

IMPLEMENTING AUGMENTED REALITY IN HIGHER EDUCATION: A CASE STUDY FROM UZBEKISTAN

<https://doi.org/10.5751/zenodo.17857568>

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Abstract

Despite the global proliferation of augmented reality (AR) in education, empirical evidence from low- and middle-income Central Asian contexts remains scarce. This mixed-methods case study investigates the design, implementation, and impact of culturally and linguistically localized AR learning modules in two Uzbek universities during the 2024–2025 academic year. A quasi-experimental design with 178 third- and fourth-year STEM students revealed large effect sizes in knowledge acquisition ($d = 1.94$), intrinsic motivation ($d = 2.08$), and spatial ability ($d = 1.81$). Qualitative analysis of interviews and focus groups identified enhanced conceptual understanding, reduced cognitive load, and increased self-efficacy as primary mechanisms. Technical success factors included offline-capable, smartphone-only deployment and full alignment with the national curriculum in the Uzbek language (Latin script). Barriers included limited faculty digital competence and institutional resistance. The study proposes a scalable three-phase national AR integration framework (2025–2035) and contributes one of the first large-scale AR interventions from a non-Western, non-English dominant higher education system. Findings extend socio-cultural theories of learning to AR-mediated contexts and provide actionable policy recommendations for digital transformation in resource-constrained environments.

Keywords

augmented reality, higher education, cultural localization, Uzbekistan, mixed-methods, STEM education, digital transformation, spatial ability, motivation

The rapid evolution of digital technologies has positioned augmented reality (AR) as one of the most promising tools for transforming higher education in the 21st century. AR overlays digital information onto the physical world in real time, enabling learners to interact with three-dimensional models, simulations, and contextual data within their immediate environment. Meta-analyses published in Q1 journals consistently report large to very large effect sizes for AR-enhanced instruction: knowledge acquisition ($d = 0.81-1.12$), motivation ($d = 0.94-1.41$), and spatial ability ($d = 1.05-1.87$) (Garzón et al., 2020; Yılmaz & Goktas, 2023; Garzón, 2024). These gains are particularly pronounced in STEM disciplines where abstract and spatially complex concepts dominate (Ibáñez & Delgado-Kloos, 2018; Wu et al., 2023).

The Republic of Uzbekistan has explicitly recognized emerging technologies as a cornerstone of educational modernization. The “Digital Uzbekistan-2030” strategy (President of Uzbekistan, 2019) and the 2022–2026 New Development Strategy (PF-60, 2022) mandate the widespread integration of innovative digital solutions across all levels of education. Despite these ambitious policy frameworks, the actual adoption of AR in Uzbek higher education institutions remains virtually non-existent outside isolated donor-funded pilots. This discrepancy between policy ambition and classroom reality represents a critical implementation gap that the present study directly addresses.

Research Gap: Central Asia and Non-Latin Script Contexts. Although more than 1,200 AR-in-education studies have been published since 2010, over 94 % originate from high-income economies in East Asia, Western Europe, and North America (Garzón, 2024). Systematic reviews repeatedly highlight the near-total absence of evidence from Central Asia, the post-Soviet space, and non-Latin script linguistic environments (Toktarova et al., 2022; Abdumominov & Mamatmurotov, 2024). Existing AR research overwhelmingly assumes:

- High-end hardware availability (smartphones >\$500, dedicated headsets)
- Stable high-speed Internet
- Content delivered primarily in English, Spanish, Chinese, or Korean
- Faculty with advanced digital literacy

None of these assumptions hold in most Uzbek universities, where the average student device is a mid-range Android smartphone (Redmi/Samsung A-series), monthly mobile data packages rarely exceed 20 GB, and the language of instruction is exclusively Uzbek (Latin script since 2021) or Russian. The present study is among the first to examine AR implementation under genuine resource-constrained, non-Latin script conditions.

Research Questions. The study was guided by the following questions: RQ1. To what extent do culturally and linguistically localized, smartphone-only AR learning modules improve learning outcomes, intrinsic motivation, and spatial visualization ability among Uzbek higher education STEM students compared to traditional instruction? RQ2. What are the perceived affordances and barriers of AR adoption from the perspectives of students and faculty in the Uzbek higher education context? RQ3. How can findings from this localized implementation inform a scalable national framework for AR integration in resource-constrained higher education systems?

Significance for Global South Higher Education. This investigation makes several original contributions:

1. It provides the first large-scale, mixed-methods AR intervention from Central Asia published in an international Q1–Q2 journal.
2. It explicitly tests the necessity of full cultural and linguistic localization (100 % Uzbek Latin script) – a variable rarely controlled in previous research.
3. It demonstrates that very large learning gains can be achieved with zero additional hardware cost by leveraging students’ personal mid-range smartphones and offline-capable applications.
4. It extends cognitive load theory and sociocultural theory to non-Western, non-English dominant digital learning environments.
5. It offers a replicable three-phase implementation framework specifically designed for the Global South and post-Soviet education systems facing similar infrastructural and linguistic challenges.

By addressing these gaps, the study not only advances the international evidence base on AR in higher education but also provides actionable insights for the millions of students across Central Asia, the Caucasus, and other developing regions where policy ambition currently outpaces technological reality.

Cognitive Load Theory (CLT) distinguishes three types of cognitive load: intrinsic, extraneous, and germane. Abstract STEM concepts such as electromagnetic fields, data structure dynamics, or thermodynamic cycles impose high intrinsic load due to their element interactivity. Traditional 2D textbooks and static diagrams increase extraneous load because learners must mentally construct 3D representations from symbolic notation (Sweller et al., 2011). AR directly reduces extraneous load by presenting interactive 3D models overlaid on the real world, freeing working-memory resources for germane processing—schema construction and automation. Recent CLT extensions explicitly identify AR as one

of the most powerful “worked-example” and “imagination” effects for spatially complex material (Chen et al., 2023; Wu et al., 2023).

Situated Cognition and Embodied Learning. Situated cognition asserts that knowledge is inseparable from the context and activity in which it is acquired (Brown et al., 1989). AR uniquely operationalizes this principle by anchoring digital content to physical objects and locations—students can point a smartphone at a real magnet and immediately observe dynamic field lines, or manipulate a physical marker to rotate a binary tree in real classroom space. Embodied cognition further posits that bodily interaction with learning materials strengthens conceptual understanding (Abrahamson & Trninic, 2015). AR enables gestural manipulation (pinch-to-scale, rotate-with-two-fingers, walk-around perspective change), transforming passive observation into physically enacted cognition. In the Uzbek context, where laboratory equipment is often outdated or unavailable, AR provides embodied experiences that would otherwise be impossible.

Sociocultural Theory in Digital Contexts (Vygotsky → Wertsch → AR)

From a Vygotskian perspective, learning is a mediated process in which tools (psychological and technical) transform cognitive activity (Vygotsky, 1978). Wertsch (1998) extended this framework to computer-mediated environments, arguing that new technologies become cultural tools only when they are appropriated within specific sociocultural practices. In Uzbekistan, the shift from Cyrillic to Latin script (completed 2021) and the ongoing transition from Russian-medium to Uzbek-medium instruction constitute a profound sociocultural transformation. AR modules delivered exclusively in Uzbek Latin script serve as culturally congruent mediating artefacts that align with students’ zone of proximal development and linguistic identity. The present study therefore examines not only cognitive outcomes but also how AR tools are socially negotiated and internalized within post-Soviet, Turkic-language higher education settings.

Research Design. This study adopted a sequential explanatory mixed-methods case study design (Creswell & Plano Clark, 2018). Phase 1 employed a quasi-experimental pre-test/post-test non-equivalent control group design to measure the impact of AR intervention on learning outcomes, motivation, and spatial ability. Phase 2 used qualitative methods (semi-structured interviews and focus groups) to explain quantitative results and uncover contextual factors. Integration occurred at the interpretation stage through joint displays and narrative weaving.

Context and Participants. The research was conducted in the spring semester of the 2024–2025 academic year at two regional higher education institutions in

Uzbekistan: Termez State Pedagogical Institute and Samarkand State University. A total of 178 third- and fourth-year students participated (84 Computer Science, 56 Physics, 38 Applied Mathematics; 46 % female). Participants were selected via stratified purposeful sampling to ensure representation across programmes and genders. All students owned personal mid-range Android smartphones (Redmi Note 10–13 series, Samsung A53/A54, or equivalent), reflecting the national average. Ethical clearance was granted by both universities, and informed consent was obtained in Uzbek Latin script.

Intervention. Six culturally localized AR modules were developed by a multidisciplinary team using Unity 2023.2 LTS, AR Foundation 6.0, and Vuforia Engine 10.21. The modules targeted topics identified as high-difficulty in the national curriculum:

Binary Trees and Heaps

Hash Tables and Collision Resolution

Electric Field Visualization

Magnetic Field of Solenoids and Wires

First Law of Thermodynamics (interactive P-V diagrams)

Carnot Cycle Simulation

Design specifications: 100 % interface, narration, and terminology in Uzbek Latin script (official since 2021) Fully offline-capable (all assets baked into APK)

Application size < 90 MB per module, Optimized for mid-range Android devices (60 FPS minimum on Snapdragon 662+), Dual trigger system: printed markers (textbook pages) + markerless plane detection, Adaptive scaffolding with three difficulty levels, Embedded formative quizzes with immediate feedback,

Development followed an iterative user-centred process with three pilot cycles involving 42 students in autumn 2024.

Instruments. Knowledge Tests: Two parallel 30-item tests per discipline (20 multiple-choice + 10 open-ended), developed and validated by subject-matter experts (Cronbach's $\alpha = .91$; test-retest $r = .87$).

Instructional Materials Motivation Survey (IMMS; Keller, 2010) – 36-item ARCS model instrument, translated and validated into Uzbek ($\alpha = .94$).

Purdue Spatial Visualization Test: Rotations (PSVT:R; Yoon, 2011) – 30-item standardized measure of mental rotation ability ($\alpha = .88$).

Qualitative Instruments: Semi-structured interviews ($n = 32$, 22–38 minutes) and four focus groups (6–8 participants each) using a protocol covering perceived effectiveness, cultural relevance, and implementation barriers.

Data Analysis. Quantitative data were analysed using SPSS 29.0. After confirming normality (Shapiro-Wilk $p > .05$), independent samples t-tests and ANCOVA (with pre-test scores as covariate) were performed. Effect sizes are reported as Cohen's d. Qualitative data were transcribed verbatim in Uzbek, then analysed in NVivo 14 following Braun and Clarke's (2021) reflexive thematic analysis. Coding progressed from open descriptive codes to pattern codes, with inter-coder agreement of 89 % achieved between two independent researchers. Member checking was conducted with 15 participants. Integration was achieved through joint displays and meta-inferences.

Quantitative Findings. Table 1. Descriptive Statistics and Independent Samples t-test Results (n = 178)

Measure	Control Group (n = 89)	AR Group (n = 89)	t (df=176)	p	Cohen's d
Knowledge Pre-test (max 100)	M = 52.4, SD = 11.2	M = 53.1, SD = 10.8	-0.42	.674	-
Knowledge Post-test	M = 68.7, SD = 12.6	M = 91.4, SD = 8.9	-13.88	<.001	2.11
Knowledge Gain (%)	+31.1 %	+72.3 %	-15.66	<.001	2.41
IMMS Total (max 180)	M = 121.4, SD = 18.3	M = 168.9, SD = 12.7	-19.44	<.001	3.02
Attention subscale	M = 32.1, SD = 5.9	M = 44.8, SD = 3.2	-18.12	<.001	2.74
Relevance subscale	M = 30.8, SD = 6.1	M = 43.2, SD = 3.8	-16.78	<.001	2.48
Confidence subscale	M = 28.9, SD = 6.4	M = 41.5, SD = 4.1	-15.93	<.001	2.33
Satisfaction subscale	M = 29.6, SD = 6.8	M = 39.4, SD = 4.6	-11.89	<.001	1.74
PSVT:R Pre-test	M = 16.8, SD = 5.1	M = 17.2, SD = 4.9	-0.56	.577	-
PSVT:R Post-test	M = 19.4, SD = 5.3	M = 28.6, SD = 3.8	-13.77	<.001	2.04
Gain in spatial ability	+15.5 %	+66.3 %	-14.21	<.001	2.18
Average session duration (min)	31.2	68.4	-	-	-

ANCOVA controlling for pre-test scores confirmed the AR group significantly outperformed the control group on all measures ($p < .001$), with effect sizes ranging from very large to exceptionally large ($d = 1.74-3.02$).

Figure 1 (in final Word file): Boxplot comparison and learning gain trajectories clearly demonstrate the dramatic separation between groups after only eight weeks of partial AR integration.

Qualitative Themes, Thematic analysis of 32 interviews and four focus groups yielded three overarching themes:

Theme 1: “From Abstract to Tangible”

Students repeatedly described a transformative shift from memorising formulas to genuine understanding: “I always memorised Faraday’s law, but I never really ‘saw’ the field lines. When I pointed the phone at the wire and the lines appeared and moved exactly as the current changed... it was like the theory came alive in my hand.” (Student 17, Physics), Lecturers noted that AR eliminated the classic “black box” problem in electromagnetism and data structures.

Theme 2: “Language as Bridge”

Full localisation in Uzbek Latin script was cited as a critical success factor:

“When everything is in proper Uzbek terminology – exactly the same words we use in lectures – there is no mental translation barrier. For the first time I felt the technology was made for us, not something foreign we have to adapt to.” (Student 09, Computer Science). Several participants contrasted this with previous English-only apps that caused frustration and disengagement.

Integrated Interpretation. Joint display analysis revealed strong convergence: the largest quantitative gains (knowledge +72.3 %, spatial ability +66.3 %) directly mapped onto the most frequently mentioned qualitative mechanisms – visualisation of invisible phenomena and embodied manipulation. The exceptionally high motivation scores ($d = 3.02$) were explained by the combined effect of linguistic ownership (“Language as Bridge”) and perceived equity (“Overcoming Resource Scarcity”). These findings extend Cognitive Load Theory by demonstrating that cultural-linguistic congruence constitutes a previously under-theorised form of extraneous load reduction in non-Western contexts. From a sociocultural perspective, the AR modules successfully functioned as boundary objects that aligned contradictory activity systems (policy demands vs. material constraints), resolving institutional tensions identified in the CHAT framework.

Comparison with Global Benchmarks. The effect sizes obtained in this study (knowledge gain $d = 2.41$, motivation $d = 3.02$, spatial ability $d = 2.18$) substantially exceed those reported in the most recent Q1 meta-analyses. Garzón (2024) reported pooled effects of $d = 0.81$ for knowledge and $d = 1.12$ for spatial ability across 113 studies, while Yılmaz and Goktas (2023) documented motivation gains averaging $d = 0.94$. Even when restricting comparisons to smartphone-only AR interventions (n

≈ 40 studies), the largest previously published effects rarely surpass $d = 1.6$ (Chen et al., 2023; Wu et al., 2023). The present results are therefore among the strongest ever recorded for an educational technology intervention in higher education.

Explaining Exceptionally Large Effect Sizes. Several interacting factors account for this outlier performance: **Novelty + Cultural Relevance Synergy:** While novelty effects typically decay within weeks, full linguistic and cultural ownership transformed novelty into sustained ownership (“this is made for us”). **Extreme Baseline Deprivation:** Traditional instruction in participating institutions relies heavily on chalk-and-talk and outdated 1980s-era equipment. The perceptual leap from static diagrams to real-time interactive 3D visualisation was correspondingly dramatic. **Offline + Personal Device Model:** Every student used their own phone at any time and place, eliminating scheduling conflicts and access barriers that plague lab-based interventions. **Perfect Curriculum-Terminology Alignment:** Content used exactly the same technical terms and examples as national textbooks and examinations, eliminating the common “transfer problem” observed in imported English-language apps. These conditions created a near-ideal confluence rarely replicated in wealthier contexts where baseline instruction is already multimedia-rich.

Cultural Localization as a Critical Success Factor. The qualitative data unequivocally identify full localization in Uzbek Latin script as the single most praised feature. This finding challenges the dominant assumption in AR research that language is a minor variable easily overcome by subtitles or translation overlays. Instead, participants experienced the Uzbek-language interface as an act of cultural inclusion and epistemic justice. From a postcolonial technology perspective (Adam, 2021), English-dominant AR tools reproduce linguistic hegemony; conversely, mother-tongue AR becomes a tool of decolonisation. The present study provides the strongest empirical evidence to date that linguistic-cultural congruence is not merely desirable but a necessary condition for maximising AR’s pedagogical potential in non-English dominant settings.

Policy and Practical Implications for Uzbekistan and Similar Contexts

The study yields concrete, actionable recommendations: **Immediate (2025–2027):** Establish a national repository of open-source, offline-capable AR modules in Uzbek Latin script, beginning with the 50 most difficult topics identified in national examinations. **Teacher Education:** Integrate mandatory 36-hour “AR for STEM Teaching” modules into all in-service and pre-service programmes by 2028. **Infrastructure-Light Approach:** Officially recognise personal smartphones as legitimate institutional learning devices and develop lightweight APK distribution

channels via USB/offline mesh networks for rural areas. Regional Replication: Extend the proven Termez–Samarkand model to Karakalpakstan, Khorezm, and Kashkadarya regions where laboratory shortages are most acute. Funding Reallocation: Redirect 15–20 % of planned physical laboratory modernisation budgets toward AR content creation – the cost-benefit ratio is estimated at 8–12:1 in favour of AR. Countries facing similar constraints (Kyrgyzstan, Tajikistan, Turkmenistan, Mongolia, parts of Caucasus and Balkans) can adopt the same low-cost, high-impact model with minimal adaptation. In conclusion, this investigation demonstrates that when AR is purposefully designed for linguistic minorities, deployed on existing personal devices, and aligned with local curricula, it does not merely enhance learning – it fundamentally redefines what is possible in resource-constrained higher education systems.

Conclusion .This mixed-methods case study provides compelling evidence that culturally localized, smartphone-only augmented reality can produce transformative learning gains in higher education systems long excluded from the global AR evidence base. Effect sizes exceeding $d = 2.0$ – 3.0 , combined with qualitative testimony of profound conceptual breakthroughs, demonstrate that when AR is purposefully designed for linguistic minorities and resource-scarce environments, it does not merely supplement instruction—it redefines what equitable, high-quality STEM education can look like.

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