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The impact of digital technology on the development of mathematics thinking in early childhood education: A South African perspective

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Abstract

While global curricula promote the use of technology to enhance early mathematics skills, many South African classrooms lack sufficient digital resources. This empirical paper explored how digital technology influences the development of mathematical thinking in early childhood education within the South African context. Guided by the technological pedagogical content knowledge (TPACK) framework, the research investigated how teachers integrate digital tools to support mathematics learning. Using an interpretive qualitative approach and hermeneutic phenomenology, the study captured the lived experiences of twelve foundation phase teachers from four public primary schools in Limpopo. Data was gathered through semi-structured interviews, document analysis and non-participant observations, and analyzed using interpretative phenomenological analysis with NVivo 12. Findings revealed that teachers understand the value of game-based learning for mathematical thinking and problem-solving. However, limited access to digital tools in rural areas hinders consistent classroom application. The study offers insights into applying TPACK in resource-limited educational setting.

Keywords: digital technology, early childhood, game-based learning, mathematical thinking, TPACK

INTRODUCTION

Using digital technology in teaching and learning mathematics is reshaping how the subject is taught in South Africa. While South Africa is navigating the challenges of education inequality, overcrowded classrooms, and a lack of knowledge on integrating African culture in teaching and learning activities, using digital technology in teaching mathematics poses benefits and limitations in developing mathematical thinking in young learners. According to Al-Hassan et al. (2025), the benefits of using digital technology in teaching early mathematics are to enhance learners' cognitive development. Jannah et al. (2025) confirm that digital tools improve young learners' conceptual understanding of mathematics vocabulary. Against this backdrop, the authors argue that digital technology positively impacts the development of mathematical thinking skills in young learners. This paper, therefore, investigates the impact of digital technology on developing mathematical thinking in early childhood.

Children between 0-9 years learn by exploring and playing to develop the holistic skills (Shah et al., 2024), including mathematical thinking. By understanding the views of Shah et al. (2024), educators in early childhood need to use different approaches and pedagogies to expand their children's cognitive development. While studies from Clemente-Suárez et al. (2024) and Meng et al. (2024) argue that using technology in early childhood hinders children's mental development, the evidence from Wang and Li (2024) and Mutia et al. (2025) suggests that the quality and context of using digital technology allows learners to develop digital and thinking skills. Despite this, South Africa's implementation of digital technology in the classroom is uneven between urban and rural schools. In addition, the curriculum does not guide educators using this approach, especially in early childhood education.

Educators' competencies in implementing digital technology in early childhood critically influence the impact of mathematics understanding and thinking. However, educators are not equipped with the skills of

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Contribution to the literature

- This study contributes to the literature by providing empirical evidence on the impact of digital technology to support mathematics thinking in South African early childhood, highlighting its relevance to educational progress and policy development.
- It extends the Technological Pedagogical Content Knowledge (TPACK) literature by demonstrating how early childhood teachers integrate digital tools into mathematics teaching in under-resourced rural schools.
- In addition, this paper highlights the significance of game-based learning for problem-solving and mathematical thinking skills, while revealing how limited access to digital resources constrains effective classroom implementation.

selecting and using digital manipulatives despite limited digital tools (Dilek Eryigit et al., 2025). In addition, South African learners continue to perform poorly in mathematics and science compared to other countries (Boateng et al., 2025). In a different international study on trends in international mathematics and science study, South Africa ranks second last in socioeconomic countries (Mokgwathi, 2025). Other curricula outside South Africa increasingly emphasize the use of digital technology in teaching mathematics to understand its impact to enhance children's conceptual learning, problem-solving and thinking skills. For example, the Australian early years learning framework and the United Kingdom's early years foundation stage support the use of age-relevant and context of digital technology to teach early mathematics through an interaction of play-based pedagogies (Bay, 2022). Ghana education service and United Nations children's fund also corroborate integrating information communication technology and play-based pedagogy in early grades (Munyengabe et al., 2017). Rwanda introduced the 'one-laptop-per-child' initiative to integrate digital technology in early childhood (Munyengabe et al., 2017). These global trends highlight a gap in the South African curriculum and policies, where digital integration in early mathematics is limited, especially in rural schools. As such, aligning South African early childhood curricula with these international best practices can contribute to more equitable and effective mathematics teaching. It is against this backdrop that the paper asks:

Research question: *What is the impact of digital technology on developing mathematical thinking in early childhood?*

THEORETICAL FRAMEWORK

This research paper investigated the impact of digital technology on developing mathematical thinking in early childhood through the lens of the technological pedagogical content knowledge (TPACK) framework. It further explored educators' magnitude of their technological knowledge, pedagogical approaches, and understanding of mathematical content to interconnect to create meaningful and engaging teaching and learning experiences of mathematical thinking in young learners. Nafiu and Olaitan (2025) agreed that educators with strong technological knowledge can integrate relevant digital technologies to enhance children's mathematical skills. Priyanda et al. (2025) confirm that technological pedagogical knowledge allows educators to use digital tools in mathematics activities meaningfully to improve learners' mathematical thinking and problem-solving skills. It is against this background that digital technology has a significant potential impact on developing mathematical thinking in young children. Conversely, educators' knowledge of using digital technology to develop learners' mathematics skills in early childhood should be investigated.

Understanding How to Use Digital Technology to Develop Learners' Mathematics Thinking

In the South African context, the curriculum policy gap is evident in rural schools where educators understand the role of digital technology in teaching mathematics but experience limited resources and training on how to use it. Venketsamy and Hu (2022) corroborate that foundation phase educators misalign the use of technology and teaching mathematics. The literature from Lee (2021) affirms that digital tools are limited in enhancing learners' problem-solving skills. Addressing this gap is vital to ensure learners access equitable, meaningful, and quality education aligned with the international and national sustainable development goals. Drawing on the TPACK framework, educators need to be supported in using technological pedagogical content of teaching mathematics early childhood to deepen children's thinking skills.

Even though Maharjan (2023) asserts that unequal access to digital tools often challenges mathematics achievement, Makda (2025) argues that collaborative digital tools bridge conceptual gaps through interactive learning experiences. As such, the author believes educators with limited digital tools can share them among learners to create a collaborative learning space to develop their mathematical thinking skills. Since play-based pedagogies are considered proactive early childhood strategies, educators can use digital technology to align with their pedagogical and mathematics content. Pedagogical content knowledge encourages educators to use games, storytelling and visual manipulatives to develop mathematics skills in early childhood settings (Benavides-Varela et al., 2023). For example, a mathematics game can be played in groups on digital devices to encourage learners to understand numbers and counting skills. Technological content knowledge supports educators in selecting relevant digital technologies to make teaching activities accessible to different learners in mathematics. As noted, the author agrees that educators need to know when and how to use various technological tools to develop mathematical ideas for young learners.

LITERATURE REVIEW

Early childhood is a critical period for developing early mathematical thinking, which includes number sense, spatial reasoning, measurement, and problem-solving skills (Chen, 2024). The literature from Budiarti (2025) and Sinclair (2018) indicates that over the past two decades, digital technological tools have become increasingly integrated into early childhood classrooms, offering opportunities to enhance mathematical learning through visual, tactile, and interactive experiences. Research from Novita and Herman (2021) and Papadakis et al. (2018) has shown that digital technologies that suit the holistic development of young children can significantly enhance mathematical understanding. Manches (2011) corroborates that digital manipulatives can help young children visualize mathematical relationships and experiment with abstract concepts concretely. Internationally, the research conducted by Tang et al. (2022) in Indonesia shows a satisfactory result of integration of technology into mathematics lessons to junior students. Tang et al. (2022) did not focus on early childhood learners, their findings support intentional pedagogical approaches, teacher support and digital technologies relevant to appropriate strategies in developing mathematical thinking skills in South African perspective. Can (2020) and Syarfina et al. (2023) assert that digital games that promote early numeracy have also been shown to improve children's counting, subitizing and pattern recognition skills. To situate the context, Nakawa and Furuta (2024) explains subitizing is the ability to recognize the quantity of objects without counting them. Theorists such as Vygotsky (1976) affirm that tablets and coding toys are cognitive tools that mediate mathematical understanding through guided play activities.

While international studies from Papadakis et al. (2018), Can (2020), and Syarfina et al. (2023) demonstrate the potential impact of digital technology in early mathematics teaching, South African classrooms face unique challenges. In South Africa, the integration of digital technology into early childhood is gaining momentum, though challenges related to infrastructure, teacher preparedness, and contextual relevance persist. Two studies from Macharia (2023) and Saal et al. (2025) were conducted in South Africa to explore the benefits and challenges of using digital technologies in mathematics classrooms. Macharia (2023) found that even though digital technology increases learners' interest in mathematics, teachers still face limited training on these approaches. In the same vein, Saal et al.'s (2025) findings indicated that digital technology potentially impacts engagement in mathematics. Their study showed that South African teachers lack confidence in using digital game-based mathematics learning due to limited exposure to technology (Saal et al., 2025). Thus, implementing these approaches in early childhood settings in South Africa remains uneven, especially in rural schools. To fully realize the impact of digital technology in early mathematics, efforts must focus on teacher development, contextual relevance and equitable access.

METHODS AND MATERIALS

An interpretivist research paradigm was selected, as guided by Rotella (2023), which is used to interpret the reality of participants shaped by their history, culture and social class. Similarly, Paudel (2024) asserts that the interpretivist paradigm assumes that reality is subjective and influenced by an individual's experiences. In addition, this paradigm supports the philosophical assumptions that shape the researcher's choice of relevant research paradigm (Paudel, 2024). Thus, for this paper, an interpretivist paradigm was used to interpret the participants' meaningful subjective views to investigate the impact of digital technology on developing mathematical thinking in early childhood. This was also supported by the theoretical lens of TPACK, which argues that curriculum development influences educators' perspectives on using digital technology to develop young learners' mathematical thinking. Muzari et al. (2022) advise that researchers who select the interpretivist paradigm must employ qualitative research approaches. Dawadi et al. (2021) agree that qualitative research allows for in-depth, thick, and rich data collected from a social environment. As such, the researcher can interpret the data to understand the underlying subjective educational issues. For these reasons, a qualitative research approach was employed to collect rich data and analyze it to understand the impact of digital technology on developing mathematical thinking in early childhood.

Among other research designs in quantitative research, hermeneutic phenomenology was used to elicit teachers' lived experiences using digital technology to develop mathematics skills in early childhood. Gillo (2021) explains that hermeneutic phenomenology is a qualitative research design used to explore and interpret the lived experiences of individuals. For this paper, hermeneutic phenomenology was employed due to its emphasis on the subjective experiences of individuals. In essence, it was used to explore the impact of digital technology on developing mathematical thinking in early childhood.

Participants

A homogeneous purposive sampling was used to select appropriate participants in this study. Tajik et al. (2024) assert that homogeneous purposive sampling involves selecting a small group of participants with similar characteristics, such as experiences, profession, cultural and/or educational background, to solicit rich insights on a phenomenon under study. In addition, Akkaş and Meydan (2024) affirm that homogeneous characteristics enable an in-depth, detailed investigation under the research. Guided by Tajik et al. (2024) and Akkaş and Meydan (2024), a homogenous purposive sampling assisted in selecting 12 foundation phase teachers, from grade 1 to grade 3. Three teachers from each of four public schools were selected based on their homogenous characteristics, such as at least three years' teaching experience in the Foundation Phase, a professional qualification and willingness to use digital technology in teaching mathematics in rural schools. These public schools were required to implement the CAPS as their guiding framework. They relied on the Department of Basic Education (2011) to provide formal guidelines for digital technology development in mathematics skills.

Data Collection Instruments

Semi-structured interviews, document analysis and non-participant observations were used to collect data. Karatsareas (2022) explains that semi-structured interviews are guided conversations between a researcher and participants using open-ended and follow-up questions based on the participants' responses. Henriksen et al. (2022) emphasize that semi-structured interviews in hermeneutic phenomenology allow for profound, reflective experiences and narratives of participants. Firstly, the semi-structured interviews were used to elicit teachers' experiences and narratives on the impact of digital technology on developing mathematical thinking. In line with Henriksen et al. (2022), interviews were conducted in two phases: constructing experiences and stimulated recall interview sessions. During the construction of the experience interview session, participants were asked open-ended questions about their views and experiences on the phenomenon.

Additionally, stimulated recall interviews were used after the classroom observations and lesson plans. This allowed the participants to reflect on their narratives from the construction of experiences, classroom observations and how they planned their lesson activities. An audio recorder was used to capture the conversations from both sessions. An interview schedule was designed with open-ended questions aligned with the research questions for both the constructing experiences and stimulated recall interview sessions. In the first phase, the construction of an experience interview session, each participant was interviewed for at least 50 minutes.

Secondly, document analysis was used to corroborate participants' responses on the phenomenon from the first phase of the interview sessions. Morgan (2022) describes document analysis as a systematic process of reviewing and interpreting the content of documents to extract the patterns and insights relevant to the study's research questions. Morgan (2022) continues to explain that document analysis is usually used as a supplementary method to explore and interpret the meanings related to participants' lived experiences. Against this background, 12 teachers' lesson plans were requested, analyzed and interpreted to corroborate their responses from the construction of experiences interview session. A document analysis tool was designed with open-ended questions linked to the study's research questions.

Lastly, non-participant observations were used to triangulate the data from the interviews and lesson plans to see how teachers implement digital technology in their mathematics classrooms. Laurier (2016) highlights that non-participant observation is a method where the researcher observes and records what happens in a setting without becoming involved. This helps deepen and enrich their understanding of participants' lived experiences by watching behaviors, interactions, and the environment as they naturally occur (Laurier, 2016). The observations were conducted with four grade 3 teachers from each school, assuming they were similar across all foundation phase grades. An observation checklist was developed with open-ended questions to answer during the observation sessions. Each session was conducted for 45 minutes. Field notes were written reflexively and later interpreted through the hermeneutic circle to understand the lived experience of teachers on the phenomenon under investigation. In addition, the observations were used to investigate the impact of digital technology on developing mathematical thinking in the classrooms.

After the observations, the second phase of interviews stimulated recall interview sessions. Participants were requested to share their narratives and reflections from the construction of experiences, lesson plans, and classroom observations. This session took approximately 15 to 20 minutes with each participant.

Lim (2025) differentiates credibility as the confidence, truth, and authenticity of the research findings, while dependability is the stability and consistency of the research processes. Following the views of Lim (2025), for this paper, credibility was ensured by using a range of data collection instruments such as semi-structured interviews, document analysis, and non-participant observations. Moreover, using two phases of interview sessions, the construction of experiences, and stimulated recall enhanced the richness of the narratives, in-depth narratives, and prolonged engagement with the teachers to build trust and rapport. During the stimulated recall interviews, member checking was used to validate the interpretations' accuracy and clarify any misrepresentations. Dependability was ensured by maintaining an audit trail documenting all research process stages, including data collection instruments. Audio recording during the interviews increased the internal validity of the results. Drisko (2025) explained that transferability is the extent to which the findings can be transferred or applied in other settings. Thus, transferability was strengthened by using homogeneous purposive sampling, which allowed thick and rich descriptions of participants and determined the findings' applicability. Lim (2025) agrees that confirmability refers to the degree to which the findings are shaped by the participants' experiences and perspectives. Since this study used the interpretivist research design, it was important to outline all the data collection and analysis processes to avoid the researcher's bias or assumptions through an audit trail. In addition, peer debriefing with the teachers was also done to reduce the subjectivity and enhance the confirmability.

Before data collection, ethical clearance was obtained from the University of South Africa's Department of Early Childhood Education and Development Research Ethics Committee, reference number 2023/10/11/ 64019209/38/AM. At the department of basic education, permission to conduct research in the Capricorn South, Limpopo, was obtained with the reference number, LPREC/144/2023: PG. All participants and parents of the children received detailed information sheets outlining the study's purpose, procedures, and scope, along with a consent form to review and sign should they agree to participate (Sherwood & Parsons, 2021). The assent forms were sent to the children involved in the study with their parents' permission. The voluntary nature of participation was emphasized, including the right to withdraw at any stage without penalty or consequences. With informed consent, interviews were audio-recorded and later transcribed verbatim. Together, these transcriptions supported the accuracy and reliability of the data collected. Participants were assured confidentiality, anonymity and secure data storage (Badampudi et al., 2022). This was achieved by ensuring that no unauthorized persons could overhear the interviews or access the raw data materials and by using the pseudonyms of the participants during the presentation and discussion of findings. Thus, pseudonyms such as school 1 foundation phase teacher 1 (S1FPE1) to school 4 foundation phase teacher 3 (S1FPE3) were used.

Data Analysis

Interpretative phenomenological data analysis was used to analyze the data collected from the semi-structured interviews, document analysis and non-participant observations. The author emphasized that interpretative phenomenological analysis was deliberately selected to interpret the participants' subjective experiences on digital technology's impact on developing early childhood mathematical thinking. This selection is supported by Eatough and Smith (2017), who view interpretative phenomenological analysis as used in qualitative studies to understand participants' perspectives and lived experiences in their cultural and social realities. In the same notion, William (2024) supports that the chosen analysis links with the interpretivist paradigm selected in this study, which assumes that reality is socially constructed, and that knowledge is best understood through participants' perspectives.

Before the analysis, the data collected was prepared by transcribing the recorded data from the interviews and cleaning the field notes from the document analysis tools and observation checklists. Like other data analysis strategies in quantitative research, interpretative phenomenological analysis allows data to be broken down into manageable codes and categories to uncover trends, patterns, and emerging themes (Smith & Fieldsend, 2021). Three coding phases were performed: coding, recoding, and co-coding. Firstly, the author coded the data manually using a computer; codes were created using the keywords from the study's research questions. Secondly, three data sets from all the participants were uploaded into NVivo 12, a qualitative analysis software for coding. The recoding was done using the same codes used during the coding phase. Finally, co-coding was performed by an independent coder who coded the same data to ensure the transparency, authenticity, consistency and reliability of data analysis (Friedman et al., 2024). Similar codes were grouped into categories, guided by the reviewed literature, and later the categories were also grouped to form the emerging themes that align with the theoretical framework. This ensured that the theoretical framework remained the guiding lens for the study throughout the research process. The author explored different visualizations on NVivo 12 to assist in interpreting the analyzed data and investigate the impact of digital technology on developing mathematical thinking in early childhood. For instance, **Figure 1** illustrates the word cloud exported from NVivo 12, which explicitly illustrates the implications of digital technology in teaching mathematics in early childhood.

As illustrated in **Figure 1**, the word cloud visually represents the most frequently occurring codes drawn

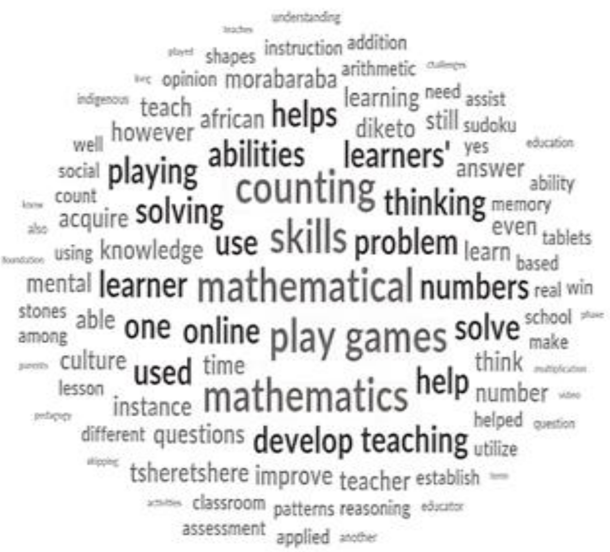

Figure 1. A word cloud on the impact of digital technology in mathematics teaching (Figure generated by author using NVivo 12)

from participants' data from the interviews, lesson plans and non-participant observations regarding the impact of digital technology in teaching mathematics. The largest, bolded codes int center of the cloud, such as "*counting skills*," "*play*," "*games*," and "*mathematics*", show the dominant concepts in participants' discourse, and they emphasize the impact of digital technology in teaching mathematics in early childhood. Subjectively, while the prominence of specific codes used is influenced by how often they are used, their significance is not necessarily in the participants' lived experiences of the phenomenon under study. Thus, **Figure 1** reflects the surface-level frequency count rather than a nuanced, interpretative phenomenological analysis and should be interpreted in conjunction with the results of the in-depth, rich, thick and accurate findings (Lim, 2025).

RESULTS

The results reveal that digital technologies, when integrated with game-based learning, contribute significantly to developing cognitive and mathematical thinking skills in early childhood education. The data from the participants' lived experiences on the phenomenon from the interviews, lesson plans and non-participant observations highlighted that digital technologies enhance learner engagement and conceptual understanding in mathematics. To be more explicit, the participants' conceptual understanding manifests in lesson planning and their classroom practices that promotes learners' mathematical thinking skills. At the same time, game-based learning improved counting, mathematical thinking and problem-solving skills. On the other hand, challenges such as limited access to digital technologies in rural schools and gaps in lesson plans provide pointers to improvement in planning and classroom practices.

Development of Mathematical Thinking and Problem-Solving Skills Through Game-based Learning

The results indicated that digital technology positively impacts developing learners' mathematical thinking and problem-solving skills, particularly when integrated with game-based learning activities. Mikrouli et al. (2024) explain that game-based learning is a teaching pedagogy that uses digital and traditional games to promote classroom learning. To ensure conceptual clarity, game-based learning in mathematics refers to using games in lessons to teach mathematics, unlike gamification that uses badges to non-game activities (Moon et al., 2024). S1FPE1 described how using a digital Ludo game develops learners' problem-solving skills and independence in learning mathematics. To situate the readers within the study, Schmitt et al. (2018), a digital Ludo game is an electronic or computer-based version of the traditional Ludo board game played on digital devices. When learners play this game and try to navigate the strategic moves to win the game against the opponent, they need to think mathematically and logically, which participants link to real-life problem-solving challenges. S1FPE1 said:

> "Ludo game teaches learners how to solve mathematical problems. Learners should be able to defend themselves from the assailants while they play this game. They can solve challenges in real life because of this. It instils independence in them." (S1FPE1)

Across S3FPE1, S3FPE3, and S4PFE2, shared lived experiences and perspectives emerged that game-based activities enhance learners' mathematics skills.

> "Games assist with mathematical skills. Through play activities, learners develop a sense of different shapes and counting skills." (S3FPE1)

> "Game-based activities assist learners to enhance their cognitive and improve their decision-making skills …" (S4PFE2)

S3FPE3 extended this view by explaining how digital adaptations of traditional games like Morabaraba actively promote problem-solving skills and mathematical skills.

> "Morabaraba on digital devices engages learners in problem-solving and mathematics skills …" (S3FPE3).

The lesson plans largely corroborated these results, often indicating that games such as Morabaraba (S3FPE3) aim to develop learners' counting, problem-solving and mathematical thinking skills. Providing a contextual framework for this paper, Morabaraba can be downloaded on smartphones, iPads, and touch-screen control devices (Abah et al., 2025). However, S3FPE3 did not clearly explain how Morabaraba would be integrated with digital technologies. Furthermore, as noted, the lesson plans from S1FPE3, S2FPE3, and S3FPE3 did not illustrate the integration of digital technologies and their impact in mathematics. Their lesson plans showed traditional game-based learning in teaching and learning mathematics in early childhood. These results indicate a need for more deliberate integration into formal planning to reflect the rich lived experiences shared by participants. Classroom observations confirmed with these claims that in S1FPE3's classroom, learners often played Sudoku to learn counting, problem-solving, mathematical thinking and social interaction skills. Learners in S2FPE3's classroom, a hopscotch game (watched a video from YouTube) was used to improve learners' counting and mathematical thinking skills. Similarly, Google videos were projected in S3FPE3's classrooms as a stimulus during mental mathematics activities to teach learners patterns. Observations revealed that S4FPE3's classroom lacked the integration of digital technologies, primarily because these tools were unavailable. The stimulated recall interviews reiterated these results, with educators thinking aloud about using digital technologies in lesson plans and classroom practices. They said:

> "I would use digital games to improve learners' problem-solving, mathematical thinking and reasoning skills … As I reflect, I learnt that digital technologies have potential in developing learners' understanding." (S1FPE3)

> "I believe that digital game develops learners' mathematical thinking skills." (S2FPE3)

> "I have discovered the potential benefits of using technology in teaching young learners as it develops their mathematical thinking skills." (S3FPE3)

> "Technology could assist in improving counting skills." (S4FPE3)

Participants' reflections during the stimulated recall interview sessions strengthened their lived experiences in constructive lived experiences interview sessions, highlighting a strong understanding of the impact of digital technologies in developing mathematics skills. Across their lived experiences, there was a consistent view that technological tools and game-based learning could enhance learners' counting, mathematical thinking and problem-solving skills. These results indicate a shared awareness of the cognitive and conceptual gains that digital technologies can offer in early mathematics education, even where such tools were not consistently integrated into classroom practice among participants.

Integration of Digital Technologies in Mathematics Classrooms

The data disclose that participants integrate various digital technologies, including YouTube, Thutong, smartboards, and Google manipulatives, to facilitate mathematics activities and engagement in early childhood classrooms. These digital technological platforms teach learners mathematics concepts such as number patterns, operations, counting skills, and problem-solving through multimedia resources including videos, songs, and interactive games. For instance, during the construction of lived experiences interview sessions, S1FPE2 and S3FPE3 narrated how they use digital technologies to improve mathematics understanding in their lesson activities. They expressed their lived experiences as:

> "Digital technology improves learners' counting, recognition of numbers, sharing, patterns and grouping skills. I use Google manipulatives and YouTube videos to enhance their cognitive and social interaction skills." (S1FPE2)

> "I stream videos on Google to teach mathematics." (S1FPE2)

> "I integrate videos from Google to play rhymes songs related to the mathematics concepts …" (S3FPE1)

> "I do not use digital technologies more often." (S1FPE3)

In accordance with the nature of semi-structured interviews, the researcher asked a probing question on why S1FPE3 used digital technology in their mathematics classrooms. S1FPE3 acknowledged that they have limited access to digital tools in their schools. The lesson plans vastly contrasted the participants' responses to the constructive interview sessions on their experiences in digital technology integration. For instance, from S1FPE2's interviews where the Google manipulatives and YouTube videos usage were indicated, the corresponding lessons often referenced concrete manipulatives for teaching counting and number patterns. To contextualize the readers, concrete manipulatives refer to physical objects that learners can handle and use to explore and understand mathematical concepts in hands-on activities (Byrne et al., 2023). S1FPE3's lesson plan highlights the disconnection between the responses from the interviews with what the lesson plan reflects. **Figure 2** shows S1FPE3's snapshot of a lesson plan.

Figure 2 illustrates S1FPE3's use of concrete manipulatives during mathematics teaching, specifically

S1FPE3'S PRIMARY SCHOOL

Grade: 3
Week: 1
Day: Monday
Subject: Mathematics
Duration: 1 hour
Topic: Place Value & Number Recognition using Base Ten Blocks and Printable Number Chart

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EDUCATION

Mental Maths	Recall and Strategies	Homework/Corrections	Lesson Content	Classwork and Homework Activity	Reflection
Counting forwards and backwards in 1s, 2s, 5s, and 10s from 0–100 (5 min) using number chart.	Picking the biggest and smallest number (10 min): Teacher shows two numbers on the number chart or with base ten blocks and learners identify which is bigger/smaller. Examples: 34 or 43, 27 or 72, 44 or 55, 53 or 35.	Complete homework corrections (15 min): Learners practice writing numbers in symbols and words using the number chart.	Whole class activity: 1. Call out number names and have learners point to them on the printable number chart. 2. Show numbers using base ten blocks – learners match them to symbols on the chart. 3. Break down numbers into tens and ones using base ten blocks. Example: 47 → 4 tens + 7 ones.	Learners work individually: • Write number names and symbols. • Represent numbers with base ten blocks. • Highlight numbers on the printable chart.	Reflection after lesson: • Were learners able to link base ten blocks to number symbols and names? • Did all learners participate in counting activities? • Adjust future lessons for learners needing more support.

Figure 2. A snapshot of S1FPE3's lesson plan (Source: Author)

applying base ten blocks and a printable number chart as outlined in the lesson plan. The lesson plan details activities that demonstrate hands-on teaching rather than integration of digital technologies. In addition, while digital manipulatives and technology-enhanced tools were frequently emphasized by participants during interviews as crucial for mathematics teaching, these approaches were noticeably underrepresented or absent in many formal lesson plans. This contrast highlights a disconnect between educators' lived classroom experiences and documented planning, indicating a gap between practice and formal lesson documentation. This gap could result from limited technological tools, as noted by S1FPE3. The non-participant observations validated the interviews and lesson planning. During the classroom observation, S2FPE3 used digital tools, including smartboards and projectors. However, inconsistencies were seen in S4FPE3's classrooms when the participant did not implement digital technologies when teaching mathematics. Stimulated recall interviews strengthened participants' insights into the phenomenon under study. Educators were requested to reflect on their responses from constructive interview sessions, lesson planning and observation, and to think about what they would do should they be given another opportunity for these activities. They highlighted:

> "If I were given a chance again for the classroom activities, I would download the Videos and teach learners ascending and descending mathematics." (S1FPE3)

> "I would have used games from the tablets, but it was not my turn to use them in my classroom, as I have indicated in the first interview that they are not enough." (S3FPE3)

> "I think my lesson went well, I did not integrate technology in the lesson plan and teaching activities, I used the materials from the National Education Collaboration Trust." (S4FPE3)

These reflections reinforce the gap between participants' expressed understanding of the impact of digital technology and its practical inclusion in mathematics classroom teaching. While educators recognize the pedagogical potential of videos, games, and interactive tools, logistical challenges (e.g., device shortages and resource allocation) and planning habits result in minimal representation of digital technology in both lesson plans and classroom practice. The verbatim extract from S4FPE3 shows that lesson plans from the National Education Collaboration Trust do not encourage digital technology integration in mathematics in early childhood. The National Education Collaboration Trust is collaborating with the Department of Basic Education (2011) to support teachers in teaching in South Africa.

DISCUSSION OF FINDINGS

Theme 1. Teachers' Pedagogical Content Knowledge of the Impact of Game-Based Learning in Mathematics Teaching

This theme links to this paper's research question and aim because it integrates participants' pedagogical and content knowledge of teaching mathematics in early childhood. It highlights how participants denote how game-based learning, digital technology and teachers' pedagogical content knowledge shape how impactful these elements are used in classroom practices to develop mathematical thinking skills. Furthermore, theme 1 investigates participants' lived experiences in understanding and applying digital technology to develop learners' mathematical thinking skills.

The findings from the participants' interviews reveal that integrating game-based learning with digital technologies significantly enhances early childhood learners' cognitive and mathematical thinking skills. For instance, S1FPE1 and S3FPE3 highlight those digital adaptations of traditional games like Ludo and Morabaraba, which enhance learners' problem-solving, counting, mathematics skills and independence, corroborating the literature from Vygotsky (1976), who believed that technology can be used as a cognitive tool to mediate learning through game-based learning. Similarly, Can (2020), Syarfina et al. (2023) and Tang et al. (2022) confirm that using relevant pedagogical approaches, such as digital games, in early childhood contributes to mathematics understanding. In the same vein, Chen (2024) supports integrating digital technology from the early years to realize its impact in developing mathematical thinking.

The findings from the stimulated recall interview demonstrate that conceptually, the participants understand that digital technology has an impact on developing mathematical thinking, even if these practices are inconsistent in the lesson planning and classroom practices. S1FPE3, S2FPE3, S3FPE3, and S4FPE3 believe in mathematics skills development, reaffirming Papadakis et al. (2018) who shows that interactive and visual features in digital tools support deeper conceptual understanding. Manches (2011) similarly observed that digital manipulatives enable learners to visualize relationships and manipulate abstract ideas, corroborating S1FPE2 and S3FPE's lived experiences using Google manipulatives. This study's findings support the TPACK framework, elaborating that teachers require technological, pedagogical, and content knowledge in teaching mathematics in early childhood. The interviews demonstrated that participants understood how game-based learning and digital technology impact mathematical thinking skills. The TPACK framework supports that strong pedagogical knowledge (game-based learning), technological knowledge (relevant digital tools to young learners [Nafiu & Olaitan, 2025]) and content knowledge (teaching mathematical concepts [Priyanda et al., 2025]) can be used to improve learners' mathematical thinking and problem-solving skills significantly

Theme 2. Limited Access to Digital Technology in Rural Schools

This theme is interconnected with theme 1, as the knowledge and access to digital technology support the practical usage of mathematics in early childhood. Even though the participants have lived experiences on pedagogical content knowledge about the role of game-based learning (as seen in theme 1), the potential impact is threatened by limited access to digital technology in schools. Conversely, restricted access to technology negatively affects teachers' knowledge in planning and practice. This background indicates that improving mathematics skills in early childhood through digital game-based learning requires teacher training to enhance teachers' pedagogical knowledge and equitable provision of technological resources, particularly in under-resourced rural contexts. The findings indicate a gap between knowing how to use technology effectively and implementing it consistently in real classrooms.

However, while lesson plans from S1FPE3, S2FPE3, and S3FPE3 often cited traditional games, the explicit integration of digital games was less evident, suggesting a need for more deliberate planning to implement game-based learning fully. South African research from Macharia (2023) and Saal et al. (2025) reveals persistent challenges that align with this study's findings, which show that teacher training in effectively using digital technology in mathematics is still needed. Saal et al. (2025) posited that the lack of use of digital technology is caused by limited digital resources in rural schools. This was validated from the observations, and even though S2FPE3 and S3FPE3 attempted to integrate Google videos and YouTube projections through smartboards, relevant digital content remains a challenge. Additionally, digital technologies were unavailable in S1FPE3 and S4FPE3's classroom, supporting Saal et al.'s (2025) study. These findings suggest professional development to strengthen teachers' pedagogical content knowledge for digital game integration, ensuring that lesson plans intentionally embed both traditional and digital play to enhance mathematical thinking. The theoretical framework underpinning this study confirms that limited access to digital tools (Lee, 2021; Maharjan, 2023) negatively affects teachers' TPACK in teaching mathematics.

Additionally, interventions must address infrastructural inequalities and promote culturally relevant digital resources that align with rural teaching contexts. There is also a gap in longitudinal research on the impact of sustainable digital game-based learning on developing learners' mathematical thinking in early childhood in the South African context. The findings reveal that limited access to these resources and lesson planning constrain implementation in mathematics classrooms.

Theme 3. Disconnect Between Planning and Implementation Affecting Teachers' Pedagogical Content Knowledge

A pronounced disconnect emerged between teachers' expressed understanding of digital technologies in teaching mathematics and their actual planning and classroom implementation. While constructive and stimulated recall interview sessions from S1FPE2 demonstrated awareness of technology's pedagogical potential, the lesson plans from S1FPE3 often focused on concrete manipulatives, non-digital approaches; classroom observations confirmed inconsistent use of digital tools by S2FPE3 and S3FPE3; and S4FPE3 showed non-digital approaches and implementation. This disconnect indicates a gap in pedagogical content knowledge related to integrating technology into mathematics teaching. S4FPE3 during the interviews suggested that a lesson plan from NECT was used; this reliance on established lesson planning resources, like those from the curriculum, which do not show how digital technology is used, further establishes this disconnect in the classroom implementations. Stimulated recall interviews revealed teachers' intentions to incorporate digital games and videos if resources were available, highlighting planning constraints rather than pedagogical reluctance. These findings echo the literature from Venketsamy and Hu's (2022) study that Foundation Phase educators often misalign technology use with mathematics teaching, revealing a critical area for professional development. Lee (2021) agrees that there is a need to develop teachers' understanding in bridging the planning and practice with technology integration, which can enhance pedagogical content knowledge and thus improve mathematics teaching quality.

This paper contributes to the context-specific knowledge on using the TPACK framework and pedagogical approaches to adapt technology within resource-constrained environments. This research addresses the gap between teachers' conceptual understanding of game-based learning and digital technology integration and the actual implementation in early childhood mathematics classrooms. Drawing from TPACK, teachers need to understand the interplay between pedagogical content knowledge and rural schools' limited access to digital resources. Against this backdrop, there is a need for targeted professional development on equitable technological provision. Despite limited technological resources, this paper highlights intentional lesson planning that integrates game-based learning to develop mathematical thinking skills.

CONCLUSION

This paper concludes that teachers have a conceptual understanding of the impact of digital technologies and game-based learning in developing mathematical thinking skills in early rural childhood contexts. However, systemic constraints such as limited access to technological resources and curriculum policies contribute to the disconnect between lesson planning and classroom practices. The findings reveal that teacher training and professional development are insufficient without concurrent improvements in access to technology in teaching mathematics. While the TPACK framework is a valuable lens for understanding the interplay of technology, pedagogy, and content knowledge, its implementation is limited by systemic challenges. Therefore, this paper recommends that

(1) teacher training and professional development programs incorporate digital technology and explicitly focus on aligning lesson planning with classroom practice and

(2) the TPACK framework, with an emphasis on sustainable game-based learning in mathematics, be embedded into instructional design.

According to Caridade (2024), sustainable game-based learning refers to contextually adaptable, and culturally responsive games that promote mathematical thinking. This paper highlights significant implications for future curriculum development suggesting adaptable, developmentally and culturally responsive, sustainable game-based learning approaches in early mathematics teaching in South African context.

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