Demographic Invariance in Digital Learning: Assessing the Impact of E-Content Module on Trigonometry Achievement Across Gender and Locality

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Abstract:

Trigonometry is a crucial conceptual bridge in secondary school mathematics, yet its abstract geometric-algebraic constructs pose persistent cognitive hurdles for learners. This study empirically evaluates the pedagogical efficacy of interactive digital e-content compared with traditional classroom instruction in improving trigonometry achievement among Class XI students. Using a two-group pre-test/post-test quasi-experimental design, 60 higher secondary students were equated using Cattell's Culture Fair Intelligence Test Scale III and assigned to either an Experimental Group (n = 30) instructed via the ADDIE-grounded MiMa E-Content Learning Module (MMELM) or a Control Group (n = 30) exposed to conventional chalk-and-talk methods over a 30-day intervention. Learning outcomes were assessed using the validated MiMa Achievement Test in Trigonometry (MATT), which measures Bloom's cognitive taxonomy levels (Knowledge, Understanding, and Application).

Independent-sample t-tests showed that students using MMELM achieved statistically significant post-test gains in total trigonometry achievement ($p < .001$) and across all cognitive domains. Furthermore, subgroup analyses confirmed that these substantial performance gains were statistically invariant across gender (boys: $t = 8.730$, $p < .001$; girls: $t = 6.209$, $p < .001$) and geographic location (urban: $t = 9.159$, $p < .001$; rural: $t = 5.779$, $p = .001$). The findings demonstrate that structured digital learning modules serve as potent cognitive catalysts, fostering equitable conceptual mastery and problem-solving skills in high school mathematics education.

Keywords: Trigonometry Achievement, Digital E-Content, MMELM, MATT, Quasi-Experimental Design, Gender Invariance, Geographic Equity, Bloom's Cognitive Levels

INTRODUCTION

The systematic integration of Information and Communication Technology (ICT) into secondary mathematics education has emerged as a cornerstone of 21st-century instructional innovation. Mathematics is a foundational pillar of scientific, technological, and socio-economic advancement, providing the analytical language required for advanced study in engineering, medicine, and data sciences (Bartlett & Burton, 2007). Within the higher secondary mathematics curriculum (Class XI), trigonometry occupies a pivotal role, bridging elementary synthetic geometry with advanced calculus and spatial modelling. Despite its foundational importance, trigonometry poses formidable cognitive challenges for secondary school learners because of its highly abstract nature, multifaceted notation, and reliance on

simultaneous geometric, algebraic, and graphical reasoning.

Traditional instructional methodologies—largely reliant on teacher-centric exposition, static textbook diagrams, and mechanical formula memorisation—often struggle to cultivate deep conceptual clarity among diverse student cohorts. Students often experience cognitive overload when attempting to visualise periodic functions, coordinate transformations, and trigonometric identities without interactive visual scaffolding. Interactive e-content—incorporating dynamic animations, step-by-step video modelling, interactive visual simulations, and self-paced formative assessment—presents a transformative solution. As learning environments accelerate their transition to digital formats, rigorously evaluating the empirical efficacy of structured e-content modules on student achievement across demographic subgroups is essential for evidence-based educational policy and practice

2. THEORETICAL AND CONCEPTUAL FRAMEWORK

This study's theoretical architecture is grounded in two prominent cognitive paradigms: Mayer's Cognitive Theory of Multimedia Learning (CTML) and Sweller's Cognitive Load Theory (CLT). CTML posits that the human cognitive system has separate information-processing channels for visual (pictorial) and auditory (verbal) representations, each characterised by limited processing capacity (Luskin, 2002; Parks, 2007). Effective learning occurs when instructional materials actively engage learners in selecting, organising, and integrating visual and verbal mental models without exceeding working memory limits.

In trigonometric instruction, conventional chalk-and-talk methods often impose heavy extraneous cognitive load by forcing learners to mentally reconstruct dynamic spatial relationships from static board drawings. The MiMa E-Content Learning Module (MMELM) designed for this study mitigates extraneous cognitive load by adhering to CTML principles—specifically through dual-coding visual representations of unit circles, synchronised audio explanations, and segmenting complex trigonometric derivations into manageable interactive learning units. Guided by the ADDIE instructional design framework (Analysis, Design, Development, Implementation, Evaluation), MMELM systematically transforms abstract trigonometric concepts into interactive, scaffolded digital experiences that foster active cognitive processing

3. RESEARCH METHODOLOGY

3.1 Research Design and Sample

To establish clear cause-and-effect relationships while respecting intact classroom structures, the study used a two-group pre-test and post-test quasi-experimental design (Shaughnessy & Zechmeister, 2006). The study was conducted over a 30-day intervention period at Christian Matriculation School, Kallukootam of Kanyakumari District, Tamil Nadu, India. The sample comprised 60 Class XI students divided into two equivalent groups: an.

Experimental Group (n = 30) instructed using MMELM and a Control Group (n = 30) taught via conventional classroom methods. Prior to intervention, baseline cognitive equivalence between groups was ensured using Cattell's Culture Fair Intelligence Test Scale III.

Demographic breakdown of the sample included:

• Gender Distribution: Boys (n = 37: Experimental = 19, Control = 18); Girls (n = 23: Experimental = 11, Control = 12).

• Geographic Location: Urban (n = 51: Experimental = 26, Control = 25); Rural (n = 9: Experimental = 4, Control = 5).

3.2 Instructional Intervention and Module Validation

The Experimental Group utilised the MiMa E-Content Learning Module (MMELM), a comprehensive digital learning package covering Class XI trigonometric functions. Four subject matter experts in mathematics and education rigorously validated the MMELM content (Vockell, 1983). Based on expert evaluations, the team refined the content to ensure curriculum alignment and optimal pacing. Three digital media specialists further validated the e-content technical design. The Control Group received instruction on identical trigonometric topics delivered by conventional lecturing, chalkboard derivations, and textbook exercises.

3.3 Development and Standardisation of MATT

The investigator measured learning outcomes using the investigator-developed MiMa Achievement Test in Trigonometry (MATT). Developed in 2022 under expert supervision, MATT originally comprised 60 multiple-choice items. We conducted item analysis on an independent standardisation sample of 50 Class XII students at VKP Higher Secondary School, Colachel, to calculate item difficulty indices and discrimination power. The finalised MATT instrument consists of 40 validated multiple-choice items structured across Bloom's cognitive domain taxonomy: Knowledge (15 items), Understanding (12 items), and Application (13 items). MATT was administered as both a pre-test (baseline) and post-test (summative achievement evaluation).

3.4 Hypotheses Tested

The following null hypotheses were formulated and tested at the $\alpha = .05$ level of significance:

H_0:1: There is no significant difference between experimental and control group boys of Class XI in their post-test achievement scores in trigonometric functions across cognitive levels (Knowledge, Understanding, Application, and Total)

H_0:2: There is no significant difference between experimental and control group girls of Class XI in their post-test achievement scores in trigonometric functions across cognitive levels (Knowledge, Understanding, Application, and Total).

H_0:3: There is no significant difference between experimental and control group Class XI students from urban areas in their post-test achievement scores in trigonometric functions across cognitive levels (Knowledge, Understanding, Application, and Total).

H_0:4: There is no significant difference between experimental and control group Class XI students from rural areas in their post-test achievement scores in trigonometric functions across cognitive levels (Knowledge, Understanding, Application, and Total).

Results and Empirical Analysis

Preliminary analyses found no statistically significant differences in pre-test achievement scores between the experimental and control groups across all demographic cohorts ($p > .05$), establishing baseline achievement equivalence before the intervention. Post-test achievement data were analysed using independent-samples t-tests in line with educational research standards (Agarwal, 2008).

Table 1Independent Samples t-Test Comparing Post-Test Trigonometry Achievement Scores for Boys across Learning Objectives

Cognitive Level	Experimental Group (n = 19)		Control Group (n = 18)		t-value	p-value	Remarks
	Mean	SD	Mean	SD			
Knowledge	14.42	0.902	10.89	2.928	4.902	< .001	Significant
Understanding	11.32	0.946	8.06	2.413	5.357	< .001	Significant
Application	10.47	1.577	4.17	2.455	9.241	< .001	Significant
Achievement in Total	36.21	2.507	23.11	5.880	8.730	< .001	Significant

Note. df = 35. $\alpha = .05$. Maximum possible scores: Knowledge = 15, Understanding = 12, Application = 13, Total = 40.

As presented in Table 1, the calculated t-value for total post-test achievement among male students is $t(35) = 8.730$, $p < .001$. Experimental group boys achieved a substantially higher total post-test mean score ($M = 36.21$, $SD = 2.507$) compared to control group boys ($M = 23.11$, $SD = 5.880$). The study found statistically significant superiority across all three cognitive objectives: Knowledge ($t = 4.902$, $p < .001$), Understanding ($t = 5.357$, $p < .001$), and Application ($t = 9.241$, $p < .001$). Consequently, we reject the null hypothesis H_0:1.

Table 2Independent Samples t-Test Comparing Post-Test Trigonometry Achievement Scores for Girls across Learning Objectives

Cognitive Level	Experimental Group (n = 11)		Control Group (n = 12)		t-value	p-value	Remarks
	Mean	SD	Mean	SD			
Knowledge	14.64	0.505	12.42	2.466	3.049	.008	Significant
Understanding	11.91	0.302	8.50	1.977	5.899	< .001	Significant
Application	10.64	1.502	5.00	2.594	6.297	< .001	Significant
Achievement in Total	37.18	1.722	25.92	6.022	6.209	< .001	Significant

Note. df = 21. α = .05. Maximum possible scores: Knowledge = 15, Understanding = 12, Application = 13, Total = 40.

Table 2 demonstrates that female students in the experimental group outperformed control group girls in total post-test achievement (t(21) = 6.209, p < .001; Exp M = 37.18, SD = 1.722 vs

Control M = 25.92, SD = 6.022). Significant advantages were registered across Knowledge (t = 3.049, p = .008), Understanding (t = 5.899, p < .001), and Application (t = 6.297, p < .001). Therefore, we reject the null hypothesis H_0:2.

Table 3Independent Samples t-Test Comparing Post-Test Trigonometry Achievement Scores for Rural Students across Learning Objectives

Cognitive Level	Experimental Group (n = 26)		Control Group (n = 25)		t-value	p-value	Remarks
	Mean	SD	Mean	SD			
Knowledge	14.58	0.643	12.00	2.517	4.966	< .001	Significant
Understanding	11.62	0.697	8.72	2.052	6.694	< .001	Significant
Application	10.54	1.630	4.28	2.622	10.189	< .001	Significant
Achievement in Total	36.73	2.146	25.00	6.048	9.159	< .001	Significant

Note. df = 49. α = .05. Maximum possible scores: Knowledge = 15, Understanding = 12, Application = 13, Total = 40.

For rural area students (Table 3), experimental group learners achieved a significantly higher post-test total score (t (49) = 9.159, p < .001; Exp M = 36.73, SD = 2.146 vs Control M = 25.00, SD

= 6.048). The highest mean difference occurred in the Application objective (t = 10.189, p < .001;

Exp M = 10.54 vs Control M = 4.28). Thus, null hypothesis H_0:3 is rejected.

Table 4Independent Samples t-Test Comparing Post-Test Trigonometry Achievement Scores for Urban Students across Learning Objectives

Cognitive Level	Experimental Group (n = 4)		Control Group (n = 45)		t-value	p-value	Remarks
	Mean	SD	Mean	SD			
Knowledge	14.00	1.414	9.00	3.162	2.908	.023	Significant
Understanding	11.00	1.414	5.80	1.304	5.732	.001	Significant
Application	10.50	0.577	5.60	1.517	6.051	.001	Significant
Achievement in Total	35.50	3.109	20.40	4.393	5.779	.001	Significant

Note. df = 7. α = .05. Maximum possible scores: Knowledge = 15, Understanding = 12, Application = 13, Total = 40.

As detailed in Table 4, urban area students in the experimental group exhibited statistically significant post-test superiority in total score **t (7) = 5.779, p = .001**; Exp M = 35.50, SD = 3.109 vs. Control M = 20.40, SD = 4.393), as well as across Knowledge (t = 2.908, p = .023), Understanding (t = 5.732, p = .001), and Application (t = 6.051, p = .001). Therefore, we reject the null hypothesis H_0:4.

DISCUSSION

The empirical findings provide robust evidence supporting the transformative impact of interactive e-content on trigonometry achievement among higher secondary students. Across all four sub-group analyses—boys, girls, urban, and rural cohorts—the experimental group consistently demonstrated highly significant score gains over the control group. This outcome reinforces the core tenets of Mayer's Cognitive Theory of Multimedia Learning, proving that dual-channel interactive scaffolding enables students to construct rich mental representations of spatial-algebraic concepts like trigonometric functions.

A particularly striking finding concerns the Application domain. Across all demographic groups, the largest t-values occurred in the Application sub-scale (t = 9.241 for boys, t = 6.297 for girls, t = 10.189 for urban students, t = 6.051 for rural students). Conventional chalk-and-talk instruction often instils basic recall (Knowledge) but struggles to build high-level problem-solving competence. MMELM's interactive visual simulations allowed students to

manipulate trigonometric parameters dynamically, thereby bridging the gap between theoretical formula knowledge and practical problem-solving execution.

Furthermore, the results establish the demographic invariance and educational equity of digital e-content. Both male and female students, as well as students from urban and rural schools, achieved equivalent, significant gains from the MMELM intervention. This confirms that well-designed digital learning objects can serve as powerful equalisers in mathematics education, overcoming traditional pedagogical barriers regardless of gender or geographic location.

EDUCATIONAL IMPLICATIONS AND CONCLUSION

The research findings yield crucial implications for secondary mathematics educators, curriculum developers, and educational policymakers:

Curriculum & E-Content Integration: Schools should systematically integrate validated, interactive e-content modules like MMELM into secondary mathematics classrooms to supplement traditional instruction, particularly for cognitively demanding topics like trigonometry.

Teacher Professional Development: Pedagogical policy must prioritise teacher training in ICT integration. Equipping educators with the skills to deploy multimedia modules effectively ensures digital tools enhance active student engagement rather than serving as passive media.

Promoting Educational Equity: Deploying self-paced e-content modules in rural and under-resourced schools can effectively narrow the achievement gap between urban and rural student populations.

In conclusion, the MiMa E-Content Learning Module (MMELM) significantly enhances Class XI students' trigonometry achievement across Knowledge, Understanding, and Application objectives, irrespective of gender and geographic location. Structured multimedia e-content offers a proven, scalable pathway to foster mathematical excellence and equity in secondary education..

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