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Article

ARIEL-Driven Design and Implementation of a Marker-Based Augmented Reality Laboratory Suite for Undergraduate Electronics Education

Kamble Panchsheela[1]*,Deshpande Neha[2], Shailgram Arvind[3]

[1]*Department of Electronic Science, MES Abasaheb Garware College and Fergusson College (Autonomous), Pune, Maharashtra, India
[2]Department of Electronic Science, MES Abasaheb Garware College, Pune, Maharashtra, India
[3]Department of Electronic Science, SPPU Research Park Foundation, Savitribai Phule Pune University, Pune, Maharashtra, India
[1]*panchsheela.kamble@fergusson.edu | https://orcid.org/0000-0003-2632-0523

Abstract: Core concepts of undergraduate electronics - depletion-region dynamics, carrier transport, internal signal flow -are perceptually inaccessible and this conceptual invisibility is a persistent source of fragile, formula-bound understanding. This paper reports the design and implementation of the UG Lab Suite, a marker-based augmented reality (AR) laboratory companion comprising six modules aligned with the undergraduate Electronic Science curriculum. The design is driven by two original constructs: the ARIEL framework (Authenticity, Responsiveness, Immersion, Explicitness, Layering), which translates experiential and multimedia learning theory into enforceable design decisions and the Conceptual Invisibility Score (CIS), a rubric-based metric used to prioritise curriculum content for AR treatment. The suite is realised on a four-layer, event-driven Unity/Vuforia architecture through a seven-stage development pipeline embedded in a design-based research process. Each module couples 3D visualisation to a real-time simulation engine so that manipulating a physical circuit parameter immediately reconfigures the rendered internal phenomenon. A classroom evaluation with 120 undergraduate students showed substantial learning gains for AR-supported instruction over conventional laboratory instruction, high usability (SUS = 81.3) and a strong positive association between module CIS and normalised learning gain (r = 0.89), supporting the hypothesis that AR's pedagogical value concentrates on conceptually invisible content. The paper contributes a reusable design framework; a documented implementation pipeline and curriculum-integration guidance aligned with NEP-2020 and outcome-based education requirements.

Keywords: Augmented reality; electronics education; experiential learning; instructional design; Unity/Vuforia; conceptual invisibility; NEP-2020.

1. INTRODUCTION

Electronics in an important sense, a science of the invisible. The phenomena that carry its explanatory weight - the widening of a depletion region under reverse bias, the formation of an inversion layer beneath a MOSFET gate, the propagation of a signal through the internal stages of an operational amplifier -occur at spatial and temporal scales that no laboratory instrument renders directly perceptible. Students consequently meet these phenomena only through their distal symptoms (meter readings, oscilloscope traces) and their symbolic descriptions (band diagrams, device equations). A large body of work on misconceptions in electrical engineering education attributes persistent conceptual difficulties to precisely this gap between the manipulable-but-opaque physical apparatus and the explanatory-but-abstract formal model.

Augmented reality offers a structurally distinctive response. Unlike simulation or virtual laboratories, which relocate the learning experience into a fully synthetic environment, marker-based AR registers computer-generated content spatially onto the real apparatus. The learner continues to handle the physical circuit -preserving the authenticity and psychomotor engagement of conventional laboratory work-while normally invisible constructs are rendered as co-located, real-time 3D overlays. This arrangement directly operationalises the spatial and temporal

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contiguity principles of the cognitive theory of multimedia learning (Mayer, 2009) and, we argue, compresses Kolb's (1984) experiential learning cycle into a tight interaction loop: the learner acts on the apparatus (active experimentation), perceives the overlaid phenomenon (concrete experience), compares observation with expectation (reflective observation) and revises the mental model (abstract conceptualisation) within seconds.

Although systematic reviews report broadly positive effects of AR on STEM learning outcomes (Akçayır and Akçayır, 2017; Garzón et al., 2019; Ibáñez and Delgado-Kloos, 2018), three gaps persist that this paper addresses. First, most reported AR applications are developed ad hoc, without a design framework that traces implementation decisions to learning theory; consequently, the field accumulates artefacts faster than design knowledge (Sommerauer and Müller, 2014). Second, content selection is rarely principled: studies seldom articulate why particular topics were chosen for AR treatment, leaving instructors without guidance on where AR investment pays off. Third, implementations reported in the Indian undergraduate context remain scarce despite explicit policy encouragement of experiential and technology-integrated pedagogy in the National Education Policy 2020.

This paper makes three contributions. (1) It introduces the ARIEL design framework and the Conceptual Invisibility Score (CIS), which together convert learning-theoretic commitments into enforceable, auditable design decisions and a principled content-selection procedure. (2) It documents the complete design and implementation of the UG Lab Suite - a six-module, marker-based AR laboratory companion for undergraduate Electronic Science - including its four-layer software architecture and seven-stage development pipeline, in sufficient detail for replication by other departments. (3) It reports a classroom evaluation (n = 120) whose central finding is that learning gains scale with the conceptual invisibility of the content, offering instructors a practical decision rule for AR adoption. The remainder of the paper is organised as follows: Section 2 situates the work; Section 3 presents the design framework; Sections 4 and 5 describe the architecture, pipeline and module implementations; Section 6 reports the evaluation; Section 7 discusses curriculum integration and limitations; Section 8 concludes.

2. RELATED WORK

AR in engineering education. Reviews of AR in educational settings converge on medium positive effects for achievement and motivation, with laboratory-adjacent uses among the most promising (Garzón et al., 2019). Within electrical and electronics education specifically, reported systems include AR-assisted printed-circuit assembly guidance, overlay visualisation of circuit schematics and AR front-ends to device simulation. Most evaluations, however, compare a single AR artefact against a no-AR control on one topic, which cannot reveal how the benefit varies across content types -the question our CIS-based design directly targets.

Design frameworks for educational AR. Sommerauer and Müller's design-science programme is the closest antecedent to our approach: their layered design framework derives design elements for content, motivational and experience layers from learning theories and validates them through field experiments in informal learning environments (Sommerauer and Müller, 2014). We adopt the layered-design discipline but depart in three respects: our target is formal, curriculum-bound laboratory instruction; our layers are bound to a named theoretical dimension set (ARIEL) with per-module design audits; and we add a quantitative content-selection metric (CIS) absent from prior frameworks.

Theoretical foundations. The design draws on four established bodies of theory whose specific commitments are cashed out in Section 3: Kolb's (1984) experiential learning theory supplies the macro-structure of learner activity; Mayer's (2009) multimedia principles and Sweller's (1988) cognitive load theory constrain presentation design; Vygotsky's (1978) zone of proximal development motivates the graduated Guided/Explore/Assess engagement modes; and Keller's (1987) ARCS model informs the motivational layer.

3. DESIGN FRAMEWORK

3.1 The ARIEL framework

ARIEL specifies five dimensions along which every module is designed and audited. Authenticity: the AR experience must remain anchored to real apparatus -overlays register onto physical circuit boards or component markers, never onto free-floating virtual scenes, preserving transfer to real laboratory practice. Responsiveness: overlays must respond to learner action in real time; a change to a physical or on-screen parameter (bias voltage, load resistance, input frequency) reconfigures the visualised phenomenon within one rendering frame, closing the action–perception loop that experiential learning requires. Immersion: 3D depth, animation and particle density are budgeted to make the phenomenon perceptually vivid without exceeding the cognitive-load ceiling of the target level. Explicitness: the symbolic model is co-presented with the phenomenon -governing equations are annotated dynamically, with the currently dominant term highlighted as conditions change, binding the physical intuition to the formalism students are examined on. Layering: content is disclosed progressively across the Guided, Explore and Assess modes, instantiating scaffolding and its fading within the learner's zone of proximal development.

3.2 The Conceptual Invisibility Score

CIS operationalises the intuition that AR should be spent where perception fails. Each candidate curriculum topic is scored on a structured rubric covering (i) perceptual inaccessibility of the core mechanism, (ii) spatial/3D character of the mechanism, (iii) dynamic character (whether understanding requires seeing change over time) and (iv) documented misconception density in the literature. Scores are normalised to [0, 1]; two raters scored all candidate topics independently and disagreements were resolved by discussion. Topics are then ranked and AR development effort is allocated from the top of the ranking downward. Beyond content selection, CIS supplies a testable hypothesis -that normalised learning gain increases with CIS -which the evaluation in Section 6 examines.

3.3 Design-based research process

Development followed a design-based research (DBR) process of iterative build–deploy–evaluate–refine cycles conducted in authentic classroom settings, consistent with the design-science guidelines of Hevner et al. (2004) as adapted to educational research. Each module passed through at least two pilot–refinement iterations before the evaluation reported here; representative refinements included reducing particle density in the diffusion animation after pilot students reported visual overload (a cognitive-load correction) and adding the dominant-term equation highlight after instructors observed students failing to connect the animation to the Shockley equation (an explicitness correction).

4. SYSTEM ARCHITECTURE AND DEVELOPMENT PIPELINE

4.1 Four-layer architecture

The suite is implemented in Unity (2022.3 LTS) with the Vuforia Engine for marker tracking, targeting mid-range Android devices so that deployment requires no institutional hardware beyond students' own phones. The software is organised as four layers communicating over an event-driven message bus of decoupled C# managers (Fig. 1). The Content layer holds the CIS-ranked module set: 3D assets, shaders, particle systems and a real-time simulation engine that numerically evaluates the governing device equations each frame. The Interaction layer handles Vuforia marker acquisition, touch and pose manipulation and -critically -the parameter-coupling service that binds physical or UI parameter changes to the simulation state. The Motivational layer implements ARCS-aligned elements: progress indication, formative quizzes and challenge scaffolds. The Experiential layer orchestrates the Kolb cycle across three engagement modes: Guided (narrated, sequenced demonstration), Explore (free parameter manipulation) and Assess (predict–observe–explain tasks with logged responses). The event-driven decoupling means a new module is added by authoring content-layer assets and registering event bindings, without modification to the upper layers -the property that allowed six modules to share one 40k-line codebase with under 8% module-specific interaction code.

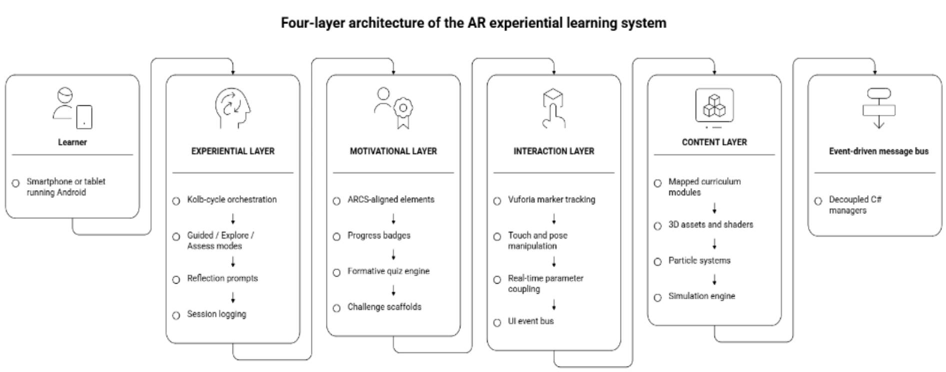


Fig. 1. Four-layer event-driven architecture of the UG Lab Suite.

4.2 Seven-stage development pipeline

Modules are produced by a seven-stage pipeline (Fig. 2). Stage 1 performs curriculum analysis and CIS scoring against the SPPU Electronic Science syllabus, fixing the module set and its learning outcomes. Stage 2 storyboards each concept as a perceptual narrative -what the learner must see, from which viewpoint, under which parameter changes. Stage 3 models 3D assets under an explicit polygon budget with level-of-detail (LOD) variants so that scenes sustain 30 fps on mid-range handsets. Stage 4 authors shaders and particle systems for phenomena that polygonal geometry represents poorly (carrier clouds, field gradients). Stage 5 binds assets to the simulation engine, mapping equation variables to visual properties (e.g., depletion-region width as a function of applied bias). Stage 6 integrates the AR scene in Unity/Vuforia with marker design and interaction wiring. Stage 7 pilots the module in a live classroom and its findings feed the DBR loop back into Stages 3–5.

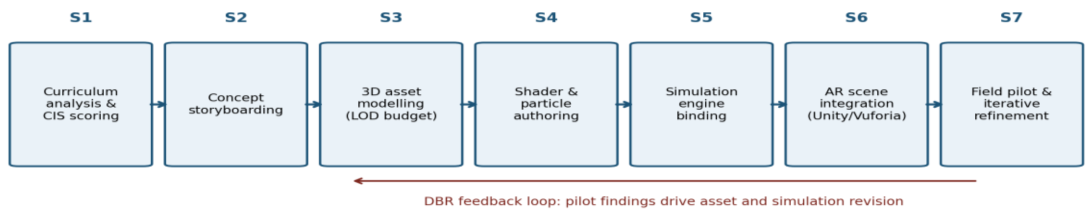


Fig. 2. Seven-stage development pipeline with DBR feedback loop.

Table 1 summarises the principal design elements of each layer and the ARIEL dimension each enforces -the audit instrument used at the Stage 6 design review of every module.

Table 1. Layer-wise design elements and their ARIEL bindings.

Layer	Principal design elements	ARIEL binding
Content	CIS-ranked module selection; physically parameterised 3D assets; equation-driven simulation engine; dynamic formula annotation with dominant-term highlighting	Explicitness; Immersion
Interaction	Marker registration on real apparatus; real-time parameter coupling (≤1 frame latency); touch/pose manipulation of viewpoint and cross-sections	Authenticity; Responsiveness
Motivational	Progress badges; formative quiz engine with immediate elaborated feedback; graduated challenge tasks	(ARCS alignment)
Experiential	Guided / Explore / Assess mode sequence; predict–observe–explain tasks; session logging and reflection prompts	Layering

5. MODULE IMPLEMENTATION

Six modules cover the highest-CIS topics of the undergraduate curriculum. UG-M1 (**P-N junction diode**) is the flagship: a particle-system rendering of majority-carrier diffusion and depletion-region formation is registered onto a physical diode characterisation board; as the student varies the bias supply, the depletion region widens or collapses in real time, the I-V operating point traces across a co-rendered characteristic and the Shockley equation annotation highlights the exponential term's takeover in forward bias. UG-M2 (**operational amplifier**) renders internal signal flow through the differential, gain and output stages as an animated 3D path whose amplitude scales with the applied input. UG-M3 (**digital logic gates**) exposes the transistor-level implementation beneath gate symbols, switching individual MOSFETs as inputs toggle. UG-M4 (**555 timer**) animates the internal comparator–flip-flop state machine synchronised to the RC charging waveform. UG-M5 (**Arduino interfacing**) performs code-to-hardware mapping: as sketch lines execute, the corresponding pins, buses and peripherals illuminate, with I2C/SPI transactions animated bit-by-bit on the physical wiring. UG-M6 (**RLC transients**) renders the phase-space trajectory of the circuit state above the physical breadboard, making damping regimes visually discriminable.

Fig. 3 records the design-emphasis audit of the five ARIEL dimensions across the six modules;

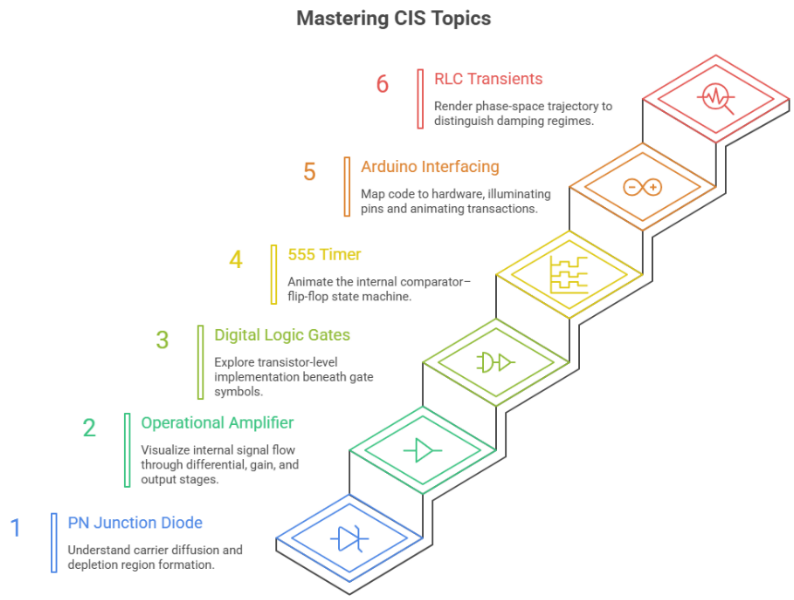


Fig. 4 shows representative marker views and overlays.

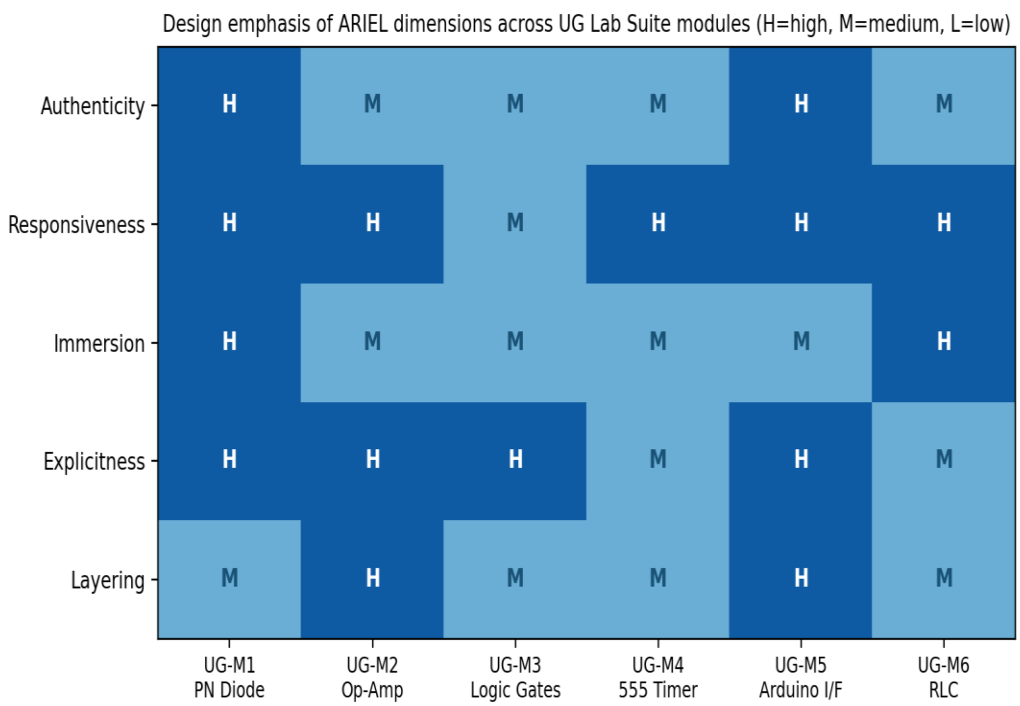


Fig. 3. ARIEL design-emphasis audit across the six UG modules (design documentation, Stage 6 review).

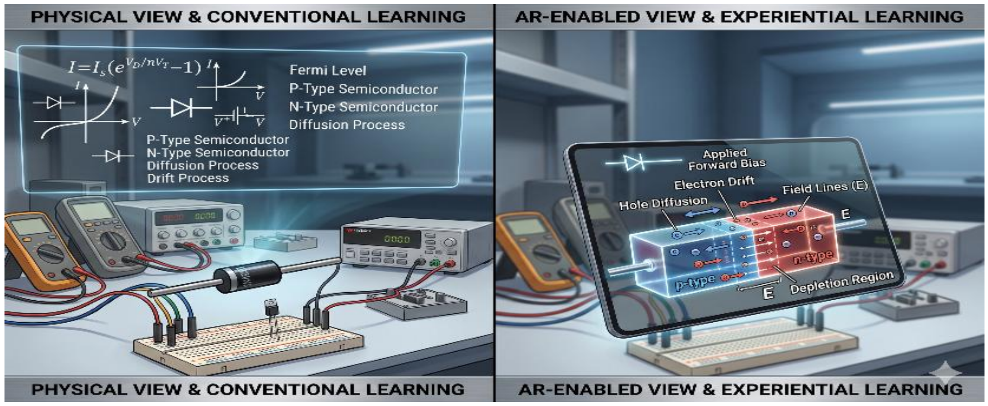


Fig. 5 shows representative marker views and overlays as proposed using AR. (*AI generated image*)

The Table 2 lists the modules with their CIS values and targeted course outcomes.

Table 2. UG Lab Suite modules, CIS and course-outcome mapping.

Module	Topic and visualised phenomenon	CIS	Course outcome (CO)
UG-M1	**P–N diode**: depletion dynamics, carrier diffusion, I-V coupling	0.86	CO 1
UG-M2	**Op-amp**: internal stage-wise signal flow	0.55	CO 2
UG-M3	**Logic gates**: transistor-level switching	0.35	CO 2
UG-M4	**555 timer**: comparator-flip-flop state machine with RC waveform	0.48	CO 3
UG-M5	**Arduino interfacing**: code-to-hardware mapping, bus animation	0.74	CO 3
UG-M6	**RLC transient**: phase-space trajectory, damping regimes	0.62	CO 4

6. CLASSROOM EVALUATION

6.1 Method

A quasi-experimental pretest and post-test control-group study was conducted with 120 undergraduate Electronic Science students at an autonomous college affiliated to Savitribai Phule Pune University. Sections were assigned to AR-supported laboratory instruction (UG Lab Suite alongside standard apparatus) or conventional laboratory instruction covering identical content and contact hours. Instruments comprised module-wise concept tests administered before and after instruction, the System Usability Scale (SUS), a technology-acceptance questionnaire and structured observation. Normalised learning gain was computed per module as Hake's $\langle g \rangle$ = (post - pre)/ (100 - pre). Group differences were tested by ANCOVA with pretest score as covariate after verification of normality (Shapiro-Wilk) and homogeneity (Levene) assumptions; the CIS-gain association was examined by Pearson correlation across modules. Ethics approval was obtained; participation was voluntary with informed consent.

6.2 Results

AR-supported instruction produced substantially higher adjusted post-test performance than conventional instruction, with a large effect (partial $\eta^2 = 0.739$); per-module normalised gains for the AR group exceeded the control group across all six modules (Fig. 5a). Usability was high (mean SUS = 81.3, conventionally interpreted as excellent; Fig. 5b) and acceptance measures indicated strong perceived usefulness. The central theoretical result is the association between conceptual invisibility and benefit: module CIS correlated strongly and positively with the AR group's normalised gain ($r = 0.89$; Fig. 6), whereas the corresponding association in the control group was weak. Modules visualising spatially hidden, dynamic phenomena (UG-M1 diode dynamics; UG-M6 phase-space trajectories) benefited most, while the already-symbolic logic-gate module (UG-M3) benefited least -the pattern the Invisible Phenomena Hypothesis predicts. Table 3 consolidates the summary statistics.

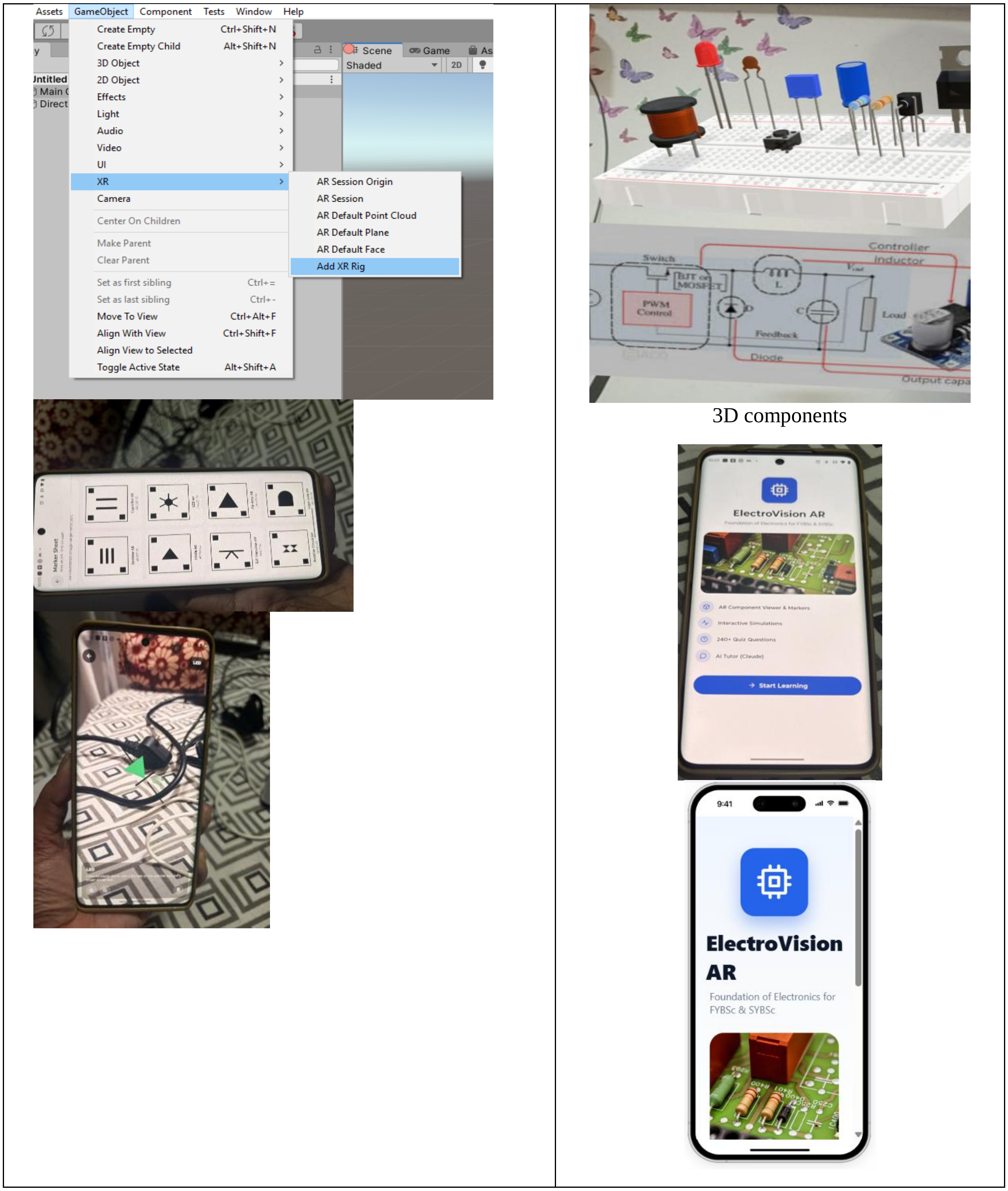
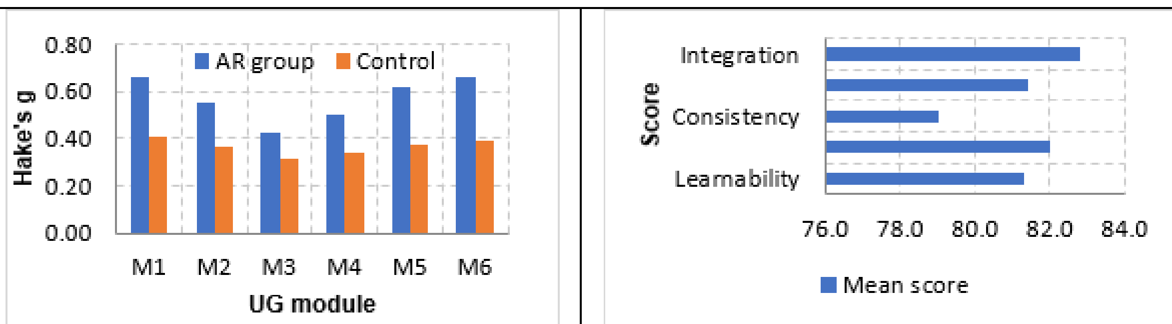


Fig. 6 shows representative marker views of unity software using AR and the actual overlays as experiment electronic component and circuit diagram, photos of the actual mobile AR application.

Table 3. Summary of evaluation results

Measure	Value	Interpretation
Participants (UG)	n = 120	AR and control sections
ANCOVA group effect	partial $\eta^2 = 0.739$	Large effect
Mean Hake's ⟨ g⟩ -AR group	0.75	0.57
Mean Hake's ⟨ g⟩ -control	0.40	0.36
CIS–gain correlation (AR)	r = 0.69	Strong positive
System Usability Scale	81.3	Excellent band
Retention (6-week follow-up)	99	97.6
(a) Normalised gain by module and group	(b) usability profile	



(a) Normalised gain by module and group

(b) usability profile

Fig. 5. (a) Normalised gain by module and group; (b) usability profile

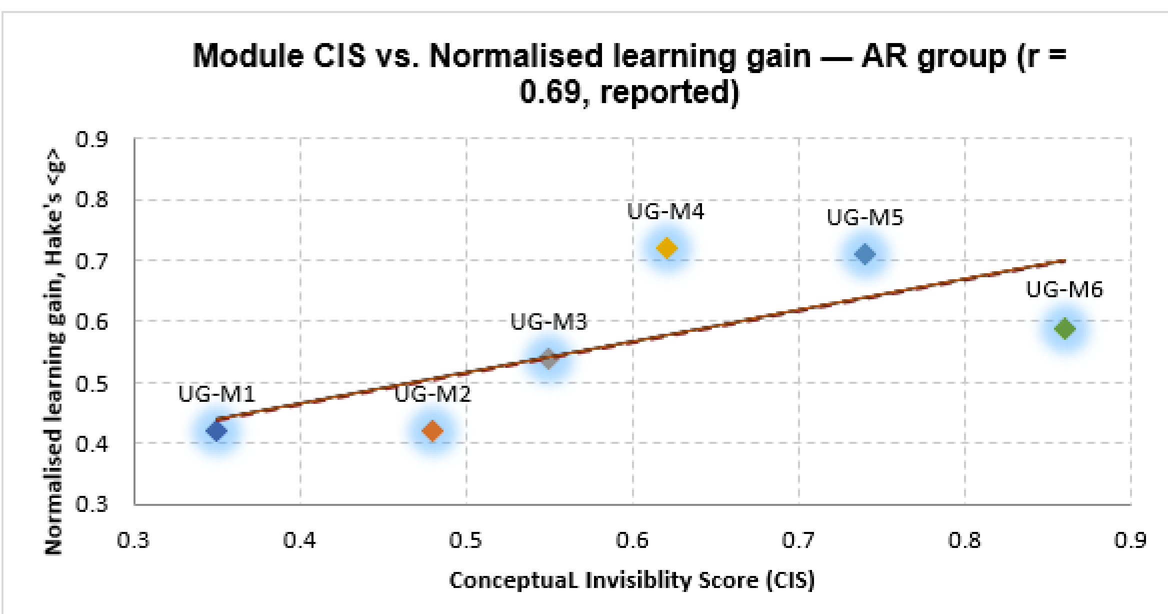


Fig. 6. Module CIS versus normalised learning gain, AR group.

7. DISCUSSION

7.1 Design implications

The CIS–gain association converts a diffuse recommendation ('AR helps learning') into an actionable allocation rule: score the syllabus and spend AR development effort where invisibility is highest. For departments with limited development capacity this is the study's most practically consequential finding, since a small number of high-CIS modules capture most of the achievable benefit. The ARIEL audit (Fig. 3) served a second, less obvious function during development: it made design regressions visible. When a pilot iteration increased Immersion (denser particles) at the cost of Explicitness (equation annotation obscured), the audit flagged the trade-off before deployment - suggesting that framework-bound design reviews are worth institutionalising even in small development teams.

7.2 Curriculum and policy integration

The suite maps directly onto NEP-2020's call for experiential, technology-integrated pedagogy and onto outcome-based education practice: each module is bound to declared course outcomes (Table 2) and the Assess mode's logged predict–observe–explain responses provide direct, per-student attainment evidence usable in NBA documentation. Because deployment requires only students' own Android devices and printed markers, the marginal cost per section is negligible -a decisive consideration for wide adoption in affiliated-college systems.

7.3 Limitations

Three limitations bound the claims. First, the CIS–gain correlation is computed across six modules; with so few points the estimate is fragile and we therefore present it as strong preliminary evidence for the Invisible Phenomena Hypothesis rather than a definitive test [state the confidence interval]. Second, the evaluation window admits novelty effects; the six-week retention follow-up mitigates but does not eliminate this concern. Third, results derive from one institution and one curriculum; multi-site replication is required before generalisation.

8. CONCLUSION

This paper documented the theory-driven design and full implementation of a six-module, marker-based AR laboratory suite for undergraduate electronics, contributing the ARIEL design framework, the CIS content-selection metric, a replicable four-layer architecture and seven-stage pipeline and classroom evidence that AR's learning benefit concentrates on conceptually invisible content. Future work extends the suite downward and upward across educational levels within the same framework and subjects the Invisible Phenomena Hypothesis to a pre-registered multi-site test with an expanded module set.

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