World Journal of Mechanics, 2026, 16(7), 67-81
https://www.scirp.org/journal/wjm
ISSN Online: 2160-0503
ISSN Print: 2160-049X

# Development of an Immersive Automotive Education Module for Beginner Learners: A Developer-Centered Systems Design, Constructivist Learning Framework, and Empirical Evaluation of the VR Car Engine Educational Simulator—Paper I: Systems Architecture and Foundational Evaluation

**Brian Warren, Saikiran Madhavaram**

Department of Computer Science, Southern University and A&M College, Baton Rouge, LA, USA
Email: saikiran.madhavar@sus.edu

**How to cite this paper:** Warren, B. and Madhavaram, S. (2026) Development of an Immersive Automotive Education Module for Beginner Learners: A Developer-Centered Systems Design, Constructivist Learning Framework, and Empirical Evaluation of the VR Car Engine Educational Simulator—Paper I: Systems Architecture and Foundational Evaluation. *World Journal of Mechanics*, **16**, 67-81.
https://doi.org/10.4236/wjm.2026.167004

**Received:** June 9, 2026
**Accepted:** July 28, 2026
**Published:** July 31, 2026



## Abstract

The comprehension of internal combustion engine anatomy and component function represents a persistent challenge in automotive, mechanical, and vocational education. Traditional instructional methods relying on static two-dimensional diagrams and constrained access to physical engine hardware frequently fail to convey the three-dimensional spatial relationships that define engine operation. This challenge is compounded at resource-constrained institutions, including Historically Black Colleges and Universities (HBCUs). This paper presents the developer-centered systems design rationale, theoretical framework, and empirical evaluation of the VR car engine educational simulator—an immersive Unity 3D learning module for the Meta Quest standalone head-mounted display developed at Southern University and A&M College. Grounded in constructivist learning theory, spatial cognition research, Recognition-Primed Decision (RPD) theory, and Cognitive Load Theory (CLT), the simulator features a four-stage interaction pipeline: bonnet opening, engine extraction, exploded-view component separation, and controller-based component selection with contextual information retrieval. A one-group quasi-experimental pre-test/post-test/follow-up study with 32 undergraduate participants yielded statistically significant learning gains (mean gain: 47.4 percentage points; Cohen's d = 3.96 vs. pre-test baseline), strong two-week retention (matched follow-up gain of 44.9 pp across 28 participants), excellent usability

(SUS = 85.6), and satisfactory immersive presence (IPQ GP = 4.2/6.0). Findings support standalone VR as an accessible and pedagogically grounded medium for automotive component education in HBCU and resource-constrained educational settings.


## Keywords

Virtual Reality, Unity 3D, Meta Quest, Automotive Learning, Exploded View, Constructivist Learning, Spatial Cognition, RPD Theory, Cognitive Load Theory, HBCU, System Usability Scale


## 1. Introduction

The internal combustion engine remains one of the most spatially complex systems encountered by students entering automotive technology and mechanical engineering programs. Its operation depends on the precise three-dimensional arrangement of interdependent components that two-dimensional instructional diagrams are structurally ill-equipped to convey [1] [2]. Research in spatial cognition establishes that learners with limited spatial visualization ability are disproportionately disadvantaged by flat instructional formats, as the cognitive demand of constructing a 3D mental model from diagrams frequently overwhelms working memory capacity [3]. This challenge is particularly acute at Historically Black Colleges and Universities (HBCUs) such as Southern University and A&M College, where resource constraints often limit access to physical engine specimens. Virtual reality on standalone platforms like the Meta Quest offers a compelling

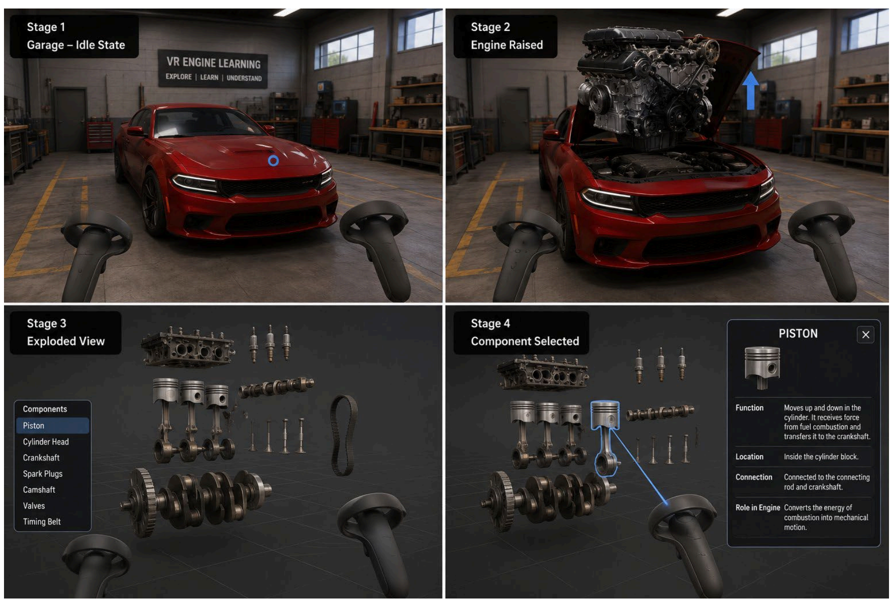


Figure 1. The VR car engine educational simulator—all four interaction stages: (a) Stage 1: garage idle state, (b) Stage 2: engine raised, (c) Stage 3: exploded view, (d) Stage 4: component selected with information panel.

alternative: immersive three-dimensional interactive environments at consumer price points far below physical laboratory costs, with no PC dependency enabling direct classroom deployment [4].

Figure 1 presents the complete VR car engine educational simulator showing all four interaction stages as experienced by the learner.

This paper pursues four objectives: 1) documenting the integrated theoretical framework guiding simulator design; 2) presenting a developer-centered account of the technical architecture; 3) reporting a quasi-experimental evaluation; and 4) situating contributions within the VR-based STEM education literature.

## 2. Literature Review

### 2.1. VR in STEM and Technical Education

Merchant *et al.* [5] meta-analyzed 69 experimental studies and reported a weighted mean effect of d = 0.51 favoring VR instruction, with particularly large effects for spatial reasoning tasks. Radianti *et al.* [6] identified immersion, presence, and interaction as primary mediators. Potkonjak *et al.* [7] identified spatial visualization and assembly procedure learning as domains most consistently benefiting from VR simulation.

### 2.2. Spatial Cognition and Mechanical Learning

Uttal *et al.* [8] meta-analyzed 217 spatial training studies, finding spatial skills are malleable and transferable (d = 0.47). Tversky [9] established that mental models of mechanical systems are fundamentally spatial. Heiser and Tversky [10] demonstrated that dynamic animated exploded views produce superior comprehension of assembly relationships versus static diagrams—directly motivating Stage 3 of the simulator's interaction pipeline.

### 2.3. Constructivist and Cognitive Learning Theories

Constructivism [11] [12] holds that learners actively construct knowledge through environmental engagement. Brown, Collins, and Duguid's [13] situated learning theory argues knowledge acquisition is inseparable from context, motivating the simulator's realistic garage setting. Moreno and Mayer's [14] multimodal framework identifies selecting, organizing, and integrating as three cognitive processes for deep multimedia learning. Sweller's [3] Cognitive Load Theory motivates the two-action controller paradigm and structured information panels that minimize extraneous cognitive load.

### 2.4. Recognition-Primed Decision Theory and Research Gap

Klein's [15] RPD theory motivates contextual realism: embedding component learning within a realistic garage seeds recognition-based memory schemas that activate in real-world automotive contexts [16]. Published VR automotive systems disproportionately target professional maintenance training [17] [18] rather than foundational anatomy education for novice learners. Most published VR education research uses tethered PC-dependent HMDs [19], limiting applicability to HBCU settings. The present paper addresses all three gaps.

## 3. Integrated Theoretical Framework

Figure 2 illustrates the integrated theoretical framework showing how Constructivism, Spatial Cognition, RPD Theory, and Cognitive Load Theory map to specific design principles and implementation decisions in the simulator.

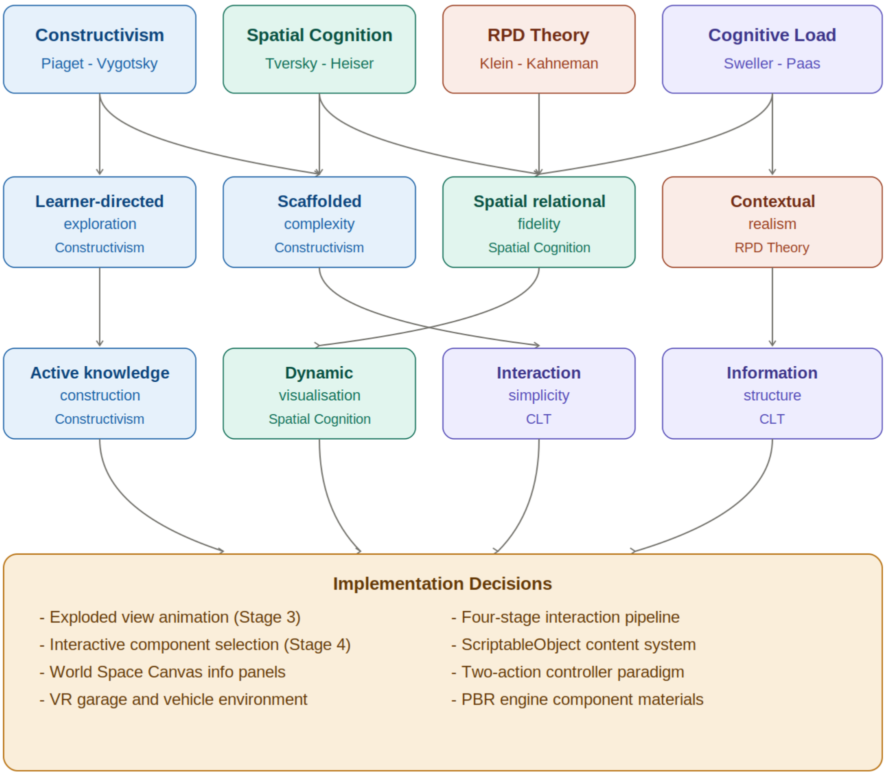


Figure 2. Integrated theoretical framework diagram: four theoretical sources mapped through design principles to implementation decisions in the VR car engine educational simulator.

Table 1 presents the complete theory-to-implementation mapping. Constructivism governs learner-directed exploration, scaffolded complexity progression, and active knowledge construction. Spatial cognition motivates spatial relational fidelity and dynamic exploded-view animation. RPD theory drives contextual realism. CLT motivates the two-action controller paradigm, structured four-field information panels, and visually subordinated background elements.

Table 1. Theoretical framework: theory → design principle → implementation decision.

| Theory | Design principle | Decision | Component |
|---|---|---|---|
| Constructivism | Learner-directed exploration | Free-order component selection | Stage 4 |
| Constructivism | Scaffolded complexity | Whole-to-part animation | Stage 2 - 3 |

Continued

| | | | |
|---|---|---|---|
| Situated learning | Contextual authenticity | Realistic garage + vehicle | Scene architecture |
| Spatial cognition | Spatial relational fidelity | Assembly-vector explosion | Stage 3 |
| Spatial cognition | Dynamic visualization | Animated separation | Animator |
| RPD theory | Contextual realism | PBR materials, environment | Asset design |
| CLT | Interaction simplicity | Two-action paradigm | XRIT configuration |
| CLT | Information structure | Four-field template | Scriptable object |
| Multimodal [14] | Multimodal integration | 3D + verbal panels | Info panel |

## 4. Developer-Centered Systems Architecture

### 4.1. Development Environment and Platform

The simulator was developed in Unity 3D (version 2022.3 LTS) with the XR Interaction Toolkit (XRIT v2.3.2) and Oculus Integration SDK (v54.0), deployed as a standalone APK on the Meta Quest 2. Unity was selected for its XRIT cross-platform abstraction layer, automotive Asset Store ecosystem, and lower C# scripting entry barrier. The Meta Quest 2 was selected for standalone operation (no PC dependency), USD $299 acquisition cost, and 90 Hz display sustaining 72 fps comfortable VR.

### 4.2. Virtual Garage Environment: Stages 1 and 2

Figures 3-4 show the virtual garage at Stage 1 (idle, intact vehicle) and Stage 2 (engine raised). The scene measures 12 m × 8 m × 4 m. Consistent 72 fps was achieved through baked Progressive Light mapper lighting, LOD groups on all components, static batching reducing approximately 340 draw calls to 12, and texture atlasing on background assets.

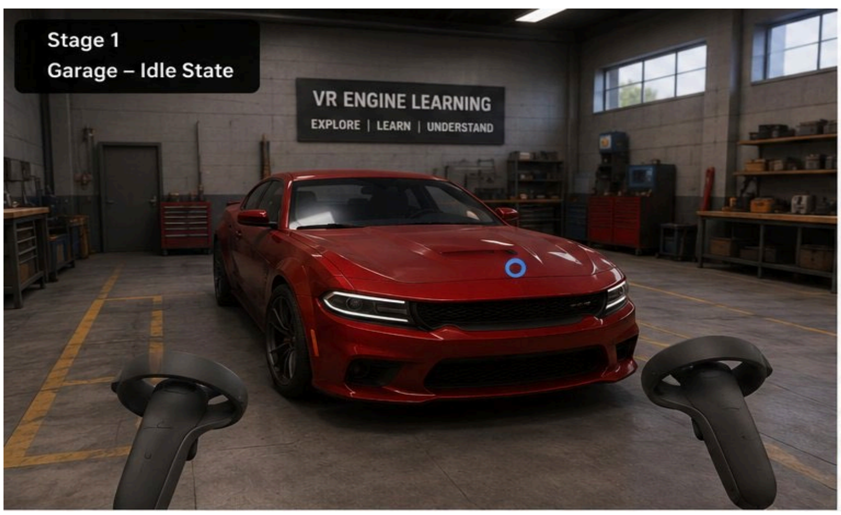


Figure 3. Stage 1—virtual garage idle state: learner view at scene entry showing the intact vehicle, photorealistic garage environment, and Meta Quest controller models.


Figure 4. Stage 2—engine raised: the vehicle bonnet opens via proximity trigger and the engine assembly animates upward to interaction height (y = 2.18 m).

### 4.3. Asset Pipeline and Model Specifications

Engine component models were authored in Blender 3.6 using subdivision surface modeling, UV-unwrapped, and assigned PBR materials (Principled BSDF) to approximate real engine metal surfaces. Table 2 presents per-component polygon counts and LOD specifications.

Table 2. Engine component 3D model specifications.

| Component | Tris | Material | LOD |
|---|---|---|---|
| Piston (×4) | 12,400 | Forged steel PBR | 3 levels |
| Crankshaft | 28,600 | Forged steel PBR | 3 levels |
| Cylinder head | 34,200 | Cast iron PBR | 2 levels |
| Camshaft | 14,800 | Forged steel PBR | 3 levels |
| Spark plug (×4) | 6200 | Ceramic/steel PBR | 2 levels |
| Valve assembly | 18,400 | Hardened steel PBR | 2 levels |
| Timing belt | 9600 | Rubber/composite PBR | 2 levels |

### 4.4. The Four-Stage Interaction Pipeline

Figure 5 presents the interaction pipeline as a state machine diagram, illustrating all trigger conditions, state transitions, and the reset arc returning any state to idle.

*Stage 1—Bonnet Proximity Trigger*

A box-shaped trigger collider on the bonnet detects controller entry and invokes Bonnet Animator.SetTrigger("Open"), initiating a rigged hinge animation (0˚ → 62˚) over 1.8 seconds.

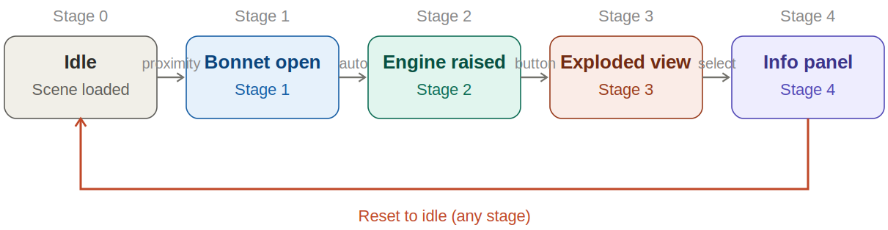


**Figure 5.** Four-stage interaction pipeline state machine: transitions from idle through bonnet open, engine raised, exploded view, and info panel shown, with a reset arc returning to Idle from any state.

*Stage 2—Engine Extraction*

An Animation Event at the final frame of the bonnet-open clip triggers the engine assembly translation from y = 0.62 m (engine bay) to y = 2.18 m (interaction height) using a smooth easing curve.

*Stage 3—Exploded View*

Figure 6 shows the exploded-view state. A world-space UI button triggers Exploded View Controller. Trigger Explosion(), activating each component's Animator in a staggered 0.15-second sequence along assembly-accurate translation vectors. Table 3 presents parameters.


**Figure 6.** Stage 3—exploded view: all seven engine components separated along assembly-accurate translation vectors with the component selection menu visible.

**Table 3.** Exploded view component translation parameters.

| Component | Direction | Distance (m) |
|---|---|---|
| Piston (×4) | −Y local | 0.55 |
| Crankshaft | −Y, +Z local | 0.80 |
| Cylinder head | +Y local | 0.60 |

**Continued**

| | | |
|---|---|---|
| Camshaft | +Y, −Z local | 0.65 |
| Spark plug (×4) | +Y, ±X local | 0.45 |
| Valve assembly | +Y, ±X local | 0.50 |
| Timing belt | +Z local | 0.70 |

***Stage 4—Component Selection and Information Display***

Figure 7 shows Stage 4. The XRIT Ray Interactor fires Select Entered on component XR Simple Interactables, instantiating a World Space Canvas panel from a Scriptable Object asset with four fields: Part Name, Function, Location, and Connected Components (see Table 4).

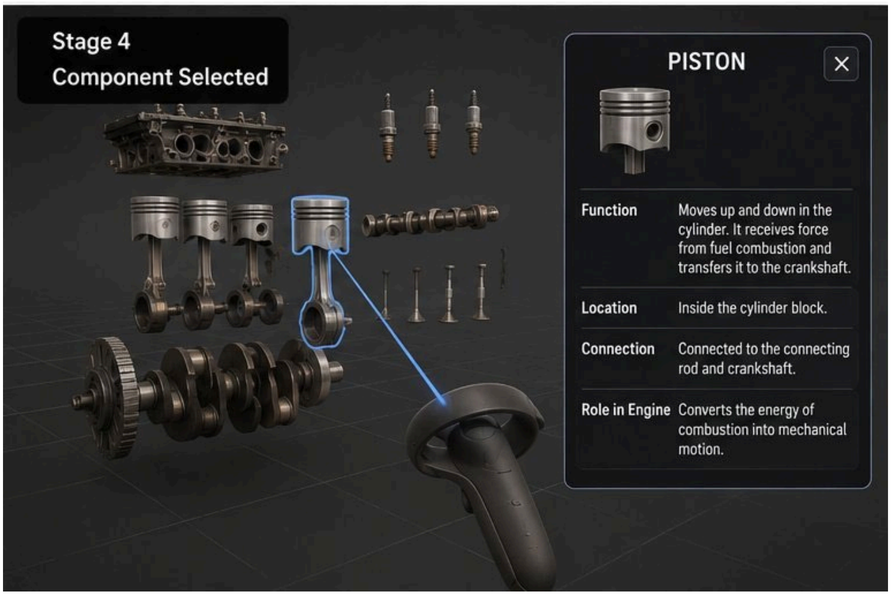


Figure 7. Stage 4—component selected: the piston is highlighted and the information panel displays part name, function, location, connection, and role in engine FIELDS.

Table 4. Component information panel content.

| Part | Function | Location | Connected |
|---|---|---|---|
| Piston | Converts combustion energy into linear motion. | Cylinder bore | Crankshaft, cylinder head |
| Crankshaft | Converts reciprocating motion to rotation. | Lower block | Pistons, timing belt |
| Cylinder head | Seals combustion chamber; houses valves. | Top of block | Pistons, valves, plugs |
| Camshaft | Controls valve timing at half crank speed. | Upper block | Timing belt, valves |
| Spark plug | Delivers ignition spark at correct moment. | Cylinder head | Cylinder head |
| Valve assembly | Controls intake/exhaust gas flow. | Head ports | Camshaft, head |
| Timing belt | Synchronizes crankshaft and camshaft. | Front of block | Crankshaft, camshaft |

### 4.5. State Management and Reset

A singleton Scene State Manager gates all inputs through a five-state enumeration (Idle, Bonnet_Open, Engine_Raised, Exploded_View, Resetting), preventing concurrent animation conflicts. The Reset function reverses all animations over 4.2 seconds, returning to Idle and enabling repeated exploration cycles without scene reloading.

## 5. Evaluation Methodology

### 5.1. Study Design and Internal Validity

This evaluation employed a one-group quasi-experimental pre-test/post-test/follow-up design. All 32 participants completed the same protocol without a control condition. This design carries well-recognized internal-validity risks: history effects (events during the study period may have influenced scores independently), maturation (participants may have incidentally encountered engine content between sessions), and test-practice effects (repeated exposure to the same CKA items may artificially inflate gains). These limitations are discussed in Section 7.

### 5.2. Research Questions

(RQ1) Does simulator interaction produce significant gains in engine component knowledge? (RQ2) Are gains retained at two-week follow-up? (RQ3) How do learners rate system usability? (RQ4) What degree of immersive presence is experienced?

### 5.3. Participants and Sample Rationale

Thirty-two undergraduate students were recruited from introductory Computer Science and Technology courses at Southern University and A&M College (19 male, 13 female; mean age 20.7, SD = 1.9). Introductory CS/Technology students were selected as a proxy for beginner automotive learners because they (a) represent the simulator's intended audience of first-exposure learners with no prior formal automotive instruction, (b) are accessible at the host institution, and (c) provide a demographically relevant HBCU sample for the transferability claim. Eligibility required no prior formal automotive engineering instruction and fewer than 10 cumulative VR hours. Two-week retention data were collected from 28 of 32 participants (four were unavailable for follow-up).

### 5.4. Instruments

The Component Knowledge Assessment (CKA) comprised 28 items across four knowledge dimensions—identification (naming a component from an image), function (describing what a component does), location (identifying spatial position within the engine), and connectivity (identifying directly interfacing components)—for all seven engine components (four items per component). Items were developed collaboratively by the two authors and a mechanical engineering faculty consultant with 12 years of automotive instruction experience. Alignment between items and each of the seven components was verified through a structured content mapping matrix ensuring each component was represented across all four dimensions. Two independent raters scored open-ended function items; inter-rater agreement was $\kappa = 0.87$.

The same 28 CKA items were administered at pre-test, post-test, and follow-up. To address potential practice effects from repeated item exposure, the item order was randomized across administrations, and a minimum 20-minute gap separated pre-test from simulator interaction. The very large effect (d = 3.96) may nonetheless partly reflect familiarity with item format; this is noted as a limitation in Section 7.

The System Usability Scale (SUS) [20] is a validated 10-item instrument (0 - 100 scale); scores above 80.3 are classified "Excellent" [21]. The Igroup Presence Questionnaire (IPQ) [22] assessed General Presence, Spatial Presence, Involvement, and Experienced Realism.

### 5.5. Procedure

Each 50-minute session proceeded: 1) informed consent + demographics (5 min); 2) CKA pre-test (10 min); 3) 3-minute standardized VR orientation tutorial; 4) unguided simulator interaction (20 min); 5) headset removal + rest (5 min); 6) CKA post-test, SUS, IPQ (10 min); 7) open-ended qualitative questionnaire (7 min). Two-week follow-up sessions administered the CKA only.

### 5.6. Analysis Plan

Paired-samples t-tests assessed pre-to-post and post-to-follow-up CKA change; Cohen's dz (= $t/\sqrt{n}$) was used as the effect size for paired-samples designs. SUS and IPQ scores were reported descriptively. Open-ended responses were analyzed using inductive thematic analysis [23] coded independently by two raters; disagreements were resolved through structured discussion until consensus was reached.

## 6. Results

### 6.1. Learning Outcomes: Pre-Test to Post-Test

Pre-test CKA scores: mean 26.4% (SD = 8.7). Post-test: mean 73.8% (SD = 10.6), gain 47.4 pp (SD = 9.8). Paired t-test: $t(31) = 22.4$, $p < 0.001$, $dz = 22.4/\sqrt{32} = 3.96$ (very large effect). The connectivity dimension showed the largest mean gain (58.1 pp). **Figure 8** shows pre-test, post-test, and follow-up scores by component.

### 6.2. Two-Week Retention

Follow-up CKA scores for the 28 matched participants: mean 71.3% (SD = 11.2). The post-test mean for the same matched 28 participants was 71.9% (SD = 10.4), yielding a mean post-test to follow-up decline of 0.6 pp. Paired t-test on the matched sample: $t(27) = 2.76$, $p = .010$, $dz = 2.76/\sqrt{28} \approx 0.52$ (moderate effect). Relative to the matched pre-test baseline, the follow-up mean represents a retained gain of 44.9 pp, or approximately 96% of the matched post-test gain (see **Table 5**).

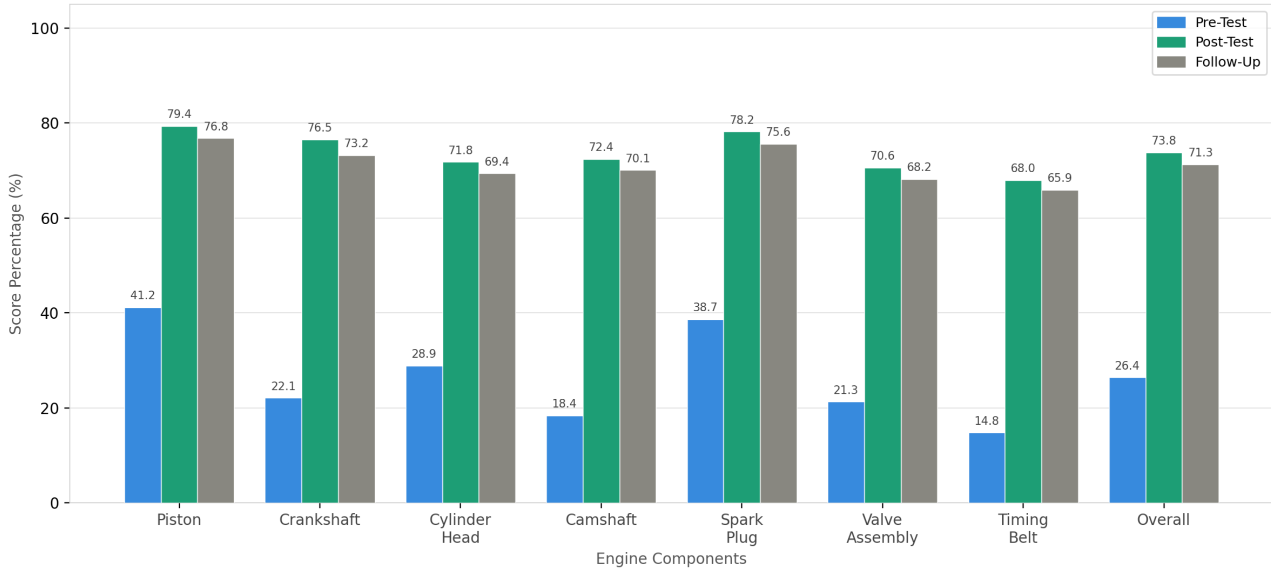


**Figure 8.** Pre-test, post-test, and follow-up CKA scores by engine component. Blue = pre-test; Orange/green = post-test; Grey = follow-up (2-week).

**Table 5.** CKA results by component (full sample N = 32; matched follow-up sample N = 28).

| Component | Pre M% (SD) | Post M% (SD) | Gain (pp) | Follow-up M%[1] |
|---|---|---|---|---|
| Piston | 41.2 (12.4) | 79.4 (11.8) | 38.2 | 76.8 (12.1) |
| Crankshaft | 22.1 (9.8) | 76.5 (10.3) | 54.4 | 73.2 (11.4) |
| Cylinder head | 28.9 (10.1) | 71.8 (12.2) | 42.9 | 69.4 (13.0) |
| Camshaft | 18.4 (8.6) | 72.4 (9.7) | 54.0 | 70.1 (10.2) |
| Spark plug | 38.7 (13.2) | 78.2 (10.9) | 39.5 | 75.6 (11.8) |
| Valve assembly | 21.3 (9.4) | 70.6 (11.4) | 49.3 | 68.2 (12.3) |
| Timing belt | 14.8 (7.2) | 68.0 (12.6) | 53.2 | 65.9 (13.1) |
| Overall | 26.4 (8.7) | 73.8 (10.6) | 47.4 | 71.3 (11.2)[2] |

[1]Follow-up data from matched sample (N = 28 of 32; four participants unavailable). Percentages are not directly comparable with the full-sample post-test scores. [2]Matched post-test mean for the 28 follow-up participants was 71.9% (SD = 10.4), yielding a matched follow-up gain of 44.9 pp relative to the matched pre-test mean of 26.4%.

## 6.3. System Usability

SUS scores: mean 85.6 (SD = 6.2, range 72.5 - 97.5), classified "Excellent" by Bangor *et al.* [21]. Nineteen of 32 participants (59.4%) scored above 85.

## 6.4. Immersive Presence

Table 6 presents IPQ results. Spatial presence was highest (4.6/6.0), confirming strong subjective sense of physical location in the virtual garage. Involvement was lowest (3.8/6.0), reflecting limited interactive affordances beyond component selection in the current prototype.

Table 6. IPQ results by subscale (N = 32).

| Subscale | Items | Scale | Mean (SD) | Level |
|---|---|---|---|---|
| General presence | 1 | 0 - 6 | 4.2 (0.6) | Moderate-high |
| Spatial presence | 5 | 0 - 6 | 4.6 (0.7) | High |
| Involvement | 4 | 0 - 6 | 3.8 (0.8) | Moderate |
| Experienced realism | 4 | 0 - 6 | 4.0 (0.7) | Moderate-high |

### 6.5. Qualitative Findings

Open-ended responses were analyzed using inductive thematic analysis [23] by two independent coders. Each coder reviewed all 32 response sets and generated initial codes; codes were grouped into candidate themes independently. The two coders then compared theme lists and resolved disagreements through structured discussion until full consensus was reached. Four themes emerged: 1) Spatial Clarity Through Animation (81.3% of participants): the exploded-view animation consistently described as revealing component spatial relationships that diagrams had not made clear; 2) Engagement and Novelty (68.8%): the VR experience rated substantially more engaging than conventional study; 3) Desire for Dynamic Function Animation (59.4%): learners requested animations showing components in operation; 4) Minor Navigation Challenges (34.4%): occasional difficulty distinguishing adjacent components and controller aim fatigue.

## 7. Discussion

### 7.1. Learning Outcomes

The observed effect size (dz = 3.96) is substantially larger than the moderate effects reported in prior VR education meta-analyses (d = 0.40 - 0.65) [5] [6], though several factors complicate causal interpretation. As noted in Section 5.1, this one-group design cannot rule out history, maturation, or test-practice effects as alternative explanations for the observed gains. The near-floor pre-test mean (26.4%) also provides a large range over which improvement can occur regardless of treatment. These gains are therefore best interpreted as promising preliminary evidence that engagement with the simulator is associated with substantial knowledge change, rather than as evidence that the simulator alone caused the gains.

### 7.2. Theoretical Framework Alignment

The qualitative theme of Spatial Clarity Through Animation (81.3%) aligns with Heiser and Tversky's [10] prediction that dynamic animated exploded views support superior spatial mental model formation. The theme of Desire for Dynamic Function Animation (59.4%) identifies a gap between current affordances and learner aspirations, consistent with Moreno and Mayer's [14] integrating process: operating cycle animations could connect component identity to systemic engine function more deeply than static information panels allow.

### 7.3. HBCU Accessibility Implications

A classroom set of 10 Meta Quest 2 units can be acquired for approximately USD $3000—a fraction of the cost of a physical engine specimen with storage, safety, and maintenance overheads. The simulator's compact interaction zone (1.5 m × 1.5 m) and APK sideloading deployment support practical classroom use at Southern University and peer HBCU institutions without dedicated hardware infrastructure.

### 7.4. Limitations

Several limitations constrain interpretation. First, the one-group quasi-experimental design (Section 5.1) prevents causal attribution of gains to simulator exposure; history, maturation, and test-practice effects remain plausible alternative explanations. Second, the same CKA items were reused across all three administrations; randomizing item order mitigates but does not eliminate practice effects. Third, introductory CS/Technology students may not fully represent the broader population of beginner automotive learners, limiting transferability. Fourth, the single-session, single-institution protocol does not support cumulative learning assessment or demographic generalization. A randomized controlled trial comparing the simulator against textbook instruction is planned for Paper II.

## 8. Conclusion

This paper has presented the VR car engine educational simulator: a Unity 3D immersive learning module on the Meta Quest standalone platform for beginner automotive learners at Southern University and A&M College. Grounded in an integrated framework of constructivism, spatial cognition, RPD theory, and CLT, the simulator features a four-stage interaction pipeline, Scriptable Object content system, and assembly-accurate exploded-view animations. A one-group quasi-experimental evaluation with 32 undergraduate participants found large pre-to-post knowledge gains (mean 47.4 pp, $d_z = 3.96$) that were substantially retained at two weeks (matched follow-up gain: 44.9 pp), along with excellent usability (SUS: 85.6) and satisfactory presence (IPQ GP: 4.2/6.0). Although internal-validity constraints preclude strong causal claims, these findings are consistent with the hypothesis that the simulator supports meaningful knowledge change and represent encouraging preliminary evidence for standalone consumer VR as an accessible medium for experiential automotive education in HBCU and resource-constrained settings.

## Acknowledgements

The authors gratefully acknowledge the support of the Center for Immersive Learning Technology at Southern University and A&M College, and the undergraduate participants who contributed their time to this study. This work was supported in part by [Grant/Funding Source—to be completed prior to submission].

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References


[1] Assouline, S.G. and Lupkowski-Shoplik, A. (2011) Developing Math Talent. Prufrock Press.

[2] Hegarty, M. and Waller, D. (2004) A Dissociation between Mental Rotation and Perspective-Taking Spatial Abilities. *Intelligence*, **32**, 175-191. https://doi.org/10.1016/j.intell.2003.12.001

[3] Sweller, J. (1988) Cognitive Load during Problem Solving: Effects on Learning. *Cognitive Science*, **12**, 257-285. https://doi.org/10.1207/s15516709cog1202_4

[4] National Science Foundation (2023) Women, Minorities, and Persons with Disabilities in Science and Engineering. National Science Foundation.

[5] Merchant, Z., Goetz, E.T., Cifuentes, L., Keeney-Kennicutt, W. and Davis, T.J. (2014) Effectiveness of Virtual Reality-Based Instruction on Students' Learning Outcomes in K-12 and Higher Education: A Meta-Analysis. *Computers & Education*, **70**, 29-40. https://doi.org/10.1016/j.compedu.2013.07.033

[6] Radianti, J., Majchrzak, T.A., Fromm, J. and Wohlgenannt, I. (2020) A Systematic Review of Immersive Virtual Reality Applications for Higher Education: Design Elements, Lessons Learned, and Research Agenda. *Computers & Education*, **147**, Article 103778. https://doi.org/10.1016/j.compedu.2019.103778

[7] Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V.M., *et al.* (2016) Virtual Laboratories for Education in Science, Technology, and Engineering: A Review. *Computers & Education*, **95**, 309-327. https://doi.org/10.1016/j.compedu.2016.02.002

[8] Uttal, D.H., Meadow, N.G., Tipton, E., Hand, L.L., Alden, A.R., Warren, C., *et al.* (2013) The Malleability of Spatial Skills: A Meta-Analysis of Training Studies. *Psychological Bulletin*, **139**, 352-402. https://doi.org/10.1037/a0028446

[9] Tversky, B. (2008) Spatial Thought, Social Thought. In: Barkowsky, T., *et al.*, Eds., Spatial Cognition VI, Springer, 1-10.

[10] Heiser, J. and Tversky, B. (2002) Characterizing Diagrams Produced by Individuals and Dyads. *Proceedings of the Workshop on Spatial and Visual Reasoning in Design*, 13-24.

[11] Piaget, J. (1950) The Psychology of Intelligence. Routledge.

[12] Vygotsky, L.S. (1978) Mind in Society: The Development of Higher Psychological Processes. Harvard University Press.

[13] Brown, J.S., Collins, A. and Duguid, P. (1989) Situated Cognition and the Culture of Learning. *Educational Researcher*, **18**, 32-42. https://doi.org/10.3102/0013189x018001032

[14] Moreno, R. and Mayer, R. (2007) Interactive Multimodal Learning Environments. *Educational Psychology Review*, **19**, 309-326. https://doi.org/10.1007/s10648-007-9047-2

[15] Klein, G.A. (1998) Sources of Power: How People Make Decisions. MIT Press.

[16] Kahneman, D. and Klein, G. (2009) Conditions for Intuitive Expertise: A Failure to Disagree. *American Psychologist*, **64**, 515-526. https://doi.org/10.1037/a0016755

[17] Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M. and Preusche, C. (2013) An Augmented Reality Training Platform for Assembly and Maintenance Skills. *Robotics and Autonomous Systems*, **61**, 398-403. https://doi.org/10.1016/j.robot.2012.09.013

[18] Bacca, J., Baldiris, S., Fabregat, R. and Graf, S. (2014) Augmented Reality Trends in Education: A Systematic Review of Research and Applications. *Educational Technology & Society*, **17**, 133-149.

[19] Hamilton, D., McKechnie, J., Edgerton, E. and Wilson, C. (2021) Immersive Virtual Reality as a Pedagogical Tool in Education: A Systematic Literature Review of Quantitative Learning Outcomes and Experimental Design. *Journal of Computers in Education*, **8**, 1-32. https://doi.org/10.1007/s40692-020-00169-2

[20] Brooke, J. (1996) SUS—A Quick and Dirty Usability Scale. In: Jordan, P.W., Thomas B., McClelland, I.L. and Weerdmeester, B., Eds., *Usability Evaluation in Industry*, Taylor & Francis, 189-194.

[21] Bangor, A., Kortum, P.T. and Miller, J.T. (2008) An Empirical Evaluation of the System Usability Scale. *International Journal of Human-Computer Interaction*, **24**, 574-594. https://doi.org/10.1080/10447310802205776

[22] Schubert, T., Friedmann, F. and Regenbrecht, H. (2001) The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments*, **10**, 266-281. https://doi.org/10.1162/105474601300343603

[23] Roediger III, H.L. and Karpicke, J.D. (2006) Test-Enhanced Learning. *Psychological Science*, **17**, 249-255. https://doi.org/10.1111/j.1467-9280.2006.01693.x