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Enhancing TPACK: Preservice mathematics teachers' experiences with digital and non-digital visualisation tools

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Abstract

This paper investigates how pre-service mathematics teachers interact with both digital and non-digital tools to visualize mathematical concepts and develop their technological pedagogical content knowledge (TPACK). Based on the TPACK framework, this study explores how preservice mathematics teachers (PSMTs) transformed their teaching approaches when visualization tools were adopted, along with the respective challenges and affordances involved. An interpretivist qualitative phenomenological design was employed, which included semi-structured interviews, reflective journals, and pre- and post-microteaching observations of six third-year Bachelor of Education students. The intervention focused on delivering graduate-level mathematics content using GeoGebra and physical manipulatives. Results demonstrate a significant difference in PSMT's technological knowledge (TK), technological pedagogical knowledge (TPK), and technological content knowledge (TCK) before and after the intervention. Participants teaching practices shifted from from being traditional, teacher-centered to modern, student-centered approaches. Challenges such as limited technical proficiency and infrastructural barriers were initially evident; however, exposure and support during the intervention improved confidence, tool fluency, and pedagogical adaptability. The study emphasizes the importance of embedding a TPACK-based teaching approach into mathematics teacher training programs to enhance PSMTs readiness for technology-integrated instruction. Consequently, the study contributes to the growing scholarship on visualization in mathematics education and highlights the pedagogical shifts necessary to prepare future teachers for 21st-century learning environments.

Keywords: Mathematics education, Pedagogical shifts, Preservice teachers, Technological pedagogical content knowledge, Visualization.

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Contents

Contribution of this paper to the literature
This study contributes to the existing literature on the integration of digital and non-digital tools in mathematics education. It expands upon previous research by providing empirical evidence to support ongoing discussions about the most appropriate approach to teacher education in the era of digital transformation, while maintaining pedagogical value.

1. Introduction

The integration of digital and non-digital tools in mathematics education has increasingly been recognized in educational discourse and practice (National Council of Teachers of Mathematics, 2000, 2014) as effective means to support learners in developing conceptual understanding (Kong, 2019; Mishra & Koehler, 2006). It is currently an essential part of the contemporary standards for secondary school mathematics teacher preparation (National Council of Teachers of Mathematics, 2020). This is in line with a large body of literature that pre-service teachers have diverse attitudes and viewpoints regarding the use of digital tools, which influence their teaching efficiency and adaptability to various teaching and learning contexts (Jimarkon, Wanphet, & Dikilitaş, 2021; Metscher, Tramantano, & Wong, 2021). Visualization plays an important role in mathematical cognition, helping learners to understand abstract concepts by using visuals to represent those concepts (Arcavi, 2003). Nevertheless, the degree to which pre-service teachers use their digital and non-digital tools for developing knowledge of the subject matter and pedagogy is a relatively under-researched field.

In spite of an increasing trend in integrating digital technologies into mathematics education, many pre-service teachers struggle to effectively use these tools to support conceptual visualization (Thomas & Hong, 2013). Research has shown the potential of digital tools (e.g., dynamic geometry, computer algebra, and virtual manipulatives) to enhance learners' learning. In addition, the effect of technology on the mathematics learning of learners has been widely reported in the literature (Clark-Wilson, Robutti, & Sinclair, 2014). However, little empirical evidence exists on how pre-service teachers develop the knowledge and skills necessary to integrate technologies successfully in the classroom. Although research has been conducted on digital pedagogy in mathematics education (Dhakal, 2018; Hoyles & Noss, 2003), fewer studies have explored how pre-service teachers implement or integrate both digital and non-digital tools to support the visualization of mathematical concepts. Furthermore, several studies have focused on secondary and higher education students rather than teacher preparation programs (Canonigo, 2024; Weigand, Trgalova, & Tabach, 2024), leaving a critical gap in understanding how pre-service teachers design their pedagogical approaches using digital and non-digital tools. Considering the recent focus on the implementation of blended learning settings (Faggiano & Montone, 2019; Jailani, Rosli, & Mahmud, 2025), a detailed understanding of how pre-service mathematics teachers (PSMTs) transition between digital and non-digital visualization modes is essential. This paper contributes to the existing body of research by documenting PSMTs' experiences with both digital and non-digital visualization tools in their teacher education. It aims to inform best practices for integrating technology in a pedagogically coherent manner, ensuring that technological tools support effective teaching and learning processes.

1.1. Research Questions

The study sought answers to the following questions:

1. How do pre-service mathematics teachers experience integrating digital and non-digital tools in visualizing mathematical concepts to enhance their technological pedagogical content knowledge (TPACK)?
2. What challenges and opportunities do pre-service mathematics teachers encounter when using digital and non-digital tools to support their understanding and teaching of mathematical concepts?

2. Literature Review

Digital tools are becoming increasingly integral to mathematics education, offering new possibilities for dynamic and interactive representations of concepts. Tossavainen, Johansson, Faarinen, Klisinska, and Tossavainen (2018) emphasized that technology may enhance learning, but only when it is purposefully integrated into pedagogy. Similarly, digital tools deepen engagement and understanding when teachers deploy them with explicit instructional purpose (Bray & Tangney, 2017). Trouche and Drijvers (2014) further showed that such tools can transform of mathematical activity by allowing visualizations and representations that are not possible in traditional paper- based environments.

In addition to digital tools, non-digital tools are essential parts of a mathematics classroom.

Manipulatives and games provide tangible experiences that ground abstract ideas in concrete form. A systematic review by Russo, Kalogeropoulos, Bragg, and Heyeres (2024) demonstrated the potential of non-digital games to inspire critical thinking and engagement. Drijvers (2020) advocated for mixed-mode learning, which combined both digital and non-digital tools, leading to richer learning. In a similar study conducted by Ngwabe and Boateng (2025), the study found that pre-service teachers who used GeoGebra in combination with physical models had stronger pedagogical content knowledge and greater confidence as teachers. These considerations highlight that a dual approach to visualization can be particularly effective in teacher education.

Studies have shown that teachers' beliefs and professional preparation strongly influence whether such tools are used effectively. An, Tillman, Smith, and Hachey (2023) observed that pre-service teachers' confidence in how to teach a lesson and their understanding of learners' behaviors and responses increased when learners created and interpreted visual representations in the classroom. Baumert et al. (2017), also found that pre-service teachers who were taught to use visualization methods became better prepared and could help their learners develop conceptual understandings of the mathematics being taught. Confidence is also linked to technology use. Bakar, Maat, and Rosli (2020) reported that teachers with higher self-efficacy in technology integration were more likely to adopt innovative methods in mathematics classrooms. These results align with the current situation in South African universities, where pre-service teachers tend to favor procedural approaches to teaching, with limited guided opportunities to experiment with representational tools.

Knowing how to choose and integrate resources is key to being a good teacher. As Su, Lin, and Lai (2023) emphasized, flexibility in choosing between digital and non-digital methods is a defining marker of pedagogical skill. This flexibility aligns with the main components of the TPACK framework, which emphasize how teachers can combine technology with their knowledge of content and pedagogy (García-Lázaro, Conde-Jiménez, & Colás-Bravo, 2022; Koh & Divaharan, 2011). Exposure to a variety of tools broadens pre-service teachers' capacity to design lessons that respond to diverse learner needs, a finding reinforced by Szeto and Cheng (2016). Research further shows that structured TPACK development plays a critical role in preparing teachers for technology-rich classrooms. Baran, Canbazoglu Bilici, Albayrak Sari, and Tondeur (2019) claimed that teacher education programmes need to offer carefully coordinated opportunities for pre-service teachers to practice the integration of the components of the TPACK systemically. Pre-service teachers with a higher level of TPACK competence achieve better learning outcomes with their learners, as indicated by Bulut and Güveli (2023). These insights highlight the need to integrate TPACK into mathematics teacher education.

This implies that visualization is not just a technical accessory but a pedagogical tool that influences the way learners make sense of mathematical ideas. Being able to use digital tools in combination with non-digital tools enhances pre-service teachers' pedagogical flexibility and adaptability, as well as their professional preparedness. The TPACK model provides a useful framework for describing such integration as it develops in practice and as teacher education programmes can support its emergence. Figure 1 illustrates the overlapping domains of knowledge that guided this study.

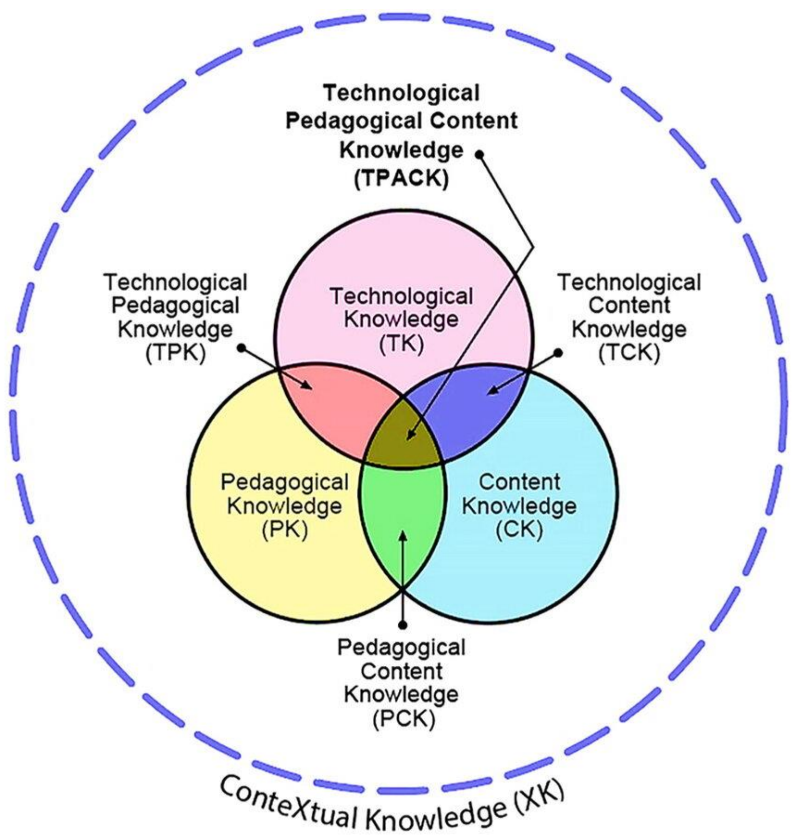

Figure 1. The TPACK model.

Note: Mishra (2019).

3. Methods

The study employed an interpretivist qualitative research design to examine how PSMTs combine digital technology and non-digital technology tools in developing their TPACK. As defined by Lichtman (2023), qualitative researchers utilize a systemic interpretive method to understand how people make meaning of their experiences in educational settings. Lichtman (2023) maintains that qualitative research seeks to understand 'the whys and hows behind human activity,' as well as the 'whats,' rendering it particularly capable of investigating complex social and educational phenomena.

This paper employed a phenomenological research design. The phenomenological approach emphasizes the subjectivity of the lived experiences of the participants and involves examining the 'what' and 'how' of their actions from their own perspectives (Oranga & Matere, 2023). In the context of mathematical education, understanding how pre-service teachers utilize digital and non-digital tools requires an approach that is sensitive to documenting their subjective realities as learners and future educators. This aligns with the work of Garcia et al. (2019), where a phenomenological approach is preferred because it is well-suited for investigating phenomena that demand rich, descriptive data on individual experiences to facilitate a comprehensive understanding.

The sample involved all 21 PSMTs who registered for the 4-year Bachelor of Education degree and who were in their third year of study at Walter Sisulu University, South Africa. The PSMTs enrolled in a semester module on digital tools and mathematics teaching integration. The PSMTs were also trained to use digital and non-digital tools to visualize mathematical concepts as part of enhancing their TPACK in mathematics. All participants who had completed the course were purposively sampled for the study. The criteria used were: participation in the training actively and reflection of their experiences with teaching demonstrations. Six PSMTs were invited to participate in the research project. To answer the research questions, a semi-structured classroom observation and reflective journals were employed to collect data. The interview questions were structured around PSMTs' past experiences, training, teaching presentations, possibilities, barriers, TPACK development, and plans (to use or not to use) digital and non-digital tools in mathematics classrooms. The questions were aligned with the TPCK framework, including ten prompts categorized into (A) demographics, (B) Technological knowledge TK, (C) Technological Pedagogical knowledge TPK, and (D) Technological Content Knowledge TCK. Each part consisted of five items aimed at collecting baseline data on PSMTs' previous knowledge and confidence in the use of digital and non-digital tools prior to training. Each interview lasted 30 minutes, was audio-recorded, and transcribed verbatim.

PSMTs were asked to keep reflective journals throughout the training. These journals detailed their learning experiences, developing views, and problems in reconciling digital and non-digital tools. In addition, participants conducted teaching demonstrations for pre- and post-intervention, demonstrating their ability to integrate digital and non-digital tools in mathematics teaching. Classroom observations were conducted on their implementation strategies, confidence levels, and their level of adaptability to the tools. One of the assessment tasks that was part of the required exercises for the year was to use a developed observation rubric to capture the teaching demonstration of pre-service teachers on microteaching, so as to determine their TPACK knowledge level.

Data was collected in three phases: (1) Pre-intervention phase: classroom observations were conducted during microteaching sessions to measure PSMTs' initial TPACK. (2) Intervention phase: a design-based intervention was applied during lectures where one researcher demonstrated how digital and non-digital tools are incorporated into mathematics instruction. The intervention focused on the teaching of mathematics grade 10 topics (functions, measurement, and analytical geometry) over a semester. (3) Post-intervention: PSMTs' TPACK was again measured through microteaching sessions, using the same observation instruments. Finally, the researchers conducted individual semi-structured interviews to gain the participants' experiences, challenges, and opportunities to develop their TPACK.

The data was analyzed using the Likert scale of the checklists to assess TPACK of PSMTs, further being converted to qualitative categories following the predetermined categories (Sugiyono, 2013; Widoyoko, 2014). Data were coded and analyzed based on three constructs of the TPACK framework: TK, TPK, and TCK. The findings from the semi-structured interviews were used to enrich the framework of the study. Sugiyono (2019) asserts that Likert scales are used to measure people's, individuals', or groups' attitudes, opinions, and perceptions of social matters. Tables 1 and 2 illustrate the scale categories.

Table 1. Likert scale categories.

Interval	Criteria
1.00 < score < 1.75	Very low
1.75 < score < 2.50	Low
2.50 < score < 3.25	Good
3.25 < score < 4.00	Very good

Source: Widoyoko (2014).

Table 2. The Percentage range values and qualitative criteria.

Value	Range	Qualitative Criteria
1	0 - 20	Very low
2	21 - 40	Low
3	41 - 60	Fair
4	61 - 80	Good
5	81 - 100	Very good

Source: Sugiyono (2013).

Interview transcripts were analyzed within a thematic analysis framework (Braun & Clarke, 2006) using a six-step process of coding, theme identification, and interpretation. Reflective journals were reviewed using narrative and thematic analysis to trace participants' changing pedagogical shifts (Riessman, 2008). This combination of analytic methods served to provide a dynamic view of the ways in which PSMTs developed TPACK.

Ethical approval was granted by the university's research ethics committee with a protocol number: FEDSECC026-06-23. The participants consented to their voluntary participation through the consent form prior to data collection. Anonymizing responses maintained confidentiality, and PSMTs consented to be part of the project and were informed about their right to withdraw at any stage without repercussions. To ensure trustworthiness, the study adhered to Lincoln and Guba (1985) criteria of credibility, dependability, transferability, and confirmability. Credibility was achieved through triangulation, peer debriefing, and member checking. Maintaining a detailed audit trail of all research procedures and data analysis ensured the study's dependability. The transferability of findings was contextualized within the specific setting but described in a manner that allows applicability in similar educational contexts. Confirmability of the study was achieved through reflexive journaling and an audit trail, which minimized the researchers' bias.

4. Findings

4.1. Profile of Preservice Mathematics Teachers

The study included six PSMTs in mathematics education during their third year of a 4-year Bachelor of Education degree. The PSMTs, averaging 21 years of age, were a cohort of 21 PSMTs comprising 6 males and 15 females from a single class. To maintain anonymity, the following codes were assigned: PSMT1, PSMT2, PSMT3, PSMT4, PSMT5, and PSMT6. Every participant exhibited a strong dedication to enhancing their technological and pedagogical knowledge in mathematics, aiming to become proficient teachers in the 4th Industrial Revolution classroom environments. This group was chosen to embody many viewpoints within the programme.

4.2. Generated Themes

The themes presented below are organized in alignment with the research questions and objectives of the study, grounded in the TPACK framework. They reflect both individual and shared experiences among PSMTs, highlighting their experiences: opportunities and challenges, pedagogical shift, and adoption to integrate digital and non-digital tools. The themes have been presented and described in subsections.

4.2.1. Theme 1: Pre-Service Mathematics Teachers' TPACK Experience with Visualization of Mathematical Concepts Before and After the Intervention

4.2.1.1. Sub-Theme 1: Technological Knowledge (TK)

Technological Knowledge (TK) experience includes proficiency in utilizing computer software and hardware, presentation equipment such as projectors, and various technological tools in educational settings (Koehler, Mishra, & Cain, 2017). Analysis of TK abilities among the six PSMTs before the interventions shows a mean score of 32, placing them in the low category. Table 3 indicates that PSMT1, with a score of 20, falls into the very low category. PSMT2, with a score of 21, PSMT3 with 34, PSMT4 with 40, PSMT5 with 38, and PSMT6 with 32 all fall within the low category. These results suggest that respondents have limited skills in technology integration for teaching mathematics. Furthermore, all scores of each component in the TK section for all PSMTs can be seen clearly in Table 3. This data shows that the technological skills required by PSMTs in each component are categorized as low, with an average score of 2.14 in the low category (Table 4). This result was confirmed by the PSMTs during the interview when they indicated that they relied on verbal explanations, writing on the chalkboard, and freehand drawings to explain mathematics concepts instead of using technological tools. These methods are low-tech and reflect a traditional classroom setup. Two PSMTs lamented:*I used traditional methods, primarily writing on the board to present the concepts without any specialised tools." "At first, I used the chalkboard to write. I didn't have any specific tools to help with visualisation* (PSMT4). Another PSMT commented: *I mostly talked and wrote on the board to explain the concepts. I relied on verbal explanations and comparisons between drawings on the board* (PSMT6).

A few PSMTs supplemented their traditional methods with physical objects to enhance understanding. These tools helped bridge abstract concepts with tangible examples. PSMT3 narrated that he used solid objects to teach: *I used solid objects (prisms) to show the difference between area and volume in measurements. I integrated non-digital posters to help learners understand. I showed students the formulas for calculating distance and midpoint and used freehand drawings on the board to illustrate these concepts. I relied on verbal explanations and comparisons between drawings on the board, as well as the 2D shapes.*

Although some PSMTs used physical objects and posters to support their teaching, the methods lacked technological integration or advanced tools for visualization. This suggests a potential gap in their preparedness to utilize diverse or innovative teaching strategies, which could be addressed in subsequent interventions. Data from the analysis of TK abilities among the PSMTs after the interventions obtained an average score of 70 in the good category. In Table 3, it can be seen that PSMT1 (with a score of 66), PSMT6 (with a score of 68), PSMT2 (with a score of 70), PSMT3 (with a score of 72), PSMT4 (with a score of 74), and PSMT5 (with a score of 72) all fall into the good category. These results indicate that the PSMTs mastered the technological knowledge, which helped them visualize and teach mathematics with technology to students effectively (Table 3). Moreover, the scores for each component in the TK section post-intervention for all PSMTs are clearly presented in Table 4. The data indicates that the performance of each component is classified as efficient, with an average score of 3.44 in the very good category (Table 4). Tables 3 and 4 present an overview of PSMT's preparedness to teach mathematics using technology.

Table 3. Analysis of TK aspect ability.

No.	Pre-service teacher code	TK score before intervention	Qualitative criteria	TK score after intervention	Qualitative criteria
1	PSMT1	20	Very less	66	Good
2	PSMT2	21	Less	70	Good
3	PSMT3	34	Less	72	Good
4	PSMT4	40	Less	74	Good
5	PSMT5	38	Less	72	Good
6	PSMT6	36	Less	68	Good
Average		32	Less	70	Good

Table 4. Average score of each TK component.

No	TK Component	Average score before intervention	Average score after intervention
TK1	Ability to effectively use digital tools (e.g., GeoGebra, virtual manipulatives) for visualizing mathematical concepts.	1.75	3.6
TK2	Ability to select appropriate technological tools and use them for my lessons.	2.20	3.8
TK3	Learn technology easily	3.00	3.8
TK4	Use of different technological tools in my lesson	1.75	3.0
TK5	Technological skills to use technology and solve technological problems.	2.00	3.0

The improved technological knowledge positively impacts the attitudes of PSMTs towards using this tool in teaching mathematics, particularly circle theorems. This aligns with the current study's findings, suggesting that when PSMTs perceive technology as beneficial, their readiness to incorporate it into their teaching increases. This suggests that the training PSMTs received prepared them for their immediate teaching responsibilities and contributed to their long-term professional development as educators.

4.2.1.2. Sub-Theme 2: Technological Pedagogical Knowledge (TPK) Experience

Technological Pedagogical Knowledge (TPK) experience explicates the interaction between technology and pedagogy. This knowledge enables comprehension of technology's potential for various pedagogical objectives, allowing teachers to choose the most suitable tools according to their relevance to particular pedagogical methods (Koehler et al., 2017). Analysis of technological knowledge abilities among the PSMTs in visualizing and teaching mathematical concepts with digital and non-digital concepts before the interventions obtained an average score of 26 in the low category. In Table 5, it can be seen that PSMT2 (with a score of 19) and PSMT6 (with a score of 18) fall into the very low category. However, PSMT1 (with a score of 33), PSMT3 (with a score of 25), PSMT4 (with a score of 29), and PSMT5 (with a score of 32) all fall into the low category. The results demonstrate that PSMTs possess limited proficiency in technology and pedagogy (Table 5). Also, the scores for each component in the TPK section for all PSMTs are clearly presented in Table 5. The data indicate that the performance of each component is classified as low, with an average score of 1.75 within the low group (Table 5).

These results indicate that PSMTs have low skills in technology and pedagogy (Table 5). The finding that PSMTs exhibit low levels of TPK, as evidenced by their limited skills in technology and pedagogy, suggests a critical need for targeted professional development interventions. This finding concurs with the findings from the interviews. The PSMTs indicated that they have limited knowledge of the technology and pedagogy for visualizing and teaching complex mathematical concepts. Two PSMTs narrated: *I found it challenging to integrate technology into my lesson plan effectively. I used a presentation tool, but it didn't engage the students as I had hoped. I'm unsure how to choose the right digital tools to complement my teaching methods and make the concepts clearer* (PSMT6). PSMT4 concurs with PSMT6 assertion: *During my microteaching session, I struggled with using the simulation software to demonstrate the concept. I wasn't confident in troubleshooting the technical issues that arose, and it disrupted the flow of my teaching. I feel I need more training on how to align technology with my teaching goals.*

The average result of 80 in the acceptable category was obtained from the analysis of TPK abilities among the PSMTs following the interventions. Table 5 illustrates that PSMT1 (with a score of 89), PSMT2 (with a score of 83), and PSMT5 (with a score of 85) are all classified as "very good." PSMT2 (74), PSMT3 (78), and PSMT6 (72) all belong to the "good" category. Table 5 illustrates that the PSMTs effectively visualised and instructed students in mathematics using technology, as evidenced by their mastery of the material. Additionally, Table 6 provides a distinct representation of the scores of each component in the PK section following the intervention for all PSMTs. According to this data, each component is classified as efficient, with an average score of 3.32 in the "very good" category (Table 6). An overview of the preparedness of PSMTs to visualise and teach mathematics concepts using technology is provided in Tables 5 and 6.

Table 5. Analysis of TPK aspect ability.

No.	Pre-service teacher code	TPK score before intervention	Qualitative criteria	TPK score after intervention	Qualitative criteria
1	PSMT1	33	Low	89	Very good
2	PSMT2	19	Very low	74	Good
3	PSMT3	25	Low	78	Good
4	PSMT4	29	Low	83	Very good
5	PSMT5	32	Low	85	Very good
6	PSMT6	18	Very low	72	Good
Average		26	Low	80	Good

Table 6. Average score of each TPK component.

No.	TPK Component	Average score before intervention	Average score after intervention
TPK1	Ability to design lesson plans that integrate digital tools meaningfully into pedagogical practices.	1.30	3.45
TPK2	Effective classroom management strategies when using dual digital and non-digital tools	1.26	3.00
TPK3	Ability to select technologies that enhance teaching approaches for the lesson.	2.40	3.40
TPK4	Competence in choosing technologies that enhance learners' learning for a lesson.	2.35	3.50
TPK5	Ability to choose technologies that enhance the content for a lesson.	1.45	3.25

Findings from the interview indicate that PSMTs emphasized using GeoGebra in conjunction with non-digital tools and illustrations to make a triangle and its midpoint more comprehensible. This combination allowed students to engage both visually and through traditional notation, enhancing understanding. Two PSMTs have this to say: *Using both digital and non-digital tools has positively impacted my teaching practices and my skills in technology usage. GeoGebra, in particular, improved my teaching practice by allowing me to demonstrate abstract concepts dynamically, which made me more confident. I even learned new aspects of exponential functions that I wasn't aware of, probably because they were taught in a more traditional way when I was in school. The tool made my teaching more effective because it provided visual support that traditional explanations alone couldn't offer. It allowed me to deliver content more confidently and accurately* (PSMT1). *I used GeoGebra for digital visualization and physical models to show students the difference in measurements, such as volume and surface area. This dual-tool approach supports different learning styles and reinforces learning by providing both visual and written representations* (PSMT3). These responses show how interactive participation (Mentimeter) and dynamic visualization (GeoGebra) work together to create a more engaging learning environment.

4.2.1.3. Sub-Theme 3: Technological Content Knowledge Experience

Analysis of TCK abilities among the PSMTs in visualizing and teaching mathematical concepts with digital and non-digital concepts before the interventions achieved a mean score of 26 in the low category. In Table 7, it can be seen that PSMT1 (with a score of 35), PSMT2 (with a score of 27), PSMT3 (with a score of 22), PSMT5 (with a score of 32), and PSMT6 (with a score of 28) all fall in the low category. However, PSMT4 (with a score of 20) falls within the very low category. In addition, scores in all categories indicate low for all aspects of TCK for all PSMTs, as shown in Table 7. Table 7 shows that each component is categorized as low, with an average score of 1.73 in the very low category (Table 8).

Data from the analysis of TCK abilities among the PSMTs after the interventions received a mean result of 75 in the category of good. In Table 7, PSMT1 (with a score of 77), PSMT6 (with a score of 70), PSMT3 (with a score of 74), PSMT4 (with a score of 63), and PSMT5 (with a score of 78) all fall into the category of good. However, PSMT2 (with a score of 85) falls into the very good category. These results indicate that the PSMTs mastered the concept, which helped them visualize and teach mathematics effectively with technology to students. Furthermore, all scores of each component in the TCK aspects after the intervention for all the PSMTs are presented in Table 7. Table 7 shows efficiency with an average score of 3.28 in the very good category. Tables 7 and 8 show an overview of PSMT's readiness to visualize and teach mathematics concepts with technology.

This was evident during the interviews. All PSMTs supplemented their digital tools with non-digital tools to enhance understanding. These tools helped bridge abstract concepts with tangible examples. PSMT3 narrated that he used GeoGebra with other non-digital tools: *In my view, GeoGebra is a very helpful tool to integrate with non-digital tools to help learners understand math concepts. I showed students how to calculate distance and midpoint with GeoGebra and used freehand drawings on the board to illustrate these concepts. For example, I would compare the lengths of lines to indicate differences in distance. I relied on verbal explanations and comparisons between drawings with GeoGebra and the 2D shapes.*

PSMTs used GeoGebra to visualize the transformation of functions and solid objects to demonstrate complex mathematics concepts. This affirms that PSMTs were knowledgeable about technologies used to understand and teach algebraic functions and analytical geometry. These findings suggest that PSMTs view GeoGebra as a valuable resource for facilitating student learning through dynamic exploration of mathematical relationships. This perspective is crucial, as it highlights the potential of GeoGebra to improve PSMTs' TCK and also to influence their pedagogical approaches positively.

Table 7. Analysis of TCK aspect ability.

No.	Pre-service teacher code	TCK score before intervention	Qualitative Criteria	TCK score after intervention	Qualitative criteria
1	PSMT1	35	Low	77	Good
2	PSMT2	27	Low	85	Very good
3	PSMT3	22	Low	74	Good
4	PSMT4	20	Very Low	63	Good
5	PSMT5	32	Low	78	Good
6	PSMT6	28	Low	70	Good
Average		26	Low	75	Good

Table 8. Average score of each TCK component.

No	TCK Component	Average score before intervention	Average score after intervention
TCK1	Proficiency in selecting digital and non-digital tools that align with specific mathematical concepts.	1.40	3.50
TCK2	Competence in demonstrating mathematical concepts both digitally and non-digitally.	1.23	3.45
TCK3	Knowledge about technologies that can be used for understanding and teaching algebraic functions.	1.50	3.20
TCK4	Knowledge about technologies that can be used for understanding and teaching analytical geometry.	2.09	3.25
TCK5	Knowledge about technologies that can be used for understanding and teaching measurements.	2.44	3.00

The findings of this study align with several key studies in TCK development. Research by Niess (2011) emphasizes that the development of TCK is crucial for teacher education programs, as it reflects the teacher's ability to blend content knowledge with technological tools to create meaningful learning experiences.

4.2.2. Theme 2: Challenges and Opportunities of Digital and Non-Digital Tools for Understanding and Teaching Mathematical Concepts

4.2.2.1. Sub-Theme 1: Accessibility and Usability of Digital and Non-Digital Tools

Integrating digital and non-digital tools presented significant opportunities and practical challenges for PSMTs. A central challenge revolved around the accessibility and usability of digital tools, particularly for those unfamiliar with GeoGebra.

As PSMT6 noted, the main challenge was time switching between tools, which *required planning. Also, becoming comfortable with GeoGebra took time, so I felt limited in what I could achieve without more practice.* Similarly, PSMT4 acknowledged: *I was not really skilled in GeoGebra, probably because of the short time I was exposed to the tool.* Technical difficulties also disrupted teaching continuity, particularly when network coverage support was lacking. PSMT1 explained, *one challenge was the technical difficulties I faced with digital tools, especially connectivity issues with GeoGebra. But once these were resolved, I was able to teach more effectively.* These accounts confirm that technical competence and access remain foundational to effective integration of digital tools. Furthermore, some PSMTs reported that their students had limited experience with educational technology, which became a barrier to fully utilising digital platforms. As PSMT3 explained, *the biggest challenge was ensuring that all students could interact with the digital tools, as not all students were familiar with using GeoGebra at first.*

Despite these challenges, PSMTs also discovered how digital tools could significantly enhance instruction. GeoGebra's dynamic functionality allowed teachers to illustrate mathematical relationships visually. PSMT5 shared: *GeoGebra allowed me to dynamically demonstrate the concepts, making the teaching process more interactive. For example, I* *could show how the gradient of a line changes with the slope, how parallel lines have equal gradients, and how perpendicular lines have gradients with a product of -1.* Moreover, the dual use of digital and non-digital tools promoted a broader pedagogical effectiveness. PSMT1 reflected: *Using both digital and non-digital tools has made me think more positively about my future as a teacher. I now realize the importance of integrating different tools in my teaching practice.* The insights from these PSMTs suggest that while technological integration requires technical and pedagogical support, it also fosters innovation and adaptability in instructional approaches.

4.2.2.2. Sub-Theme 2: Pedagogical Adaptation and Conceptual Understanding

A major sub-theme emerging from the interviews was the shift in pedagogical strategies following the intervention. Prior to the intervention, visualization relied heavily on traditional, static methods such as chalkboard drawings or verbal descriptions. For instance, some PSMTs showed students the formulas for calculating distance and midpoint and used freehand drawings on the board to illustrate these concepts and relied on verbal explanations and comparisons between drawings on the board. After the intervention, however, many PSMTs reported a transformation in their instructional methods. PSMT2 explained, using *GeoGebra allowed me to demonstrate how changing the positions of points impacts the distance... which made the demonstrations more effective and engaging for them.* Likewise, PSMT3 incorporated both physical and digital representations: *I used GeoGebra for digital visualization and physical models to show students the difference in measurements, such as volume and surface area.* The ability to dynamically manipulate visual elements enabled PSMTs to explain complex or abstract content better. PSMT4 stated: *Integrating GeoGebra helped display mathematical concepts more dynamically, which improved student engagement and understanding.* This echoes PSMT1's strategy: *I initially used posters to introduce concepts, followed up with GeoGebra for dynamic visualization. Mentimeter helped check prior knowledge at the start of the lesson.*

This blending of tools helped scaffold conceptual understanding and revealed how responsive digital environments can enhance real-time pedagogy. These adaptations reflect meaningful shifts in instructional design where preservice teachers move beyond procedural instruction toward more exploratory, inquiry-based learning environments.

4.2.2.3. Sub-Theme 3: Technical Competence and Professional Growth

PSMTs' reflections also highlighted a link between increased technical competence and their professional growth and confidence. Many acknowledged the limitations of their earlier methods and described how exposure to digital tools helped address previous gaps. For example, some PSMTs indicated that they experienced a challenge with their first traditional methods/lessons was the lack of accuracy in freehand drawings, which could lead to misconceptions. The development of digital fluency contributed significantly to self-efficacy. As PSMT6 shared, *using GeoGebra definitely boosted my confidence because I could make abstract concepts more tangible and show real-time changes, which helped students understand better.* Similarly, PSMT2 stated: *GeoGebra boosted my confidence because it supported my teaching. The tool was almost self-explanatory, so I felt more confident that the students could grasp the concepts through the visualisations.* Notably, confidence gains were not limited to digital proficiency alone. Many PSTs expressed that combining digital and non-digital tools allowed them to meet students at multiple levels of understanding. As PSMT3 described, *my confidence was uplifted because I felt more skilled and experienced with each lesson, especially using digital tools like GeoGebra. These developments also affected classroom dynamics.* PSMT6 observed: *Students were more engaged and interacted more during the lessons. I saw an improvement in their understanding, especially when comparing different graphs, as the colours and dynamic visuals made it easier for them to follow.*

In essence, most PSMTs have made it clear that the use of dual tools not only enhances their ability to teach but also enriches their professional identity and future readiness.

As PSMT2 confidently asserted, *I feel more prepared to use GeoGebra in future teaching because of the impact it had on my lesson delivery. I'm also motivated to explore other areas where GeoGebra could be useful.*

In general, integrating these tools into mathematics instruction presents challenges and opportunities for preservice teachers. The findings suggest that structured exposure to digital tools and continued support in their implementation are crucial for fostering effective and confident mathematics teachers.

5. Discussion of Findings

This study explored PSMTs' experiences with integrating digital and non-digital tools for visualizing mathematical concepts, using the TPACK framework as a lens. The discussion addresses both research questions, synthesizing evidence from microteaching sessions, interviews, reflective journals, and observation data, and drawing connections to relevant literature and theoretical foundations.

The first research question aimed to understand how PSMTs experience integrating digital and non-digital tools to enhance their TPACK. Findings from both the intervention and qualitative interviews indicate that PSMTs made significant progress in this area, transitioning from reliance on traditional, low-tech teaching methods to confidently using blended strategies that incorporate both dynamic digital tools such as GeoGebra and tactile, non-digital aids like posters and physical models. Before the intervention, most preservice teachers depended heavily on verbal explanations and chalkboard sketches, methods which, while fundamental, limited their ability to represent abstract mathematical ideas dynamically.

This text highlights the limitations of freehand drawing in effectively communicating geometric relationships, as evidenced in interviews. These narratives align with Mishra and Koehler (2006), who described a scarcity of technological knowledge (TK) as a core component of the TPACK framework. Post-intervention results demonstrated significant improvements across all three core elements of TPACK (TK, TPK, and TCK). For all indicators, PSMTs achieved significantly higher scores, transitioning from the "low" to the "good" or "very good" categories. The existing literature supports these findings. Bulut and Güveli (2023) emphasized that structured technology integration activities strongly support PSMTs' TPACK development. This study contributes to the literature by showing that a well-designed intervention can lead to substantial growth in TPACK within a single semester. The second research question explored the challenges and opportunities faced by PSMT teachers when utilizing digital and non-digital tools to enhance their understanding and teaching of mathematical concepts.

The results indicate that, though there were technical and pedagogical issues in the early phases, these were usually facilitating factors more than barriers. A major problem was a lack of familiarity with technology. These observations resonate with the concerns of Baran et al. (2019), who argue that one-off exposure to digital tools is insufficient; PSMTs need extended and scaffolded training to develop digital fluency. Technical barriers were also common. However, as the PSMTs became more familiar with the tools, they found that their pedagogical approach was changing. They moved from teaching procedures to conceptual enquiry, as in Koh and Divaharan (2011), focusing on responsive pedagogical practice.

This shift reflects growing mastery in both TPK and TCK, where technology is not just used for display but is woven meaningfully into pedagogical and content decisions. The integration of these tools enables more inclusive and multimodal teaching. This aligns with the findings of Erdogan and Dur (2014), who advocate for multiple representations to support conceptual understanding in mathematics. These practices demonstrate a shift toward reflective and student-centered pedagogy qualities of high TPACK development.

An important finding from the data was the growth in PSMTs' confidence. This finding is corroborated by Bakar et al. (2020) study, who argue that self-efficacy in technology use strongly influences teaching practices. More broadly, this resonates with the TPACK literature, which suggests that teachers' belief in their competence across TK, PK, and CK domains predicts their willingness to adopt innovative teaching practices (Lai, Wang, & Huang, 2022).

Nonetheless, this study provides evidence of the integration of these tools into mathematics education to enhance TPACK development, support adaptive pedagogy, and enable technical and professional growth. They confirm the importance of embedding TPACK-informed design into teacher education programs.

6. Conclusions

This study has provided compelling evidence that integrating digital and non-digital tools into PSMT education fosters significant growth in TPACK. The findings highlight how PSMTs transitioned from traditional, low-tech instructional strategies to more dynamic, multimodal approaches that leveraged digital tools like GeoGebra alongside tangible resources such as physical models. This shift enhanced their ability to visualize and teach mathematical concepts and cultivated their pedagogical adaptability and confidence. Despite initial technical and pedagogical challenges, PSMTs demonstrated resilience and professional growth, evolving from tool users to reflective practitioners who integrated technology with purpose.

The study underlines the transformative potential of structured, scaffolded interventions in strengthening PSMTs' TPACK competencies. Furthermore, it emphasizes the need for extended exposure, continuous support, and a reflective learning environment to solidify digital fluency and pedagogical integration.

While this study demonstrates the effectiveness of TPACK-informed training, it also highlights the importance of addressing infrastructure limitations, providing sustained professional development, and nurturing collaborative learning experiences. This study has provided compelling evidence that integrating digital and non-digital tools into PSMT education fosters significant growth in TPACK. The results demonstrate how the PSMTs moved away from traditional, low-tech teaching methods to more sophisticated, multimodal practices that incorporate digital tools, such as those afforded by GeoGebra, with concrete artefacts such as physical models. This change impacted PSMTs' capacity to envisage and teach mathematics and enhanced their pedagogical flexibility and confidence. Despite initial technical and pedagogical challenges, PSMTs demonstrated resilience and professional growth, evolving from tool users to reflective practitioners who integrated technology with purpose.

This study highlights the transformative capacity of structured, scaffolded interventions for PSMTs in enhancing their TPACK competency. It also emphasizes the importance of prolonged exposure, ongoing support, and a reflective learning culture in order to consolidate digital fluency and pedagogical integration. Although this research proved the success of TPACK-based programs, it also underscores the need to resolve infrastructure constraints, to offer ongoing professional learning, and to support collaborative learning.

7. Recommendations

This study, therefore, makes the following recommendations: (a) teacher education programs should incorporate extended and structured training on digital tools like GeoGebra, ensuring PSMTs gain fluency and confidence in their use. (b) Institutions should provide ongoing mentorship and peer collaboration opportunities to reinforce TPACK development and encourage reflective teaching practices. (c) universities and schools should invest in stable internet connectivity and access to digital tools to mitigate the technological barriers PSMTs face. (d) future curriculum design should emphasize integrating both digital and non-digital visualization strategies to support diverse learning needs. (e) provide in-service teachers with TPACK-based training to bridge the divide between preservice training and classroom implementation, thereby ensuring ongoing professional development.

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