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Technology Integration in Geometry Instruction: SEM Analysis of Pre-Service Mathematics Teachers' Perspectives and Experiences

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ABSTRACT

This study aims to examine pre-service mathematics teachers' perceptions, experiences, and challenges related to using digital tools in geometry education. A total of 229 pre-service teachers participated, most of whom were female (69.2%), under 20 years old (81.7%), and enrolled in bachelor's-level mathematics education programs (91.7%). Structural Equation Modeling (SEM) was used to examine relationships among factors affecting the effectiveness and pedagogical integration of digital tools in teaching geometry. Results showed significant positive relationships between engagement and motivation, usability and accessibility, and future training and support needs with both learning and teaching effectiveness, as well as pedagogical integration strategies. Surprisingly, reported challenges and barriers did not significantly impact these outcomes, suggesting greater technological proficiency among newer generations or improved usability of digital tools. These findings highlight the importance of motivation, accessible technology, and targeted professional development in supporting effective integration of digital tools into geometry instruction. Implications for teacher education programs and recommendations for future research are discussed.

KEYWORDS

Digital tools; geometry education; pre-service mathematics teachers; structural equation modeling; technological integration.

INTRODUCTION

Pedagogical integration refers to the intentional and meaningful incorporation of digital tools into instructional practices to improve teaching effectiveness and student learning. In this study, it involves how pre-service mathematics teachers design, implement, and align technology-supported strategies with curriculum objectives in geometry instruction. National insight, in the broader educational context, refers to the understanding of how systemic, institutional, and cultural factors within a country influence the use of educational technology, teacher preparation, and curriculum development.

The rapid integration of digital tools into mathematics education has transformed the teaching and learning of geometric concepts, offering dynamic alternatives to traditional static methods (Karlinger & Erbaş, 2024). Geometry, with its focus on spatial reasoning and visualization, particularly benefits from tools such as GeoGebra, Desmos, and TI-Nspire, which allow students to manipulate shapes, explore transformations, and visualize three-dimensional figures in ways textbooks cannot (Ng & Sinclair, 2018). As classrooms increasingly adopt these technologies, pre-service mathematics teachers must be prepared to use them effectively. However, despite the growing availability of digital tools, their specific use in geometry instruction and the experiences of pre-service teachers remain underexplored, especially in comparison to broader areas of mathematics like algebra (Trgalová, 2022).

This gap is critical given geometry's unique pedagogical demands and the crucial role pre-service teachers play in shaping educational outcomes. Research highlights digital tools' potential to improve conceptual understanding and engagement in geometry (Hillmayr et al., 2020), yet pre-service teachers frequently report technical, pedagogical, and access-related challenges that hinder effective integration (Lyublinskaya & Kaplon-Schilis, 2020). These barriers, along with inconsistent training in teacher education programs, raise concerns about how well prepared these educators are to implement technology in geometry classrooms. Existing research often emphasizes tool effectiveness or general technology adoption, leaving a gap in understanding pre-service teachers' specific perceptions and experiences in geometry instruction, a domain where visualization and interactivity are central.

This study addresses this gap by examining pre-service mathematics teachers' perceptions (Wambua, 2025), experiences, and challenges related to the use of digital tools in geometry instruction. Geometry is emphasized due to its strong reliance on visualization, where digital tools provide distinct advantages. Although research on technology integration has largely focused on algebra and calculus, the spatial nature of geometry necessitates dedicated attention (Sinclair et al., 2016). Understanding pre-service teachers' experiences with these tools in geometry is essential, as their perceptions will shape future classroom practices (Hoyles & Lagrange, 2010).

Research Questions

1. What are pre-service mathematics teachers' perceptions of digital tool use in geometry education regarding usability, engagement, pedagogical strategies, and effectiveness?

2. How do factors such as usability and accessibility, engagement and motivation, challenges and barriers, and future training and support needs affect the perceived effectiveness of digital tools in learning and teaching geometry?
3. To what extent do challenges and barriers significantly impact the effectiveness and pedagogical integration of digital tools in geometry instruction?
4. What relationships exist among the core dimensions that contribute to successful integration of digital tools in pre-service geometry education?

LITERATURE REVIEW

Introduction to Digital Tools in Mathematics Education

The integration of digital tools into mathematics education has transformed pedagogical practices, offering dynamic platforms to explore mathematical concepts beyond traditional methods. Tools such as GeoGebra, Desmos, and graphing calculators like the TI-Nspire CX CAS are software and hardware designed to enhance mathematical understanding (Bray & Tangney, 2017). These tools have evolved from basic computational aids into interactive systems that support visualization and experimentation (Hoyles & Lagrange, 2010). The National Council of Teachers of Mathematics (NCTM, 2014) emphasizes their importance in deepening conceptual understanding and preparing students for a technology-driven society, a priority that continues with ongoing innovation (Smith & Jones, 2024). In geometry, digital tools are especially valuable due to the subject's reliance on spatial reasoning and visual representation. Research shows that technology helps students visualize abstract concepts, such as transformations and three-dimensional figures, through dynamic manipulation (Ajose, 2025; Sinclair et al., 2016). For example, GeoGebra enables users to explore geometric properties interactively, providing greater insight than static diagrams (Zhang et al., 2023). This reflects broader educational trends toward active, student-centered learning (Darling-Hammond et al., 2020). The use of technology in mathematics education dates back to calculators in the 1970s, progressed to computer software in the 1990s, and now includes cloud-based and mobile platforms (Bray & Tangney, 2017). Emerging technologies such as artificial intelligence (Dos, 2025) and virtual reality are expected to further transform geometry education, though their impact in classrooms remains underexplored. The NCTM (2014) emphasizes equitable access to these tools as a means of reducing achievement gaps, a goal that relies heavily on teachers' preparedness, particularly pre-service educators who are still developing their instructional skills (Koehler & Mishra, 2009).

Theoretical Frameworks for Technology Integration in Education

The integration of digital tools into mathematics education, particularly in geometry, depends on robust theoretical frameworks that explain how technology enhances teaching and learning. One of the most influential is the Technological Pedagogical Content Knowledge (TPACK) framework, developed by Koehler and Mishra (2009). TPACK combines technological, pedagogical, and content knowledge to support effective instruction (Chai et al., 2013). Recent studies have affirmed its relevance for pre-service teachers, showing that those with well-developed TPACK demonstrate greater confidence in using digital tools for geometry instruction (Benton-Borghi, 2016). Complementing TPACK, the SAMR model (Substitution, Augmentation, Modification, Redefinition), introduced by Puentedura (2013), categorizes technology use by its capacity to transform learning. In geometry, substitution might involve replacing paper sketches with digital graphs on Desmos, while redefinition could allow students to interact with 3D models—tasks not possible without technology (Hamilton et al., 2016).

These frameworks align closely with constructivist learning theories, rooted in the works of Piaget and Vygotsky, which emphasize active knowledge construction—making them particularly relevant to the use of digital tools in geometry. Dynamic Geometry Environments (DGEs) such as GeoGebra support this approach by enabling students to manipulate shapes and test hypotheses, improving deeper understanding of geometric properties (Drijvers, 2015). Recent studies show that DGEs enhance spatial reasoning and problem-solving skills (Ng & Sinclair, 2018). Additionally, cognitive theories related to visualization support the use of technology in geometry education. For instance, multimedia learning theory (Mayer & Moreno, 1998) posits that combining visual and verbal representations enhances comprehension—a principle supported by research on geometry software (Pellas, 2024). Emerging evidence indicates that pre-service teachers who engage with such tools report improved student outcomes, although technical challenges and gaps in training remain significant barriers (Bray & Tangney, 2023).

Digital Tools in Geometry Education

Among the most used tools in geometry education are GeoGebra, Desmos, and The Geometer's Sketchpad (Sketchpad), along with others such as Cabri Geometry and the TI-Nspire CX CAS. GeoGebra, an open-source dynamic geometry software, leads the field due to its versatility in creating interactive constructions, graphing functions, and simulating 3D models (Hohenwarter et al., 2016). Recent studies have highlighted its broad adoption in teacher education programs, with pre-service teachers appreciating its accessibility and alignment with geometry curricula (Bray & Tangney, 2023). Desmos, initially developed for graphing, has since incorporated geometry features that allow students to explore transformations and properties interactively, though it remains less comprehensive than GeoGebra for advanced constructions (Clark-Wilson et al., 2020).

The features of these geometry-specific tools are designed to meet the spatial and visual demands of the subject. GeoGebra and Sketchpad, for example, enable users to manipulate shapes dynamically, revealing properties such as congruence and symmetry through drag-and-drop interactions (Leung & Baccaglini-Frank, 2017). TI-Nspire CX CAS, a graphing calculator software, combines symbolic manipulation with geometric visualization, offering a hybrid approach that pre-service teachers find effective for both instruction and assessment (Lyublinskaya & Tournaki, 2014). Cabri Geometry, though less commonly used today, offers similar dynamic capabilities with an emphasis on intuitive design for exploring geometric proofs (Laborde & Laborde, 2015).

Comparative analyses of these tools reveal distinct pedagogical strengths and limitations. GeoGebra's open-source model and extensive online resources make it highly accessible, earning strong usability ratings from pre-service teachers (Hohenwarter et al., 2016). Desmos stands out for its engaging, user-friendly interface and gamified elements, which enhance student motivation (Clark-Wilson et al., 2020). Sketchpad, a pioneer in dynamic geometry, has declined in use due to licensing fees and competition from free alternatives, though it remains appreciated for its precision in geometric constructions (Leung & Baccaglini-Frank, 2017). TI-Nspire excels in integrating with classroom hardware and supporting differentiated instruction, but its higher cost and complexity can be barriers to widespread adoption (Lyublinskaya & Tournaki, 2014).

Pre-Service Teachers' Perceptions and Preparedness

Pre-service mathematics teachers' perceptions and preparedness for integrating digital tools into geometry education are critical to their future classroom success, influencing how they adopt and apply technology. Research consistently shows that pre-service teachers view digital tools as beneficial for improving student understanding and engagement, though their attitudes often depend on prior exposure and training (Balta et al., 2020; Kenyon & Benson, 2025; Tondeur et al., 2012). A review by Tondeur et al. (2012) found that those who used dynamic geometry software during their training reported more positive perceptions of its effectiveness in visualizing complex concepts.

Confidence in using digital tools is a key factor in pre-service teachers' preparedness and is strongly tied to their training experiences. Akkaya (2016) found that pre-service teachers who completed structured coursework in educational technology felt considerably more confident in designing technology-enhanced lessons. This aligns with broader research showing that targeted, hands-on training improves both self-efficacy and the practical integration of digital tools in mathematics instruction (Ertmer et al., 2012). As such, confidence tends to grow when pre-service teachers receive purposeful and experience-based learning opportunities. Factors affecting pre-service teachers' competence include prior teaching experience and access to professional development. Lyublinskaya and Tournaki (2014) found that pre-service teachers with school-based teaching practice were more proficient in integrating TI-Nspire into geometry lessons, as real-world application reinforced both their technical and pedagogical skills. In contrast, those without such opportunities often struggled, particularly with managing technical disruptions (Pamuk, 2012). Additionally, the frequency of digital tool use in coursework affects preparedness; consistent engagement correlates with greater proficiency and a stronger willingness to incorporate these tools in future teaching (Tondeur et al., 2012).

Demographic variables such as age, gender, and level of study also affect perceptions and preparedness, though the findings remain mixed (Ertmer et al., 2012; Kozhabekova et al., 2025). A recent study by Bray and Tangney (2023) has found no significant gender differences in pre-service teachers' attitudes toward technology use in mathematics education, challenging earlier assumptions of male dominance in technological confidence.

Effectiveness of Digital Tools in Teaching and Learning Geometry

Digital tools have shown considerable potential to enhance the teaching and learning of geometry, particularly by improving conceptual understanding, problem-solving skills, and the visualization of abstract ideas. Research consistently demonstrates that DGEs help students grasp geometric concepts by enabling interactive engagement with shapes and their properties. For example, Aryüce and Turgut (2018) found that students using GeoGebra to explore triangle congruence developed a deeper understanding of related theorems compared to those taught with traditional methods, as the software allowed real-time manipulation and immediate feedback.

Evidence also highlights the role of digital tools in enhancing problem-solving skills in geometry. A meta-analysis by Hillmayr et al. (2020) revealed that technology-enhanced mathematics instruction, including geometry software, significantly improves problem-solving outcomes, with the greatest effects observed when tools facilitate interactive exploration rather than rote practice. Specifically, DGEs allow students to investigate various strategies, such as constructing perpendicular bisectors or solving locus problems, thereby supporting more flexible and effective problem-solving (Drijvers et al., 2021). Geometry relies heavily on spatial reasoning, and tools like GeoGebra and Desmos are particularly effective in visualizing 3D models and transformations that static diagrams cannot replicate (Leung & Baccaglini-Frank, 2017). For instance, GeoGebra's 3D graphing feature enables exploration of spatial relationships, such as the intersections of planes, making abstract concepts more concrete and accessible. However, the effectiveness of digital tools is not guaranteed and depends largely on how they are implemented. While research shows that these tools improve conceptual understanding and visualization, their impact is reduced without adequate teacher guidance or when technical issues interrupt instruction (Drijvers et al., 2021). Pre-service teachers note that students often struggle initially with unfamiliar tool interfaces, though these challenges tend to decrease with continued use (Lyublinskaya & Kaplon-Schilis, 2020). Additionally, the tools' effectiveness in increasing problem-solving varies by the complexity of the task; simpler exercises may yield limited benefits compared to more open-ended explorations (Hillmayr et al., 2020).

Pedagogical Integration of Digital Tools

The pedagogical integration of digital tools into geometry education involves strategically embedding technology into lesson plans, aligning with curriculum objectives, and leveraging tools for differentiated instruction and assessment. Research shows that effective integration requires pre-service teachers to move beyond using digital tools as supplementary aids, instead designing lessons where technology actively supports the exploration of geometric concepts (Clark-Wilson et al., 2020). For instance, a well-structured approach might involve using GeoGebra to guide students in constructing and analyzing the properties of a circle, fostering conjecture and discussion rather than relying on rote drawing (Badu-Domfeh, 2020).

Tools like GeoGebra align effectively with learning objectives such as understanding transformations and proving theorems, offering dynamic visualizations that static textbooks cannot provide. Research shows that pre-service teachers perceive this alignment positively, particularly when digital tools are introduced alongside curriculum frameworks during training, allowing them to see practical applications, such as using Desmos to explore congruence in real time (Bray & Tangney, 2023). Digital tools also support differentiated instruction by addressing diverse learning needs in geometry classrooms. For example, TI-Nspire's multiple representation features (graphs, equations, tables) enable teachers to scaffold tasks for struggling learners while engaging advanced students with open-ended challenges like designing 3D models (Lyublinskaya & Tournaki, 2014). Studies show that pre-service teachers who tailor instruction using tools, for instance, adapting GeoGebra tasks for visual versus analytical learners, report improved student outcomes, although this depends on their pedagogical skill and familiarity with the tools (Bray & Tangney, 2023).

The use of digital tools for assessing geometric understanding further enhances their pedagogical value. These tools often include built-in features for creating interactive assessments, such as dragging points to test geometric properties or providing instant feedback on constructions, which pre-service teachers find effective for formative evaluation (Drijvers et al., 2021). Research by Lyublinskaya and Kaplon-Schilis (2020) showed that pre-service teachers who incorporated technology into assessment were better able to gauge students' conceptual understanding—for example, identifying misconceptions about parallelism—compared to traditional paper-based methods.

Challenges and Barriers to Using Digital Tools

One prominent obstacle is limited access to necessary technology, including hardware and software such as GeoGebra or TI-Nspire. Research shows that pre-service teachers in under-resourced settings often lack consistent access to devices or reliable internet, which limits their ability to practice and implement digital tools effectively (Tondeur et al., 2012).

Technical issues also pose some challenges, frequently disrupting geometry lessons. Studies show that software glitches, slow processing speeds, and compatibility problems can interrupt instruction, leading to frustration among both teachers and students. Pre-service teachers report that these disruptions break lesson flow and reduce student engagement, requiring troubleshooting skills they may not yet possess (Pamuk, 2012). This challenge is intensified by the time commitment needed to learn and integrate digital tools; research highlights that mastering complex interfaces requires substantial time—something many pre-service teachers feel is in short supply during their training (Lyublinskaya & Kaplon-Schilis, 2020). Pedagogical barriers also present significant challenges. Pre-service teachers often find it difficult to align digital tools with geometry curricula or adapt them to meet diverse student needs. For example, while GeoGebra offers powerful visualization capabilities, its open-ended design can overwhelm novice teachers who are uncertain about how to structure lessons effectively around it (Clark-Wilson et al., 2020). Without sufficient pedagogical training, they may resort to using these tools merely as substitutes for traditional methods, rather than leveraging their transformative potential, thus limiting their instructional impact (Pamuk, 2012). Student-related challenges further complicate integration. Research shows that students often struggle to use geometry-specific tools, especially if they lack prior experience with educational technology (Bray & Tangney, 2023). Pre-service teachers report difficulties in teaching students how to navigate tools, for instance, using GeoGebra to drag points and explore geometric properties, before they can even begin addressing the underlying mathematical concepts (Ekol & Greenop, 2023; Lyublinskaya & Kaplon-Schilis, 2020).

The need for more training emerges as a consistent theme across these challenges. Studies repeatedly show that pre-service teachers often feel underprepared to integrate digital tools effectively without targeted professional development (Tondeur et al., 2012). To maximize the educational value of digital tools, teacher training programs must extend beyond technical instruction to emphasize purposeful pedagogical integration. Familiarity with software alone is insufficient; pre-service teachers need guidance on how to use these tools meaningfully within instructional frameworks. Well-designed programs address this by focusing not only on tool functionality but also on how technology can enhance conceptual understanding and support active learning, encouraging a shift from simple substitution to more transformative teaching practices (Ertmer et al., 2012). Additionally, embedding opportunities for hands-on practice and ongoing support throughout teacher preparation fosters greater confidence and adaptability, enabling future educators to manage technical difficulties and tailor digital resources to meet diverse classroom needs (Lyublinskaya & Kaplon-Schilis, 2020; Reyes, 2025).

METHODS

Research Design

This study employed a quantitative survey research design to investigate pre-service mathematics teachers' perceptions, experiences, and challenges in integrating digital tools into geometry instruction. To ensure the credibility of the findings, both validity and reliability were thoroughly assessed. Construct validity was examined through Confirmatory Factor Analysis (CFA), while internal consistency reliability was measured using Cronbach's alpha. The independent variables included Usability and Accessibility of Digital Tools (UADT), Engagement and Motivation (EM), Challenges and Barriers (CB), and Future Training and Support Needs (FTSN). The dependent variables were Effectiveness in Learning and Teaching Geometry (ELTG) and Pedagogical Integration and Teaching Strategies (PITS).

Sample

This study employed convenience sampling, a non-probability method commonly used in educational research for its practicality and accessibility (Emerson, 2021). Participants were pre-service mathematics teachers enrolled at a university in the Karasay district of the Almaty region, who voluntarily agreed to take part in the study. The sample was drawn from students in mathematics education programs, and the survey was distributed via class-specific online group chats, enabling efficient and targeted data collection within an accessible population. The final sample consisted of 229 pre-service mathematics teachers. The majority of respondents (81.7%) were under 20 years old. Gender distribution included 69.2% female and 30.8% male participants. Most were enrolled in bachelor's-level mathematics education programs (91.7%), with a smaller proportion (8.3%) in master's-level programs. In terms of academic experience, the largest group (43.7%) had studied mathematics education for 1–2 years, while others had experience ranging from less than one year to more than four years. Approximately 48.9% of respondents had taken courses related to technology integration in mathematics education. Most participants reported limited formal teaching experience: 42.8% had no teaching experience, 29.3% had completed internships, and 27.9% had classroom teaching experience.

In terms of technology use, participants reported a moderate frequency of digital tool usage in their coursework or teaching practice, with a mean frequency rating of 3.0 on a 5-point scale. GeoGebra was identified as the most commonly used digital tool in geometry lessons. Respondents also indicated a moderate level of confidence in using digital tools for teaching geometry, with a mean rating of 2.85 on a 4-point scale. Participation was voluntary, and informed consent was obtained from all respondents, ensuring confidentiality and anonymity in accordance with ethical research guidelines.

Instrument

The primary data collection instrument used in this study was a self-structured survey titled *Survey on the Use of Digital Tools in Teaching Geometry*. The survey included four items for demographics, five non-Likert type items, and 30 Likert type items The survey was designed to assess pre-service mathematics teachers' perceptions, experiences, and challenges related to the integration of digital tools in geometry instruction. Items were developed based on a comprehensive review of relevant literature and the authors' experience in teacher education. To ensure content validity, the instrument was reviewed by two experts in mathematics education and one expert in educational technology. Based on their feedback, several items were revised to improve clarity, coherence, and alignment with the study's constructs. Additionally, two students participated in a read-aloud review, during which no issues were identified.

The finalized instrument consisted of two main parts. The first section collected demographic information, including participants' age, gender, level of study, years of study in mathematics education, teaching experience, prior coursework in educational technology, frequency of digital tool use, and confidence in using digital tools for geometry instruction. The second section comprised 30 Likert-type items rated on a 5-point scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). These items were grouped under six dimensions that are presented in the design section.

CFA was conducted to assess the construct validity of the instrument. All standardized factor loadings were statistically significant ($p < .001$) and exceeded 0.83, with the majority above 0.90, indicating strong convergent validity. The overall model fit was acceptable: $\chi^2(390)$

= 842.71, $p < .001$; CFI = 0.92; TLI = 0.91; RMSEA = 0.07, with a 90% confidence interval ranging from 0.06 to 0.08. These results support the theoretical structure and confirm the validity of the measurement model. Internal consistency reliability was assessed using Cronbach's alpha for each subscale. The reliability coefficients were high across all dimensions: UADT = 0.90, ELTG = 0.93, EM = 0.91, PITS = 0.91, CB = 0.87, and FTSN = 0.92. The overall reliability of the instrument was excellent ($\alpha = 0.97$), indicating strong internal consistency and confirming the instrument's suitability for research on digital tool integration in geometry instruction.

Data Collection

Data were collected at a university in the Karasay district of the Almaty region, where both traditional and technology-enhanced methods are used in geometry instruction. In January, a survey was distributed to students preparing for careers in education to assess their perceptions of the relevance and usefulness of digital tools in geometry lessons. The survey was administered online and shared through class-specific group chats. Each participant accessed and completed the survey individually, using their own name. The instrument was designed to take approximately 10–15 minutes to complete. Ethical research standards were strictly upheld, including obtaining informed consent and ensuring participant anonymity and confidentiality throughout the process. A total of 253 pre-service teachers completed the survey, however, after data cleaning process we end up with 229 responses.

Data Analyses

Both descriptive and inferential statistical procedures were utilized to analyze the data at hand. Descriptive statistics, such as frequencies, percentages, means, and standard deviations, were used to summarize participants' demographic characteristics and responses to survey items. Structural Equation Modeling (SEM) was employed to investigate the relationships among the various dimensions of the survey. SEM analysis followed a two-step approach: first, the measurement model was evaluated to assess reliability and validity using factor loadings, composite reliability, and convergent validity criteria. Second, the structural model was assessed to examine hypothesized relationships. Model fit was evaluated using multiple indices such as Chi-square (χ^2), Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR). Robust estimation methods were used to account for potential deviations from normality. All statistical analyses were conducted using *Jamovi* version 2.6.13. Statistical significance was determined at a *p-value* threshold of less than .05.

RESULTS

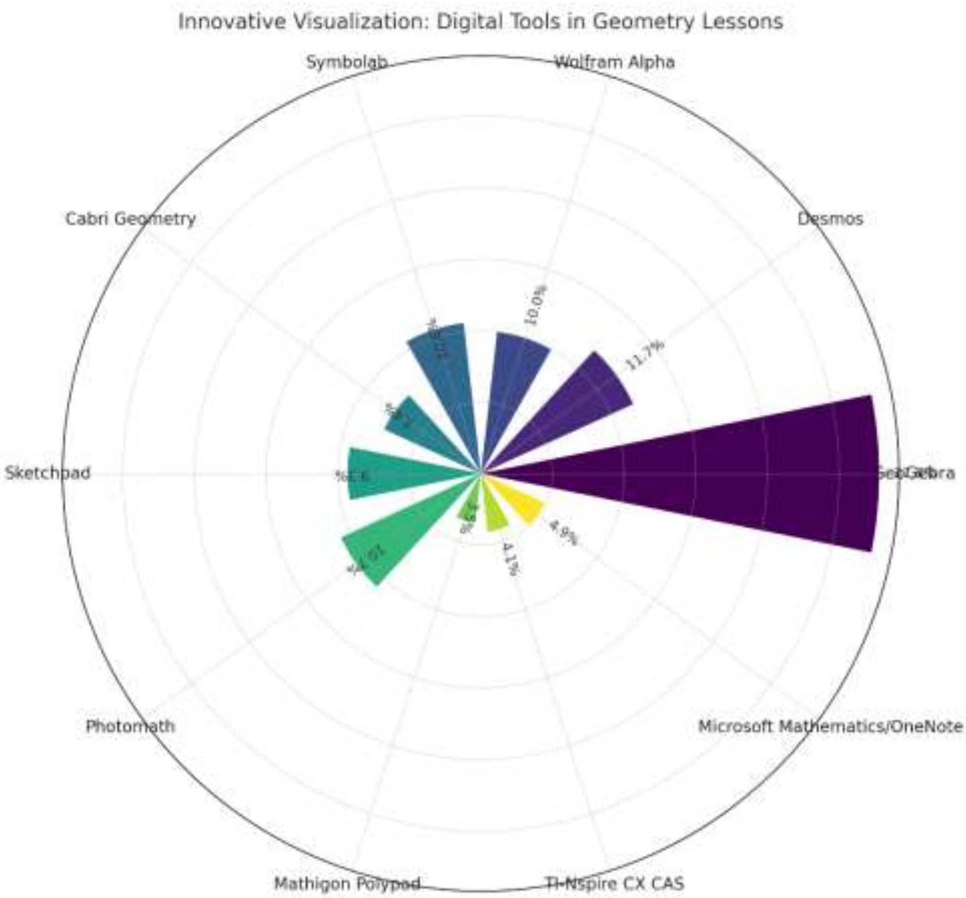
This section presents the findings of the study on pre-service mathematics teachers' use of digital tools in teaching geometry. First, descriptive statistics and visualizations illustrate the prevalence and frequency of various digital tools used in instructional contexts. Next, correlation analyses examine the relationships between demographic variables and patterns of digital tool usage. Finally, SEM is applied to analyze the underlying relationships among teachers' perceptions, experiences, and the pedagogical integration of digital tools in geometry education.

Descriptives

Figure 1 illustrates an innovative circular visualization displaying the percentage distribution of digital tools used by pre-service mathematics teachers in geometry lessons.

Figure 1.

Circular Bar Plot Depicting Usage of Digital Tools in Geometry Lessons



The visualization clearly identifies GeoGebra as the most widely used digital tool among pre-service mathematics teachers, accounting for 27.8% of reported usage, substantially higher than all other tools. Desmos (11.7%), Photomath (10.7%), Symbolab (10.6%), and Wolfram Alpha (10.0%) follow, indicating moderate levels of use. Less frequently utilized tools include Sketchpad (9.3%), Cabri Geometry (7.4%), Microsoft Mathematics/OneNote (4.9%), TI-Nspire CX CAS (4.1%), and Mathigon Polypad (3.5%), reflecting a narrower adoption in geometry instruction contexts. Table 1 presents Pearson correlation coefficients (r), degrees of freedom (df), and p-values for associations among key demographic variables and factors related to digital tool use. These include gender, level of education, prior coursework on technology integration, teaching experience, frequency of digital tool use, and confidence in using digital tools for geometry instruction.

Table 1.
Correlation Matrix of Demographic and Technological Variables

		Gender	Education level	Have you taken any courses related to incorporating technology into mathematics education?	Do you have any teaching experience?	How often do you use digital tools in your coursework or teaching practice?
Do you have any teaching experience?	r		-0.26	0.14	—	
	p		<.001	0.034	—	
How often do you use digital tools in your coursework or teaching practice?	r	-0.18		-0.16	-0.25	—
	p	0.006		0.018	<.001	—
How confident do you feel in using digital tools in teaching geometry?	r			-0.16	-0.15	0.27
	p			0.018	0.022	<.001

The findings reveal several notable relationships among key variables. Education level is negatively correlated with teaching experience ($r = -0.26$, $p < .001$), frequency of digital tool use ($r = -0.16$, $p = .018$), and confidence in using digital tools ($r = -0.16$, $p = .018$), suggesting that respondents at higher levels of education reported slightly less teaching experience and lower levels of digital tool usage and confidence. Teaching experience shows a positive correlation with prior coursework in educational technology ($r = 0.14$, $p = .034$), indicating that those with more teaching experience were more likely to have completed relevant coursework. However, teaching experience is negatively correlated with frequency of digital tool usage ($r = -0.25$, $p < .001$) and confidence in using digital tools ($r = -0.15$, $p = .022$), suggesting that more experienced pre-service teachers may not use digital tools as often or feel as confident in their application. Notably, frequency of digital tool usage is strongly correlated with confidence in their use ($r = 0.27$, $p < .001$), highlighting that increased exposure and practice with digital tools are associated with greater self-assurance in their instructional integration.

SEM Analyses

Rational for the SEM structure

In examining pre-service mathematics teachers' perceptions and experiences with digital tools for teaching geometry, *Effectiveness in Learning and Teaching Geometry* (ELTG) and *Pedagogical Integration and Teaching Strategies* (PITS) are positioned as endogenous variables, as they serve as key outcomes affected by other factors. The ELTG dimension captures the perceived impact of digital tools on student understanding, confidence in problem-solving, and enhanced visualization—marking it as a result of foundational factors such as usability, engagement, and experienced challenges (Trouche & Drijvers, 2010; Hoyles & Lagrange, 2010). Similarly, PITS reflects pre-service teachers' ability to apply digital tools within instructional contexts and align them with curriculum goals. This dimension is shaped by perceptions of accessibility, motivation, and the presence or absence of institutional or technical support (Niess, 2005; Mishra & Koehler, 2006). Defining ELTG and PITS as endogenous enables analysis of how external predictors—such as usability, motivation, barriers, and training needs—influence practical instructional outcomes in geometry education (Cheung & Slavin, 2013; Drijvers et al., 2013). This modeling approach aligns with established frameworks in mathematics education research, particularly those emphasizing the structural relationships among components of technological integration (Koehler & Mishra, 2009).

Table 2 presents the chi-square (χ^2) values, degrees of freedom (df), and p-values for both the User Model and the Baseline Model, along with their scaled versions, to assess the overall fit of the structural equation model tested in this study.

Table 2.

Model Fit Indices for Structural Equation Model (SEM)

Label	X^2	df	p
User Model	465.78	390	0.005
Baseline Model	116672	435	<.001
Scaled User	724.29	390	<.001
Scaled Baseline	20953.66	435	<.001

As presented in Table 2, the User Model yielded a chi-square value of $\chi^2(390) = 465.78$ with a p-value of 0.005, indicating a statistically significant yet relatively acceptable fit to the data. Although the significance suggests minor deviations from a perfect model fit, such results are common in large-sample SEM analyses. In contrast, the Baseline Model showed a substantially poorer fit, with $\chi^2(435) = 116{,}672.01$, $p < .001$, highlighting its inadequacy in representing the observed data compared to the more complex User Model. Scaled chi-square values, which adjust for potential issues such as non-normality or sample size effects, supported this pattern. The Scaled User Model reported $\chi^2(390) = 724.29$, $p < .001$—still showing some misfit but far outperforming the Scaled Baseline Model, which yielded $\chi^2(435) = 20{,}953.66$, $p < .001$. These results confirm that the User Model offers a substantial improvement in capturing the structural relationships outlined in the theoretical framework.

Table 3 presents the Standardized Root Mean Square Residual (SRMR) and Root Mean Square Error of Approximation (RMSEA), along with their 95% confidence intervals and associated p-values, based on Classical, Robust, and Scaled estimations of the SEM model.

Table 3.

Model Fit Indices for SRMR and RMSEA Values

			95% Confidence Intervals		
Type	SRMR	RMSEA	Lower	Upper	RMSEA p
Classical	0.04	0.03	0.02	0.04	1.000
Robust	0.04	0.11	0.1	0.11	<.001
Scaled	0.04	0.06	0.05	0.07	0.004

Table 3 reveals that the Classical estimation produced strong fit indices, with an SRMR of 0.04 and an RMSEA of 0.03, both below the recommended thresholds, indicating excellent model fit. The RMSEA p-value of 1.000 further supports the model's appropriateness under classical assumptions. In contrast, the Robust estimation yielded less favorable results, with an RMSEA of 0.11 (above the acceptable limit of 0.08) and a statistically significant p-value (< .001), suggesting potential model misfit under this method. The Scaled estimation showed moderate fit, with an SRMR of 0.04 and an RMSEA of 0.06, which is within acceptable limits but slightly inferior to the Classical results, accompanied by a statistically significant RMSEA p-value (0.004). Overall, the model's fit varies depending on the estimation method, with the Classical estimation demonstrating particularly strong performance.

Table 4 summarizes a range of comparative fit indices, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Bentler-Bonett Non-normed Fit Index (NNFI), Relative Noncentrality Index (RNI), Bentler-Bonett Normed Fit Index (NFI), Bollen's Relative Fit Index (RFI), Bollen's Incremental Fit Index (IFI), and Parsimony Normed Fit Index (PNFI), used to evaluate the User Model in comparison to the Baseline Model across three estimation methods: Model, Scaled, and Robust.

Examination of Table 4 indicates that the User Model consistently demonstrates exceptional fit across all indices under the Model estimation, with values at or near perfect (CFI = 1.00, TLI = 1.00, NNFI = 1.00, etc.). Similarly, the Scaled estimation method presents very good fit indices (CFI = 0.98, TLI = 0.98, NNFI = 0.98, RNI = 0.98, NFI = 0.97, RFI = 0.96, IFI = 0.98, PNFI = 0.87), all exceeding the commonly accepted threshold of 0.95. In contrast, the Robust estimation yields slightly lower, yet still acceptable fit indices (CFI = 0.87, TLI = 0.86, NNFI = 0.86, RNI = 0.87), indicating moderate fit and suggesting some sensitivity to data conditions or model robustness. The Parsimony Normed Fit Index (PNFI), which adjusts for model complexity, also remains consistently strong (Model = 0.89, Scaled = 0.87), reinforcing the relative efficiency and explanatory strength of the User Model compared to the Baseline Model. Overall, Table 4 demonstrates that the User Model substantially outperforms the baseline across all comparative indices.

Table 4.

Comparative Model Fit Indices for User Model versus Baseline Model

				95% Confidence Intervals				
Dep	Pred	Estimate	SE	Lower	Upper	β	z	p
ELTG	PITS	0.25	0.1	0.05	0.45	0.24	2.45	0.014
ELTG	UADT	0.16	0.06	0.04	0.27	0.15	2.72	0.006
ELTG	EM	0.44	0.09	0.26	0.62	0.43	4.81	<.001
ELTG	CB	-0.09	0.05	-0.18	0.01	-0.08	-1.8	0.072
ELTG	FTNS	0.2	0.09	0.03	0.37	0.2	2.31	0.021
PITS	UADT	0.18	0.06	0.07	0.29	0.19	3.25	0.001
PITS	EM	0.47	0.06	0.34	0.59	0.47	7.29	<.001
PITS	CB	-0.02	0.04	-0.1	0.07	-0.02	-0.4	0.689
PITS	FTNS	0.32	0.08	0.17	0.47	0.33	4.26	<.001

Table 5 presents the results of the structural paths within the SEM analysis, specifying the estimated coefficients, standard errors (SE), 95% confidence intervals, standardized beta coefficients (β), z-scores, and p-values for predictors influencing the dependent variables *Effectiveness in Learning and Teaching Geometry* (ELTG) and *Pedagogical Integration and Teaching Strategies* (PITS).

Table 5.

Parameter Estimates for Structural Paths in SEM Analysis

				95% Confidence Intervals				
Dep	Pred	Estimate	SE	Lower	Upper	β	z	p
ELTG	PITS	0.25	0.1	0.05	0.45	0.24	2.45	0.014
ELTG	UADT	0.16	0.06	0.04	0.27	0.15	2.72	0.006
ELTG	EM	0.44	0.09	0.26	0.62	0.43	4.81	<.001
ELTG	CB	-0.09	0.05	-0.18	0.01	-0.08	-1.8	0.072
ELTG	FTNS	0.2	0.09	0.03	0.37	0.2	2.31	0.021
PITS	UADT	0.18	0.06	0.07	0.29	0.19	3.25	0.001
PITS	EM	0.47	0.06	0.34	0.59	0.47	7.29	<.001
PITS	CB	-0.02	0.04	-0.1	0.07	-0.02	-0.4	0.689
PITS	FTNS	0.32	0.08	0.17	0.47	0.33	4.26	<.001

The analysis reveals significant predictors of ELTG, including *Pedagogical Integration and Teaching Strategies* (PITS, β = 0.24, p = .014), *Usability and Accessibility of Digital Tools* (UADT, β = 0.15, p = .006), *Engagement and Motivation* (EM, β = 0.43, p < .001), and *Future Training and Support Needs* (FTNS, β = 0.20, p = .021). *Challenges and Barriers* (CB) were not significantly related (β = -0.08, p = .072), indicating a weaker and non-significant impact on ELTG. For PITS, significant positive effects emerged from UADT (β = 0.19, p = .001), EM (β = 0.47, p < .001), and FTNS (β = 0.33, p < .001). Again, CB was not a significant predictor (β = -0.02, p = .689), showing minimal impact on pedagogical integration strategies. Collectively, these results emphasize the critical role of usability, engagement, and training support in enhancing geometry instruction effectiveness and pedagogical integration.

Table 6.

Measurement Model Estimates for SEM Latent Constructs

Latent	Observed	Estimate	SE	Lower	Upper	β	z	p
	UADT1	1	0	1	1	0.88		
	UADT2	0.94	0.03	0.87	1	0.83	27.3	<.001
UADT	UADT3	0.98	0.03	0.91	1.05	0.86	28.74	<.001
	UADT4	0.93	0.04	0.86	1	0.82	25.91	<.001
	UADT5	0.95	0.03	0.88	1.01	0.84	27.62	<.001
	EM1	1	0	1	1	0.89		
	EM2	0.97	0.03	0.92	1.03	0.86	33.58	<.001
EM	EM3	0.98	0.03	0.93	1.03	0.87	39.03	<.001
	EM4	0.91	0.03	0.85	0.98	0.81	27.69	<.001
	EM5	0.99	0.03	0.94	1.04	0.88	36.88	<.001
	CB1	1	0	1	1	0.8		
	CB2	0.98	0.07	0.84	1.12	0.78	13.49	<.001
CB	CB3	0.94	0.07	0.79	1.08	0.75	12.61	<.001
	CB4	0.96	0.07	0.83	1.09	0.76	14.56	<.001
	CB5	1.12	0.08	0.97	1.27	0.89	14.47	<.001
	FTSN1	1	0	1	1	0.9		
	FTSN2	0.99	0.03	0.94	1.04	0.89	37.73	<.001
FTNS	FTSN3	0.98	0.03	0.93	1.03	0.89	36.76	<.001
	FTSN4	0.93	0.03	0.88	0.99	0.84	33.88	<.001
	FTSN5	0.9	0.03	0.85	0.96	0.82	31.33	<.001
	ELTG1	1	0	1	1	0.91		
	ELTG2	0.99	0.03	0.94	1.04	0.9	39.59	<.001
ELTG	ELTG3	0.97	0.02	0.93	1.01	0.88	42.62	<.001
	ELTG4	0.95	0.03	0.9	1.01	0.87	35.48	<.001
	ELTG5	0.97	0.02	0.93	1.02	0.88	41.74	<.001
	PITS1	1	0	1	1	0.87		
	PITS2	1	0.03	0.95	1.06	0.88	37.25	<.001
PITS	PITS3	1.01	0.03	0.96	1.07	0.89	35.64	<.001
	PITS4	0.95	0.03	0.89	1.01	0.83	30.97	<.001
	PITS5	0.99	0.03	0.94	1.04	0.87	36.74	<.001

Table 6 provides the detailed measurement model estimates, including factor loadings (estimates), standard errors (SE), 95% confidence intervals, standardized loadings (β), z-values, and p-values, for each observed indicator within the latent constructs examined: *Usability and Accessibility of Digital Tools* (UADT), *Engagement and Motivation* (EM), *Challenges and Barriers* (CB), *Future Training and Support Needs* (FTSN), *Effectiveness in Learning and Teaching Geometry*(ELTG), and *Pedagogical Integration and Teaching Strategies* (PITS).

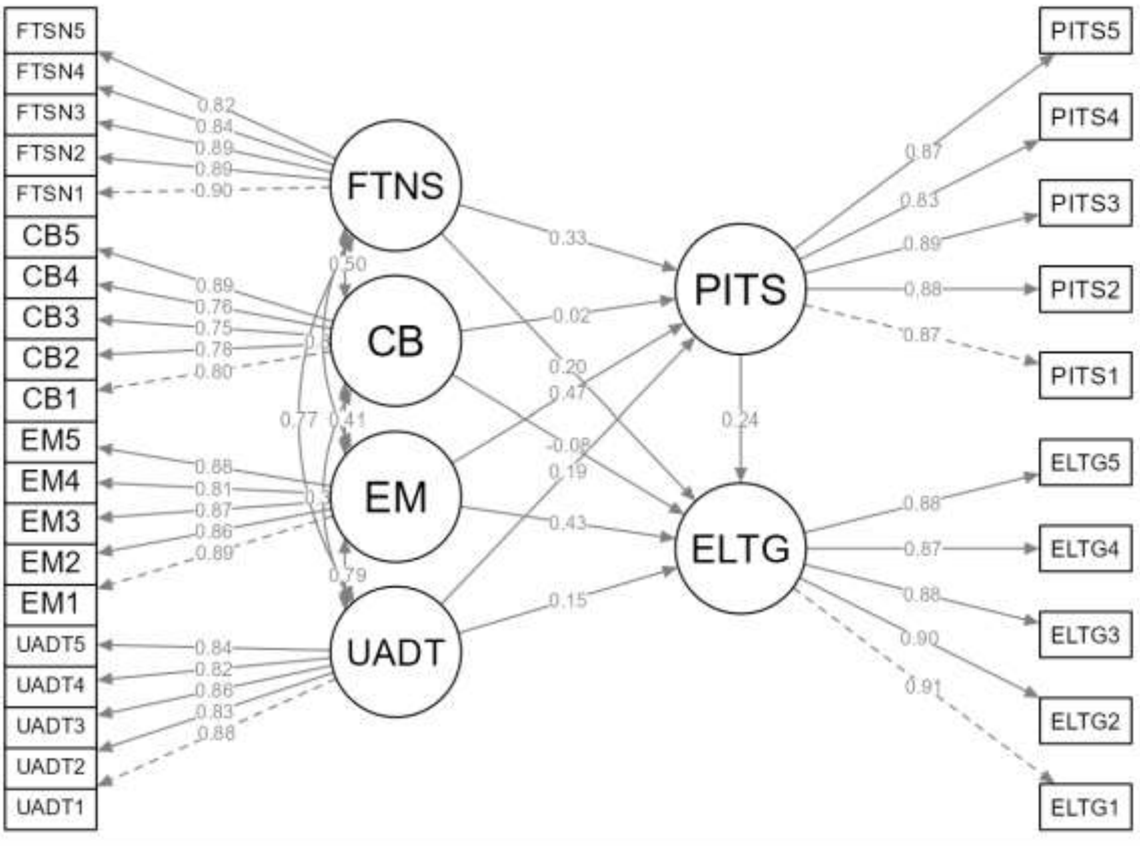
All observed indicators show robust factor loadings and statistically significant results (p < .001), indicating excellent reliability and validity of the measurement model. Standardized loadings (β) predominantly range from 0.78 to 0.91, reflecting strong relationships between indicators and their respective latent constructs. For example, items UADT1–UADT5 yielded standardized loadings between 0.82 and 0.88, demonstrating consistent measurement of the usability construct. Similarly, EM items ranged from 0.81 to 0.89, CB items from 0.78 to 0.87, and FTSN items from 0.82 to 0.90, all reflecting high internal consistency. In the same way, ELTG indicators showed standardized loadings from 0.87 to 0.91, and PITS indicators from 0.83 to 0.89. Consequently, the measurement model exhibited strong psychometric properties, confirming that all constructs were reliably measured by their observed indicators.

Figure 2 presents the path diagram illustrating the relationships among survey dimensions tested within the SEM framework. It highlights the latent variables UADT, EM, CB, FTNS, PITS, and ELTG.

All observed variables (represented by rectangles) exhibit strong factor loadings, as indicated by the standardized values on the arrows, confirming their reliability in measuring the corresponding latent constructs (depicted as circles). The structural paths between exogenous and endogenous variables reveal significant predictive relationships. Notably, Engagement with Mathematics (EM) is a strong predictor of both Effective Learning through Geometry (ELTG; β = 0.43) and Pedagogical Integration of Technology in Schools (PITS; β = 0.47). Similarly, Familiarity with Technology and Software (FTNS) significantly predicts PITS (β = 0.33) and shows a moderate predictive relationship with ELTG (β = 0.20). Usability and Accessibility of Digital Tools (UADT) also significantly affect ELTG (β = 0.15) and PITS (β = 0.19). Furthermore, PITS positively predicts ELTG (β = 0.24), suggesting a reinforcing relationship. In contrast, Challenges and Barriers (CB) display weak and statistically non-significant relationships with both outcomes. Overall, the diagram provides clear evidence that engagement, usability, and training-related factors play a pivotal role in enhancing teaching effectiveness and the pedagogical integration of digital tools, highlighting their importance in the successful implementation of geometry education technologies.

Figure 2.

Path Diagram Illustrating the Relationships Among Survey Dimensions



DISCUSSION

This study examined pre-service mathematics teachers' perceptions, experiences, and challenges related to using digital tools in geometry education. The findings highlight the factors influencing both pedagogical integration and the effectiveness of digital tools in geometry teaching, aligning with previous research emphasizing the importance of visualization and spatial reasoning (Ng & Sinclair, 2018; Sinclair et al., 2016). In response to the first research question, results indicate that pre-service mathematics teachers generally hold positive perceptions of digital tool use in geometry education, especially regarding usability, engagement, pedagogical strategies, and effectiveness. GeoGebra emerged as the most frequently used digital tool, followed by Desmos and Photomath. Significant correlations showed that higher education levels were associated with lower teaching experience and lower confidence in using digital tools, while frequent use was positively linked to greater confidence. SEM analysis identified engagement, usability, and training needs as significant predictors of effective geometry instruction and pedagogical integration. Importantly, challenges and barriers were not found to significantly affect these outcomes.

Consistent with prior research, GeoGebra emerged as the most utilized digital tool among respondents (Hohenwarter et al., 2016). Its dominant use likely reflects its versatility, accessibility, and robust visualization features. Tools such as Desmos and Photomath also showed substantial usage, confirming their roles in enhancing conceptual understanding through dynamic interaction (Clark-Wilson et al., 2020; Bray & Tangney, 2023). These preferences show a shift toward interactive platforms that significantly enhance geometric reasoning and problem-solving (Aryüce & Turgut, 2018). In response to the second research question, the SEM findings reinforced the importance of engagement, motivation, usability, and targeted training in achieving effective digital tool integration and improved geometry instruction. EM significantly predicted both ELTG and PITS, aligning with constructivist theories that emphasize active student engagement as essential for deeper understanding (Drijvers, 2015; Bray & Tangney, 2023). UADT also emerged as a significant predictor, supporting earlier studies that highlight intuitive design and minimal technical barriers as key factors for successful integration (Leung & Baccaglini-Frank, 2017; Clark-Wilson et al., 2020).

The significant role of *Future Training and Support Needs* (FTNS) emphasizes the ongoing necessity for comprehensive, targeted professional development within teacher preparation programs. These results align with the TPACK framework and the SAMR model, highlighting that pre-service teachers benefit most from explicit training that integrates technology into pedagogical strategies (Koehler & Mishra, 2009; Hamilton et al., 2016). In response to the third research question, *Challenges and Barriers* (CB) did not significantly impact outcomes, diverging from earlier studies that reported considerable issues related to technical disruptions and pedagogical difficulties (Lyublinskaya & Kaplon-Schilis, 2020). This result may reflect increased digital fluency among newer generations of pre-service teachers or improvements in tool usability and training practices. Finally, addressing the fourth research question, the correlational analysis revealed important relationships among demographic variables, confidence levels, and technology integration experiences. Higher education levels were negatively correlated with both teaching experience and confidence in using digital tools, suggesting a possible disconnect between theoretical training and practical classroom readiness, consistent with previous findings (Lyublinskaya & Tournaki, 2014; Pamuk, 2012). The strong positive relationship between frequent digital tool use and confidence reinforces the importance of hands-on, consistent exposure to technology in teacher education programs (Tondeur et al., 2012).

On the other hand, the SEM analysis revealed strong interrelationships among the key constructs. Engagement and usability had direct effects on both pedagogical integration and teaching effectiveness, while PITS itself was a significant predictor of ELTG. These interconnections show that when pre-service teachers perceive digital tools as engaging and easy to use, and when they receive appropriate training, they are more likely to integrate those tools effectively in ways that enhance student learning. Interestingly, the data also showed that higher education levels were negatively associated with teaching experience and confidence in digital tool use, challenging assumptions that academic progression naturally equips teachers with better technological readiness (Pamuk, 2012; Lyublinskaya & Tournaki, 2014). This points to a disconnect between theoretical coursework and practical training, reinforcing the need for teacher education programs to incorporate structured, hands-on digital learning opportunities into their curricula.

Conclusions, Limitations, Future Research, & Implications

This study showed the important role digital tools play in enhancing geometry instruction among pre-service mathematics teachers. GeoGebra emerged as the most widely used tool, highlighting its strengths in visualization and interactivity. Additionally, engagement, usability, and training were identified as significant predictors of both pedagogical integration and teaching effectiveness, underscoring the value of incorporating technology meaningfully into teacher training programs to build confidence and support effective instructional practices. Several limitations should be acknowledged. The sample was predominantly young, undergraduate, and homogenous, which may limit the generalizability of the findings to broader or more diverse populations. Furthermore, reliance on self-reported data introduces the possibility of response biases, potentially affecting the accuracy of reported confidence and experiences.

The study also found that *Challenges and Barriers* (CB) did not significantly affect the effectiveness of digital tools or pedagogical integration, a finding that contrasts with earlier studies highlighting the impact of technical disruptions and instructional challenges (Lyublinskaya & Kaplon-Schilis, 2020). This discrepancy may reflect increased digital familiarity among newer generations of pre-service teachers or recent improvements in software usability and teacher training approaches. Future research should explore these potential shifts more closely, examining whether reduced barriers are due to generational technological proficiency, enhanced training practices, or improvements in digital tool interfaces. Longitudinal studies or comparative cohort analyses could offer deeper insights into the evolving nature of these barriers and their implications for teacher preparation and classroom implementation.

The findings carry significant implications for teacher education programs, policymakers, and curriculum developers. Training programs should incorporate structured, hands-on experiences with digital tools, particularly those that enhance engagement and usability. Policies should promote equitable access to advanced digital technologies to ensure that all educators are adequately prepared to meet the demands of modern geometry classrooms. Curriculum developers are encouraged to embed interactive, visualization-rich digital resources within geometry curricula to support deeper student understanding and improve learning outcomes.

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