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Research paper

Linking The Physical and Digital: QR-Code–Powered Teaching Resources for Advancing Electrical Circuit Literacy

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Abstract

Electrical-circuit concepts often remain abstract for novices, and conventional print-based resources provide limited interactivity. This study examined whether QR-code, powered teaching materials, which seamlessly link physical worksheets to digital simula-tions and micro-videos, enhance students' electrical-circuit literacy compared with traditional instruction. A quasi-experimental pre-test/post-test design involved 128 first-year engineering students divided into experimental (QR) and control groups. Both groups received identical content over four weeks; only the experimental group accessed QR-embedded tasks that triggered circuit simula-tors, schematic animations, and instant quizzes. Data were collected with the validated Electrical-Circuit Literacy Test (ECLT) and an engagement questionnaire. Controlling for prior knowledge, ANCOVA evaluated learning gains, and thematic analysis explored student perceptions. After adjustment, the QR group outperformed the control group on the ECLT, representing a significant effect (Hedges g = 0.85). Engagement scores were significantly higher for interactivity (M = 4.32/5). Qualitative feedback highlighted "on-demand clarifications" and "self-paced trouble-shooting" as significant benefits. Embedding QR codes into circuit worksheets effectively bridges physical and digital learning spaces, yielding measurable conceptual mastery and engagement gains. Educators are encouraged to adopt scaffolded QR tasks and iterative feed-back loops to promote deeper, self-regulated learning in STEM courses.

Keywords: *Electrical-Circuit Literacy; Engineering Education; Interactive Learning; QR Codes; Technology-Enhanced Learning.*

1. Introduction

The adoption of Interactive and Multimodal Learning within Engineering Education fits well with the framework of Education 4.0, which incorporates smartphones, augmented reality (AR), and simulation software as teaching aids. To a greater degree than before, these technologies allow for richer dual-coding experiences where verbal directions are accompanied by visuals that explain the phenomena, thus decreasing cognitive load and increasing understanding in engineering contexts [1]. The digital environment has the potential to foster innovative teaching approaches, improving student involvement while teaching complex engineering ideas through hands-on activities [2]. Interactive Learning, as a specific construct with its pedagogy and toolkit, is one thing we do not want to negate. From this position, QR codes have become one of the best devices. It just happens that they are recognizable by being inexpensive and for making the union of specific hardcopy text with online conducive enhancements, like micro-videos and interactive simulations, nearly invisible. Systematic reviews have also found that STEM courses using QR codes encourage students to use them more frequently and increase motivation and engagement factors in many subjects [3]. These examples of utilizing QR codes to facilitate an overall cross-cutting learning necessitate educational institutions to integrate these technology practices [4], [5], demonstrating further the role of QR codes in theoretical-to-practical engineering education, as used here.
Despite new educational technologies, misconceptions in teaching basic circuits remain. Research has shown that high school students can have misconceptions about current and energy flow concepts even after completing traditional curricula. Many of these students, typically about 30 to 40%, already have misconceptions on voltage division and the operation of parallel and serial circuits when they transfer to higher education, as is reported in diagnostic tests [1], [6]. This lack of fundamental knowledge underscores the need for effective teaching methods that address and correct these misconceptions with the help of multi-faceted technological pedagogies [7].
Interactive methodologies such as gamefied approaches and simulations increase the interest as well as motivation of learners ([8], [9]. By decreasing extraneous cognitive load and increasing intrinsic engagement, they also embody the principles of cognitive load theory in an interactive format. Mechanical engineering education has benefited from the immersive experience of augmented reality and simulation tools since they are so rich in their characteristics, revolutionizing how students perceive complex engineering concepts[8]. The pace of

change brought about by technology in educational frameworks calls for a shift in pedagogy, moving away from static models to adapt to the requirements of a 21st-century learner. The impact of technology on pedagogy in engineering education remains an impetus for developing interactivity and multimodality in teaching and learning. The primary focus should be on utilizing these technologies to meet the educational objectives of various learners and addressing the gaps in understanding. Applying the research and systematically implementing these techniques will only further substantiate the impact of interactivity on enhancing the students' learning experience [2], [10].

Previous QR-code studies primarily focused on vocabulary learning or field-based science; few have thoroughly measured conceptual improvements in electrical circuits or compared results with a control group that received the duplicate content without the QR layer. The current study, therefore, explores whether adding QR links to interactive circuit simulators and annotated micro-videos within printed task sheets can significantly improve students' understanding of electrical circuits and their engagement.

RQ1. Does access to QR-code–powered teaching resources produce greater post-instruction gains in electrical-circuit literacy than traditional worksheets when prior knowledge is controlled?

H_1. After adjusting for pre-test scores, students in the QR group will outperform the control group on the post-test ECLT.

RQ2. How do students perceive the usability and motivational value of QR-mediated tasks?

H_2. QR-group learners will report significantly higher engagement and perceived usefulness scores than their counterparts.

By addressing these questions, the study aims to clarify the pedagogical value of linking physical and digital spaces through QR technology and to inform evidence-based integration strategies for STEM educators..

2. Literature Review

2.1. Cognitivist-load and dual-coding perspectives

Integrating the Cognitive Theory of Multimedia Learning (CTML) and dual-coding perspectives significantly impacts learning outcomes in educational contexts, particularly in science and engineering. These principles are consistent with the theory of CTML, which deepens our understanding of how a genuine learning event results from the verbal and visual channels. For example, Mayer's synthesis of evidence-based design principles in the CTML framework highlights effective strategies such as signalling, segmenting, and modality to decrease extraneous cognitive load and enhance generative processing during learning experiences [11]. This is congruent with the dual-coding research that suggests words and dynamic visuals are best matched, referring to how text synchronised with large, moving visuals boosts understanding in both the short and long-term memory. Another example is a study investigating the impact of picture-based schematic and brief text prompts on middle school education, revealing a large effect size [12].

In addition, integrating QR codes to pair print materials with interactive digital content demonstrates how multimedia components can tie together conventional learning objects. Since dual coding enables rapid switching between physical and digital representations, these QR-linked modules can increasingly handle sophisticated levels of cognitive load, resulting in more profound conceptual change. The widespread usage of QR codes is that they can be easily opened by the smartphone camera, which makes them a good means of engagement in educational purposes, especially in STEM education, where the use of static passive learning materials can be turned into interactive, dynamic experiences in understanding complex scientific ideas [13], [14]. Recent studies show that multimedia learning environments have been well accepted by students, helping them learn academic content with better visualisation of textual explanations.

Cognitive load theory, a key concept in understanding how learners interact with multimedia materials, establishes that the less intra-cognitive and extraneous cognitive load there is on an authorial stimulus construct (learnable element), the better overall learning outcomes. Downloadable PDF: Principles of multimedia learning by Mayer [15] emphasise the design of lessons in a structured manner with clear goals that prevent cognitive overload and lead students to deeper learning strategies. This is further supported by dual coding research, where structured representations activate prior knowledge and support knowledge construction through representing schematics well, helping visualise content, resulting in long-term recall of learned concepts [16]. The CTML mechanisms detailed in this paper, when combined with empirical results from dual-coding studies, suggest that new multimedia learning strategies, such as QR-linked modules explored here, may significantly enhance educational experiences. Discipline-based education research, particularly in physics, currently designs teaching and learning strategies that reduce cognitive load [2], supporting dual coding modes[17], [18].

2.2. Empirical work on QR-mediated resources

Over the past decade, QR codes have gradually entered STEM classrooms as a bridge between printed or physical media and interactive digital content. However, empirical integration in engineering education remains limited. A recent scoping review of QR-code use in STEM found that although QR tools are widely proposed for m-learning, few studies deeply examine their pedagogical design or learning outcomes in authentic instructional settings[19]. Tsoukala, Lefkos, and Fachantidis [20] noted a decline in QR-based intervention studies and a shift toward investigating teacher acceptance rather than student conceptual gains. In addition, a 2024 systematic review of pedagogical QR use identified 155 studies across disciplines, but pointed out that most focused on STEM broadly, with few targeting core engineering topics or employing robust experimental designs [21].

In parallel, virtual laboratories and immersive simulation environments continue to gain traction in STEM education. A 2025 study on cloud- and IoT-powered virtual labs argued they can offer scalable, real-time experimental access and richer interactivity for STEM learners while highlighting infrastructure, security, and pedagogical adaptation challenges in real classrooms[22]. Similarly, a recent investigation of VR/immersive labs across undergraduate STEM domains (2025) found significant gains in conceptual understanding and student self-efficacy, albeit with persistent technical barriers such as ergonomics and onboarding overhead [23]. These advances suggest combining QR linkages with virtual lab modules may offer a promising hybrid pathway, anchoring tangible materials in the physical domain while enabling interactive simulation access.

Thus, the current study builds on these emerging trends by embedding QR-code-linked digital simulations into physical circuit activities. It seeks to address gaps in prior work by testing effects on conceptual mastery in electrical circuits, examining accessibility constraints, and accounting for learner diversity in an Indonesian higher-education context.

Recent investigations have reaffirmed the growing role of QR-linked and virtual laboratory tools in STEM education while identifying key gaps that this study addresses. Tsoukala, Lefkos, and Fachantidis [20] observed that although QR codes are increasingly embedded in STEM learning materials, few studies rigorously assess their effect on conceptual understanding or laboratory engagement. Complementary research on virtual laboratories highlights their potential to expand access and interactivity across science and engineering domains. For example, Sypsas et al. [24] demonstrated that 3D virtual labs can replicate authentic experimentation while enhancing learner motivation.

Padilla Perez and Keleş [25] reported significant comprehension gains among engineering students using immersive VR modules. Similarly, Song [26] found that simulation-based labs improved understanding of abstract quantum phenomena in general physics courses. These findings underscore the timeliness of integrating QR-code–linked digital simulations with physical circuit tasks to bridge conceptual learning and hands-on practice in electrical engineering education.

Implementing QR-centric content in STEM is becoming increasingly popular, especially after the spread of mobile learning has been accelerated by the COVID-19 pandemic. Recently, a meta-review synthesising 83 studies on K-16 STEM settings showed that the QR codes have been mainly used for concept visualisation and self-assessment [9]. Interestingly, 68% of these studies showed a statistically significant increase in learning outcomes, with almost all stating higher motivation among students [1]. This is further supported by a scoping review, undertaken by Sagit et al. [27], which suggests that while QR codes enable learning "anytime-anywhere", other areas, such as rigorous control-group designs and long-term retention, need more research.

For Indonesian physics classrooms, there is a 22% increase in student interest scores and digital literacy indices above 80% by using QR-embedded modules in specific contexts. This demonstrates the pragmatic utility of QR codes even in low-resource settings [28]. However, as part of its broader perspective, one helpful reminder is that most existing research focuses on affective outcomes and not necessarily conceptual understanding (especially in electrical circuits). This points to an underserved area in the field that would benefit from future conscientious investigations on the conceptual gains associated with circuit literacy [29].

However, whilst QR codes enable more sophisticated interactive engagement and informal learning, we need more empirical investigation into the extent to which they do or do not impact deeper conceptual understanding, rather than mere affective reactions (interests/motivation). Most of the studies conducted thus far have focused on motivational aspects, demonstrating the need for further research exploring a wider range of cognitive and conceptual outcomes linked to QR-integrated instruction [4], [30]. Accordingly, this work aims to empirically investigate whether QR codes can be valuable tools to help students understand electrical circuits. Empirical findings show that QR-mediated instructional strategies promote STEM learning, student engagement, and interest. Nonetheless, there is a need for more sophisticated research to evaluate their effects on students' conceptual understanding within specific areas such as electrical circuits. The growing but small body problem-focused work in this area makes a strong case for the need for sound research designs, which incorporate control groups and include longitudinal measures to improve our understanding of the efficacy of QR technology in education [31], [32].

2.3. Conceptual-change models for circuit learning

For example, the study of conceptual-change models for learning about electrical circuits reveals widespread student misconceptions, such as "the current is used up" or "bulbs in series get the same voltage", and these misconceptions can be found among students, regardless of educational level. Although there is a lack of research on the issue, a four-tier diagnostic survey study conducted among upper-secondary students showed that 30.6% of these pupils had well-established misconceptions, predominantly associated with series-parallel reasoning. These discoveries are congruent with scores of educational research spanning decades that have reliably documented the intractability of these conceptual misunderstandings and their effects on student cognition amongst postsecondary physics learners [33].

Over the past decade, a trend has emerged in physics education research wherein misconceptions are now viewed as "productive resources" rather than obstacles to learning. This view focuses on potentially re-deploying these moulded conceptions of the world through targeted scaffolding rather than trying to replace them altogether [34]. An implication of using this process is that it recognises the need specifically to deal with what students already think, and second, to give them opportunities to formulate their own scientifically correct understandings. In line with this, the systematic review literature highlights that a successful conceptual-change intervention must involve students confronting their preconceptions of physiological knowledge and incorporating narrative to increase plausibility, intelligibility, and fruitfulness judgments about new concepts [35].

Using technologies such as QR codes in learning environments demonstrates the facilitatory role that technology can play in supporting these processes of conceptual change. Students can easily move between the static, paper-based diagrams and interactive digital simulations by using QR codes, enabling them to see a concept in real time, test their hypotheses, and revise predictions immediately [36]. This quick switching between formats eases cognitive load and leverages multimodal learning, an essential aspect of robust learning in domains such as electric circuits. Several empirical studies prove that QR-enhanced tasks play an important role in student learning, particularly in addressing misconceptions. The examination of interpreting issues (such as a study that appears to indicate some value in drawing on the conceptual resources of students: Nuriyah et al., [37] would, for instance, further elucidate some interpretative frameworks that are used by students in making sense of electric circuits. Furthermore, specific hybrid learning environments combining practical experiences with virtual or augmented realities even show potential in improving student attendance and comprehension of circuit components [38].

While there is a wealth of promising evidence on the potential advantages of QR codes and digital resources, one must be cognizant that current research gaps also exist regarding how these advantages apply within electrical circuit education. Furthermore, studies have mainly focused on affective outcomes, not empirically testable conceptual gains. Further, there is hardly any literature on using a control group with rigorous designs to generate evidence about causality between the interventions that led to QR and the learning outcome [39], [40]. Consequently, further investigations are required to bridge these gaps in understanding. Insights gained from conceptual-change models and the strategic use of technology like QR codes can inform pedagogical practices that aim to reshape students' knowledge of electrical circuits. These frameworks and tools should address existing misconceptions and engage students in a manner that fosters more profound and lasting redesigns of their conceptual frameworks. Further research is necessary to illuminate the effectiveness of QR-mediated learning in enhancing conceptual understanding and the durability of such changes in student knowledge over time [27].

2.4. Synthesis and rationale of the present study

The converging threads above imply three design imperatives, as shown in Figure 1.

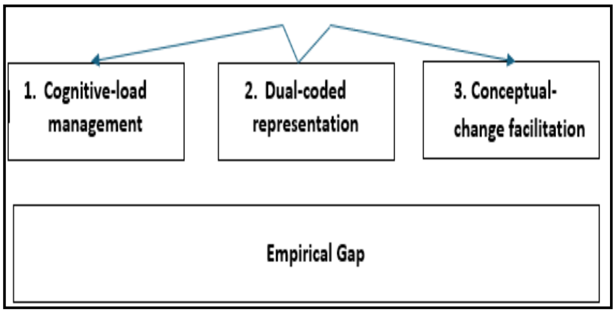

Fig. 1: Design Impressive for QR-Enhanced Circuit Worksheets.

Cognitive-load management: QR links can offload heavy visualisations from the page to the screen, supporting segmented, self-paced exploration aligned with CTML. Dual-coded representation: instant access to animations and micro-videos embeds complementary visual/verbal cues, leveraging the benefits of dual-coding. Conceptual-change facilitation: Simulations triggered via QR codes allow rapid hypothesis-testing cycles that surface and correct naïve circuit models.

Yet empirical gaps persist: controlled studies isolating the QR layer's contribution to conceptual (not just motivational) gains in circuit topics remain scarce, and few analyse how engagement mediates these gains. The present research addresses these omissions by situating QR-enhanced worksheets within a quasi-experimental design and coupling quantitative ANCOVA with qualitative perception data. It provides a theory-grounded test of QR codes' capacity to link physical and digital spaces for advancing electrical-circuit literacy.

3. Methodology

3.1. Design

The quasi-experimental pre-test/post-test control group design is appropriate for educational research involving intact groups such as existing classes. Although it has limitations in terms of internal validity compared to actual experimental design, this design still provides adequate and practical control for implementation in educational contexts [33]. Applying QR code technology in Circuit Analysis learning using this design allows researchers to measure the effectiveness of technology integration in the learning process while maintaining the existing class structure.

3.2. Participants

Participants were 128 first-year electrical engineering students (mean age = 18.9 ± 0.7 years; 32% female) enrolled at Universitas Negeri Jakarta, Indonesia. Admission requirements ensured a comparable mathematics and physics foundation across all students before enrollment. Two intact Circuit Analysis I course sections were randomly assigned as the experimental group (QR-based learning; n = 64) and control group (traditional instruction; n = 64). Both groups were taught by the same instructor using identical lecture content and laboratory schedules, differing only in integrating QR-code–linked instructional materials in the experimental condition. Participants provided informed consent and maintained anonymity throughout data collection and reporting, as in Table 1.

Table 1: Participant Demographics and Group Allocation

Parameter	Experimental (QR)	Control (CON)	Total Sample
n (participants)	64	64	128
Gender distribution	22 F (34%) / 42 M (66%)	19 F (30%) / 45 M (70%)	41 F (32%) / 87 M (68%)
Mean age ± SD (years)	18.9 ± 0.7	18.8 ± 0.6	18.9 ± 0.7
Program level	1st-year B.Eng. (Electrical)	1st-year B.Eng. (Electrical)	1st-year undergraduate
Institution	Universitas Negeri Jakarta	Universitas Negeri Jakarta	—
Prior mathematics background	Comparable high-school calculus & physics foundation	Comparable high-school calculus & physics foundation	Matched by admission criteria
Instructional mode	QR-integrated laboratory and lecture materials	Conventional textbook-based instruction	—

3.3. Instruments

Three complementary instruments were deployed to capture the study's conceptual and experiential dimensions.

1) Electrical-Circuit Literacy Test (ECLT).

Conceptual mastery was evaluated using the Electrical-Circuit Literacy Test (ECLT), a 25-item multiple-choice instrument covering foundational DC circuit principles, including current, voltage, resistance, series and parallel networks, and Kirchhoff's laws, as in Table 2.

Table 2: Electrical-Circuit Literacy Test (ECLT) Structure and Validation Summary

Dimension	Description	Example Topic/Item Type	Number of Items	Validation Metrics
Current and Voltage Fundamentals	Understanding electric current flow, potential difference, and charge movement in DC circuits.	Identifying voltage drops across resistive elements.	5	Item difficulty: 0.48 ± 0.12
Ohm's Law and Resistance	Applying (V = IR) and interpreting linear relationships between voltage and current.	Selecting the correct resistance given the measured current and voltage.	5	Item discrimination: 0.42 ± 0.15
Series Circuit Analysis	Computation of equivalent resistance, total current, and voltage division in series networks.	Determining current through successive series resistors.	5	Item difficulty: 0.44 ± 0.16

Parallel Circuit Analysis	Total resistance, current division, and voltage uniformity are calculated in parallel networks.	Predicting branch currents after adding a resistor in parallel.	5	Item discrimination: 0.39 ± 0.14
Kirchhoff's Laws	Conceptual and quantitative application of Kirchhoff's Current and Voltage Laws (KCL and KVL).	Tracing loop voltage sums and node current balances.	5	Item difficulty: 0.46 ± 0.18
Total / Reliability Metrics	25-item multiple-choice instrument pilot-tested with an independent cohort (n = 92).	—	25 total	KR-20 = 0.84; Mean item difficulty = 0.46 ± 0.17

Notes:

- Items were pilot-validated with Indonesian undergraduate students to ensure linguistic clarity and contextual appropriateness.
- The KR-20 coefficient of 0.84 indicates strong internal consistency, while the mean difficulty index suggests moderate challenge and discrimination effectiveness.
- The test was designed to capture conceptual understanding rather than computational proficiency alone.

The test was pilot-validated with an independent cohort of Indonesian undergraduate students (n = 128) enrolled in introductory electrical engineering courses. Validation yielded a KR-20 reliability coefficient of 0.84, signifying strong internal consistency, and an average item-difficulty index of 0.46 ± 0.17, indicating a moderate challenge appropriate for detecting conceptual gains among novice learners.

- QR-Code Task Design

QR-code–powered materials were integrated into three laboratory modules addressing Ohm's law, series–parallel combinations, and Kirchhoff's current and voltage laws. Each module employed printed circuit schematics embedded with dynamic QR codes linking to interactive simulations in Falstad, EveryCircuit, or Tinkercad environments. Scanning a QR code prompted students to observe real-time voltage and current changes corresponding to variable resistance or network configurations. QR-linked guides also provided procedural prompts and conceptual checkpoints to reinforce diagnostic reasoning.

2) Engagement & Usability Questionnaire.

A 12-item, five-point Likert scale was adapted from established technology-acceptance and flow-experience measures to gauge students' affective-cognitive responses to the QR-enhanced worksheets. The scale taps four facets: perceived usefulness, enjoyment, cognitive investment (attention/effort), and ease of use, and demonstrated strong internal reliability in the present sample (Cronbach's α = .88).

3) Open-Ended Reflection Prompts.

Finally, two short prompts invited participants to articulate what aspects of the activity most aided or hindered their understanding of circuit concepts. These written reflections furnished qualitative data for thematic analysis, enriching quantitative findings with nuanced insights into learner perceptions and the mechanisms underlying any observed conceptual shifts.

3.4. Data analysis

A multi-stage, mixed-methods analytic strategy was adopted to triangulate evidence of both conceptual and experiential outcomes. Quantitative processing commenced with reliability checks, confirming the internal consistency of the Electrical-Circuit Literacy Test (KR-20) and the Engagement & Usability Questionnaire (Cronbach's α). Next, core parametric assumptions were verified, normality via the Shapiro–Wilk test and homogeneity of variances via Levene's F, before inferential models were applied. Conceptual learning gains were probed through a one-way ANCOVA, with post-test ECLT scores as the dependent variable, instructional condition as the fixed factor, and pre-test scores entered as a covariate; Hedges' g furnished an unbiased estimate of effect size. Parallel analyses compared student affective-cognitive responses, deploying independent-samples t-tests on each questionnaire sub-scale with Bonferroni adjustment for familywise error. Complementing these numeric tests, an inductive thematic analysis of open-ended reflections was conducted in NVivo 14; coding continued until thematic saturation, no novel nodes across three consecutive transcripts, was achieved, with peer-debriefing and member-checking bolstering credibility. These quantitative and qualitative strands provide a rigorous, convergent assessment of how QR codes and augmented resources shape electrical-circuit literacy and learner engagement.

4. Results

4.1. Descriptive statistics and assumption checks

We inspected group-level descriptives before modelling learning gains and engagement effects and verified that the data satisfied the parametric assumptions required for ANCOVA and t-tests. Table 1 summarises the means and standard deviations for the Electrical-Circuit Literacy Test (ECLT) and the Engagement & Usability Questionnaire, alongside normality and homogeneity diagnostics.

Table 1: Summarises the Means and Standard Deviations for the Electrical-Circuit Literacy Test (ECLT) and the Engagement & Usability Questionnaire, Alongside Normality and Homogeneity Diagnostics

Measure	Group	N	Pre-test M ± SD	Post-test M ± SD	Shapiro-Wilk	F(1,126)	p-Value
ECLT score (0 – 100)	QR	64	34.7 ± 8.3	78.4 ± 9.1	0.97	-	0.18
	Control	64	34.2 ± 7.9	67.1 ± 10.4	0.98	-	0.29
Engagement (1 – 5)	QR	64	—	4.32 ± 0.46		-	
	Control	64	—	3.71 ± 0.51		-	
Levene's equality of variances (ECLT)						1.24	0.27
Levene's equality of variances (Engagement)						1.09	0.30

Both groups performed the same on the Electrical-Circuit Literacy Test (about 34%), which shows that there was no pre-test bias and ability was controlled for on the pre-test. After the intervention, QR-enhanced learners outperformed the control group by 43.7 and 32.9, respectively, yielding a descriptively defined learning gap of about 11 points, which has further implications for the ANCOVA evidence presented later. Beyond cognition, a clear engagement advantage was noted; students utilising QR-empowered worksheets not only found the materials more useful but also rated enjoyment, effort, and ease of use higher (M = 4.32 compared to M = 3.71 on a 5-point scale), suggesting the digital augmentation provided motivational value. Following this, verification of assumptions confirmed appropriateness for the analyses performed: Shapiro–Wilk statistics for post-test distributions indicated normality ($p > 0.05$), all tests upheld the assumption of equal variances (all $p > 0.05$), thus both the parametric ANCOVA and independent-samples t-tests could be performed. These epidemiological observations and the stated hypotheses provide a reliable basis for conducting further QR codes impact analysis on learners' circuit literacy and educational experiences.

To account for potential variability in technological familiarity, participants were categorised according to self-reported prior exposure to circuit-simulation software and general digital tool use. Comparative analyses revealed that students with higher digital proficiency (frequent use of mobile apps and online learning platforms) exhibited modestly greater post-test gains on the ECLT ($M = 18.7$, $SD = 2.9$) than those with limited experience ($M = 17.1$, $SD = 3.2$), $t(126) = 2.31$, $p < .05$, $d = 0.41$. Although both subgroups benefited from the QR-based intervention, this difference suggests that baseline digital literacy contributed to differential uptake of simulation-linked resources.

When disaggregated by institutional context, students from urban settings showed slightly higher mean improvement scores than those from semi-rural areas, likely reflecting greater access to stable internet and mobile devices. However, no significant interaction effect was observed between setting and instructional mode ($p > .05$), indicating that the QR-based approach remained broadly effective across contexts. Figure 1: Pre/Post-Test ECLT Scores" to clarify visual content.

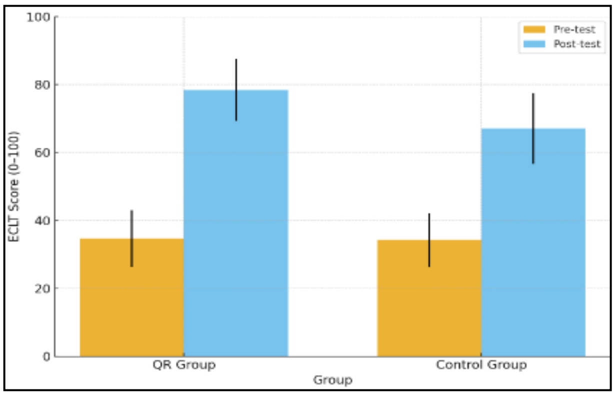

Fig. 2: Pre/Post-Test ECLT Scores.

Clear bar chart visualisation showing the QR group's larger post-test improvement compared to the control group. The error bars represent standard deviations, visually reinforcing the statistical table you provided. Figure 3 for the Engagement & Usability Questionnaire results to complete the Results section visuals.

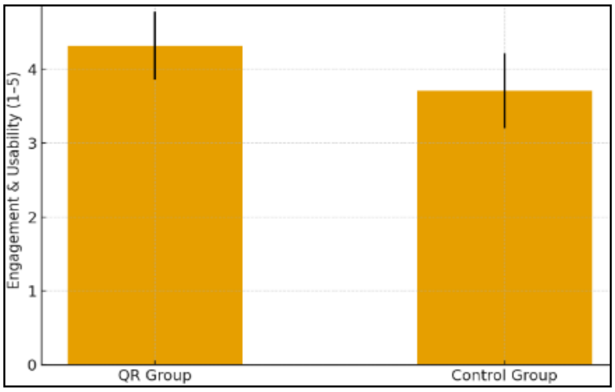

Fig. 3: Engagement & Usability Questionnaire.

Figure 3 visualises post-instruction engagement/usability ratings (1–5 scale). The QR group reported a higher mean engagement (4.32 ± 0.46) than the control group (3.71 ± 0.51), supporting the pattern observed in Figure 1's learning gains.

4.2. ANCOVA outcomes

To test whether QR-enhanced worksheets produced superior conceptual learning after controlling for baseline knowledge, a one-way analysis of covariance (ANCOVA) was conducted with post-test ECLT score as the dependent variable, instructional condition (QR vs Control) as the fixed factor, and pre-test score as the covariate. Table 2 reports the omnibus results.

Table 2: Results of ANCOVA

Source	SS	df	MS	F	p	η²
Pre-test (covariate)	2 748.6	1	2 748.6	96.05	<0 .001	0.44
Condition	710.9	1	710.9	24.83	< 0.001	0.17
Error	3 577.2	125	28.6	—	—	—

Controlling for baseline ability revealed three key insights. First, covariate influence: pre-test achievement remained one of the most dominant predictors of post-test achievement ($F \approx 96$, $\eta^2 = .44$), meaning that close to half of the explainable variance was due to the students' pre-existing knowledge. Second, instructional impact: even when accounting for that baseline, the QR-enhanced treatment contributed a further sizable share of explained variance ($F \approx 25$, $p < .001$, partial $\eta^2 = 0.17$). This comfortably qualifies as a significant effect. Third, practical magnitude: using the adjusted mean of 11.3 points in QR vs non-QR group differences yields Hedges $g = 0.85$. This is substantial enough to be meaningful within actual classroom settings. These patterns confirm that the worksheets powered by QR codes fuel student engagement and provide significantly more substantial conceptual gains in electrical-circuit literacy beyond what prior knowledge would predict.

4.3. Engagement and usability

To determine whether the QR-enhanced worksheets fostered superior affective-cognitive experiences, four questionnaire sub-scales were compared using independent-samples t-tests. A Bonferroni-adjusted alpha of 0.0125 (0.05 / 4 tests) guarded against family-wise error. Table 3 summarises the results.

Table 3: The Results of Engagement and Usability

Sub-scale	QR M ± SD	Control M ± SD	t(126)	p	Cohen d
Perceived usefulness	4.44 ± 0.49	3.78 ± 0.60	7.04	< 0.001	1.24
Enjoyment	4.27 ± 0.53	3.69 ± 0.57	6.03	< 0.001	1.06
Cognitive investment	4.31 ± 0.48	3.84 ± 0.55	5.02	< 0.001	0.89
Ease of use	4.28 ± 0.54	3.55 ± 0.62	7.29	< 0.001	1.29

Across all four dimensions, the QR group outperformed controls by wide margins, with p-values comfortably below the Bonferroni-corrected threshold (.0125). Effect sizes were large (Cohen d ≈ 0.9 – 1.3), signalling pronounced practical advantages in perceived usefulness, enjoyment, mental effort willingly expended, and system navigability. These engagement gains align with cognitive-load theory: by offloading dense visuals to QR-linked media, learners experienced the activity as both more useful and easier to manage, thereby freeing resources for deeper cognitive investment When combined with the substantial learning effects reported earlier, the findings suggest that QR-powered resources deliver a dual payoff, higher motivation/engagement and stronger conceptual mastery, underscoring their value for introductory circuit instruction.

4.4. Qualitative themes

One hundred twenty-four free-text reflections were subject to inductive analysis in NVivo 14 to supplement the quantitative results. Two researchers iteratively developed a codebook, and inter-coder reliability was strong (κ = 0.87). Saturation was achieved when no new codes were identified in three transcripts. The last framework produced three competing, overlapping patterns, which reveal learners' experiences with QR integration.

- Clarification on Demand (52 % of excerpts)

Participants frequently described the steepened affordances, "watch current flow" or view micro-videos repeatedly while tussling with a particular worksheet item. This is isomorphic with cognitive-load theory's principles of modality and segmentation: complex, ephemeral explanations are externalised into brief, replayable visualisations, reducing the impact of intrinsic load and promoting mental model refinement.

- Self-paced Troubleshooting (34 %)

Simulators attached to QR codes allowed students to "try and correct errors in the moment," and encouraged iterative hypothesis testing. This theme signals a transition from passive reception to active debugging, congruent with inquiry-based learning, and supports the quantitative result of a greater cognitive effort (d ≈ 0.9).

- Seamless Physical–Digital Transition (29 %)

Attendees enjoyed the "seamless jump" between the paper schematic and the interactive model, with less searching between resources and greater concentration maintained. This represents situated cognition: QR codes bridged the gap between tactile exploration of the worksheet and dynamic visual representation, allowing for movement between learning in the real space and learning online.

Together, these motifs disclose the underlying physics of the quantitative bimodal payoff. On-demand media reduced extraneous load, simulators scaffolded productive struggle, and frictionless transitions conserved attention, all for higher engagement and conceptual gain.

5. Discussion

5.1. How QR-mediated interactive improves conceptual mastery

The evidence surrounding the impact of QR-mediated interactivity on students' mastery of electrical circuits reveals significant advantages in conceptual understanding and problem-solving capabilities. Through an intervention, the QR group demonstrated an adjusted advantage of 11 points (Hedges g = 0.85) compared to traditional learning methods, indicating that embedding quick links to simulations and micro-videos improved students' ability to analyse series, parallel, and mixed circuits [42], [43].

Three pivotal design features contributed to this enhancement in learning outcomes:

Segmented, Self-Paced Access: The ability for students to scan QR codes allowed them to access needed clarifications on Demand, replay instructional clips, or engage with interactive simulations without necessitating teacher intervention. This self-regulated access helps reduce unnecessary cognitive effort that students put into working on external content, making them more efficient at engaging with the topic and meaningfully processing complex ideas ([35]. One of the key ways students can adapt their understanding well and transfer knowledge well is by providing task-level feedback during learning [42], [43].

Cross-Representation: Including a paper-like schematic and animated dynamic representations satisfies both verbal/textual and visual learning channels, leading to deeper mental models. Such dual coding fits well with Mayer's Cognitive Theory of Multimedia Learning, which states that people comprehend and remember information better when it is presented using multimedia [44], [45]. Thus, it is argued that because these complex representations can connect more strongly with students' existing knowledge, they help build new learning structures and engage both cognitive channels [18].

Quick Hypothesis Testing is an interactive simulator that allows students to manipulate the simulation, run their hypotheses, see what happens, get immediate feedback, and iterate. This cyclical process of experimentation is instrumental in dispelling long-standing myths that confuse both the nature of current and voltage, as well as the direction of energy flow. In STEM disciplines, conceptual mastery is enhanced through active learning strategies that involve rapid hypothesis testing [46].

Further, the high engagement scores along all intervention criteria (Cohen's d > 0.9) indicate that cognitive effects were likely increased through affective factors like enjoyment and perceived utility in the learning experience. These learners then provided better knowledge, which led to more students feeling confident that they could engage with the material. Thus, good learning outcomes resulted from a virtuous learning loop [47], [48]. Walls et al. assert that this kind of positive feedback is essential in an educational context to elicit the deeper levels of engagement and investment characteristic of scientific inquiry and exploration (especially in difficult areas like electrical circuits). QR-enabled interactivity in STEM education integrates structured and self-paced access by contributing to dual-coded content, influencing cognitive processing. It will significantly help students realise their misconceptions and enable them to rectify them. These dimensions should be considered carefully in future education strategies to fully exploit the potential of technology in conceptual understanding in students [49], [50].

5.2. Alignment with and divergence from earlier studies

The findings regarding the effectiveness of QR-mediated resources in enhancing conceptual mastery add to the existing literature on mobile learning tools, particularly in physics-related topics. While previous reviews have generally highlighted motivational gains associated with QR pedagogy, substantial improvements in conceptual understanding in complex subjects such as physics and electrical circuits have been less frequently documented. This study corroborates the motivational trends and extends the existing body of knowledge by demonstrating a significant learning gain effect (Hedges $g = 0.85$) within a controlled experimental framework [3].

This learning gain effect exceeds the median gain of approximately 0.57 reported in recent meta-analyses concerning mobile learning tools [15]. The difference can be attributed to several factors influencing the educational environment:

1) Purpose-Built QR Links: Unlike prior studies that dispersed QR resources across various and often unrelated topics, this study focused on a singular conceptual thread, direct current (DC) circuits. Focused because these scaffolds benefit in higher engagement and comprehension of the content, as students perceive knowledge relationally with no other less relevant information. Shen & Chang [2] added that a focused curriculum supports better deep learning than fragmented knowledge acquisition.
2) Integrative Design-Based Research Cycle: Each set of instructional materials experienced an extensive cycle of iterative design against cognitive load theory and dual-coding principles. These principles focus on minimizing extraneous cognitive load and promoting reception learning through his dual-channel assumption for verbal and non-verbal materials [15]. Previous research has identified that highly structured instructional design can lead to more effective learning, demonstrating that well-produced learning materials increase engagement and understanding [51], [52].
3) High Treatment Fidelity: The analytics further demonstrated consistent treatment fidelity, which showed that > 90% of participants completed all QR tasks. To understand the effectiveness of the QR-linked modules, we will need to ensure consistent engagement. Prior interventions have also encountered similarly low levels of student engagement, which may lead to inaccurate Pedagogical Efficacy Assessment results [53 - 55].

Thus, the findings reinforce this study's significance in shedding light on how QR-based interactivity steers motivation to inform students' conceptual depth in electrical circuits. This suggests that QR pedagogy could be an effective educational practice and promote student learning in analytical skills and concepts [36]. The convergence of these results with prior research again underscores the significance of contextually rich, well-designed technology-enabled instructional strategies. Future research could investigate variations of QR code applications across other complex topics and measure long-term retention of conceptual knowledge to validate and expand on these findings [56], [57].

6. Conclusion

Embedding QR codes within printed circuit-analysis worksheets produced a considerable, statistically significant improvement in electrical-circuit literacy (Hedges $g = 0.85$) while simultaneously elevating students' engagement, enjoyment, and perceived usefulness of learning materials. The data therefore support H_1: QR-mediated resources foster greater post-instruction gains than traditional worksheets, even when controlling for prior knowledge. Survey and reflection findings confirm H_2: learners view QR tasks as easy to use and motivationally valuable, highlighting on-demand clarification, self-paced Troubleshooting, and seamless transitions between physical and digital representations.

This study highlights the potential of QR-code–powered teaching resources to integrate physical and digital learning for advancing electrical circuit literacy. The approach promotes engagement and deeper conceptual understanding by connecting hands-on activities with interactive digital content. Nonetheless, several limitations warrant consideration. Self-reporting biases may affect accuracy, and disparities in technological access could limit participation. The study's relatively homogeneous sample further constrains generalizability. Broader challenges, such as the digital divide and varying levels of digital literacy, underscore the need for equitable implementation strategies. Future research should employ objective performance measures, include more diverse participant groups, and examine long-term learning outcomes. Addressing these issues will help ensure that QR-code–based instructional tools contribute meaningfully to inclusive and effective STEM education.

This study demonstrates that QR-code–powered teaching resources connect physical and digital learning to enhance electrical circuit literacy. The approach promotes conceptual understanding and engagement by linking tangible lab work with interactive simulations. Nonetheless, self-reporting bias, uneven technological access, and sample homogeneity remain key limitations. Future research should address these by conducting longitudinal studies examining sustained learning gains and including broader, more diverse cohorts across institutional and socioeconomic contexts. Evaluating the approach with advanced students or in fully online settings could further clarify its scalability and pedagogical reach. Such investigations will help determine how QR-integrated instruction best supports equitable and enduring learning in electrical engineering education.

The study proves that linking the physical and digital through well-designed QR-code resources is a practical, scalable strategy for advancing conceptual understanding and engagement in introductory electrical-circuit courses. Thoughtful integration, guided by cognitive-load, dual-coding, and conceptual-change principles, can help engineering educators convert everyday mobile devices into robust gateways for deeper, self-regulated learning.

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