 c) Peak value × √2 d) Peak value / 2	b	For pure sine waves, RMS = Vp / √2, where Vp is the absolute maximum value.
11	When measuring alternating current (AC) with a	a) Affects the reading b) Does not affect the reading c) Inverts the numerical display d) Nullifies the reading	b	In AC, the reading is independent of polarity, as the current changes direction periodically.

Item	Question	Response options	Correct response	Technical justification
	multimeter, the polarity of the probes:			
12	The "rise time" on an oscilloscope is related to:	a) The signal's amplitude b) The response capability to transients c) The ambient temperature d) The coupling type	b	Rise time is the time the signal takes to go from 10% to 90% of its final value, reflecting the response to transients.
13	On a function generator, a 50% duty cycle means:	a) High time equals low time b) Signal has no odd harmonics c) A perfect triangle wave d) Maximum amplitude	a	A 50% duty cycle indicates equal duration for the high and low levels of the signal.
14	To minimize errors when measuring very low voltages, it is recommended to use:	a) A high measurement range b) Short and shielded cables c) Long, unshielded cables d) A low-pass filter in parallel	b	Short, shielded cables reduce noise pickup and voltage drops.
15	A capacitor connected to an oscilloscope's input:	a) Filters high frequencies b) Filters low frequencies c) Increases the signal's amplitude d) Decreases the bandwidth	b	The capacitor acts as a high-pass filter, attenuating low frequencies.
16	An unstable and shifted signal on an oscilloscope:	a) Increase the time base b) Adjust trigger and DC coupling c) Reduce vertical amplitude d) Activate XY mode	b	Adjusting the trigger and using DC coupling stabilizes and centers the signal on the screen.
17	Measuring resistance on a protoboard without disconnecting the component:	a) Measurement is not possible b) Measure and subtract circuit resistance c) Use the compensation method d) Measure in parallel and average	c	The compensation method allows isolating the component's value by compensating for parasitic resistances.
18	To obtain Vpp, period, and frequency from a capture:	a) Calculate frequency and estimate amplitude b) Measure amplitude and period, calculate frequency c) Use auto-scale settings d) Measure duty cycle and calculate amplitude	b	By measuring amplitude and period, the frequency can be derived and Vpp confirmed.
19	Function generator setup for a 10 kHz, 3 Vpp, 25% duty cycle square wave:	a) Square wave, 10 kHz, 3 Vpp, 25% duty b) Triangle wave, 10 kHz, 3 Vpp c) Square wave, 5 kHz, 6 Vpp d) Sine wave, 10 kHz, 3 Vpp	a	The specified configuration matches the exact requested values.
20	Common errors when measuring DC with a multimeter:	a) Incorrect polarity and poor contact b) Using the auto range c) High ambient temperature d) Low internal impedance	a	Reversing polarity or having a poor connection alters the reading or causes instability.

Appendix II

Self-Efficacy Scale in Electronic Instrumentation (SE-EI)

Ítem	Statement
1	I feel capable of configuring a digital oscilloscope to measure alternating (AC) and continuous (DC) signals.
2	I can correctly adjust the time base and vertical scale of an oscilloscope to obtain precise measurements.
3	I consider myself competent in using the trigger control to stabilize a signal's display.
4	I can accurately interpret the voltage and frequency measurements displayed on an oscilloscope.
5	I feel capable of setting up a function generator to produce signals with desired characteristics (waveform, frequency, amplitude, and offset).
6	I can measure voltages and currents safely and accurately using a digital multimeter.
7	I feel competent in measuring resistance and checking circuit continuity with a multimeter.
8	I can assemble a basic circuit on a protoboard following an electrical schematic.
9	I feel capable of identifying and correcting simple errors in circuit assemblies on a protoboard.
10	I can select the appropriate measurement scale on the oscilloscope based on the signal type.
11	I consider myself capable of integrating the use of several laboratory instruments to solve an experimental task.
12	I can work autonomously in an electronics laboratory, applying safe and correct procedures.

Appendix III

Motivation Scale for Practical Learning in Electronic Instrumentation (MPL-EI)

Item	Statement
1	I find it interesting to learn how to use electronic instrumentation equipment.
2	I feel curious about exploring new functions and configurations on laboratory instruments.
3	I enjoy practical sessions that involve using oscilloscopes, function generators, and multimeters.
4	Laboratory practicals help me better understand theoretical concepts.
5	I am motivated to solve technical problems in the laboratory on my own.
6	I believe that learning to use these instruments is relevant to my future professional career.
7	I strive to improve my skill in using electronic instrumentation.
8	The possibility of experimenting without risk in a safe environment increases my interest in the practicals.
9	I feel personal satisfaction when I successfully complete a measurement or an assembly.
10	I prefer practical activities with electronic instrumentation over exclusively theoretical classes.