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DEVELOPING AND FORMATIVELY TESTING A PRESCHOOL CLASSROOM INTERVENTION USING A DESIGN-BASED IMPLEMENTATION APPROACH

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ABSTRACT

This paper presents the development and formative testing of a preschool spatial orientation intervention using a design-based implementation research (DBIR) approach. Over the course of eight weeks in both classroom and home settings, spatial language, navigation, and modelling skills are fostered through curriculum that incorporates books, hands-on activities, movement, and digital tools, including an augmented reality (AR) app. Co-design with teachers, user studies, and pilot testing informed iterative revisions to ensure usability, instructional support, and engagement for diverse learners. Findings indicate that the activities fill a curricular gap, promote spatial vocabulary and reasoning, and are generally well-received by teachers, parents, and children. While the AR app shows promise for enhancing motivation and collaboration, challenges related to usability and scaffolding remain. This work contributes to early childhood STEM education by providing accessible, developmentally appropriate resources that support spatial thinking, especially for underserved communities, and offers insights into integrating technology effectively in preschool learning environments.

KEYWORDS

Early Childhood, Mathematics, Spatial Thinking, Design-Based Research

1. INTRODUCTION

This research-in-progress paper describes our early design-based implementation research work to develop and test a preschool spatial orientation supplemental curriculum that leverages books, hands-on and movement-based activities, and digital tools. Employing a design-based implementation research (DBIR) approach, the project conducted a series of research activities to gather feedback, which was then used to revise the intervention materials in preparation for the next version. The final version was further tested [1] and released to the public for free, including a teacher's guide, family guide, and two digital tools. This project seeks to meet the demand for developmentally appropriate preschool spatial orientation activities suitable for both classroom and home settings, while also advancing understanding of how to these skills in young children.

The goals of both the classroom and family activities are to develop preschoolers' spatial orientation skills by fostering their understanding and use of spatial language, navigation, and modelling through engaging, developmentally appropriate experiences. The classroom activities focus on building these skills progressively over eight weeks using hands-on tasks, stories, and digital games that encourage spatial reasoning, map use, and navigation. Complementing this, the family activities aim to reinforce and extend spatial learning at home with simple, accessible books and interactive, play-based activities that incorporate spatial vocabulary and concepts, promote caregiver-child interaction, and support children's growing interest and confidence in spatial thinking and early STEM learning.

The digital tools, specifically the AR tablet app developed in this project, were intended to enhance preschoolers' spatial orientation and thinking skills through engaging, interactive experiences that integrate real-world environments with digital objects. The app was designed to offer accessible and developmentally appropriate spatial learning experiences for young children, particularly those from low-income communities who might not have access to high-quality preschool math curricula. Intended for use in both classrooms and homes, it supports hands-on, movement-based activities alongside digital play as part of an eight-week curriculum. The tools sought to leverage AR's unique affordances—such as embodied learning, interactivity, and connection between physical and symbolic representations—to foster motivation, attention, and meaningful learning while addressing usability challenges specific to young, preliterate children.

This paper describes the early, iterative development process, including co-design with teachers, a user study, and a pilot study. Throughout these phases of iterative development, the goal was to ensure that: (1) the activities are usable and comprehensible for teachers and parents to use with preschoolers, (2) the curricular materials provide enough support for teachers and parents to feasibly use, (3) to obtain feedback about the potential for an augmented reality app, and (4) to gather feedback that provides actionable feedback for revision and improvement of the curricular activities.

2. LITERATURE REVIEW

Early mathematics learning in preschool is critically important, as high-quality math education fosters future academic and career success [2,3,4,5,6]. Research demonstrates a strong connection between early math experiences and later academic success [5,6,7], while early engagement in STEM fosters positive attitudes toward these disciplines [8]. This is particularly crucial for children who are at risk of lower academic performance because of socioeconomic factors [3,9]. Preschoolers naturally engage in playful math activities that build foundational knowledge [10,11], yet many lack access to rich math experiences at home or school because adults may not know appropriate content or lack resources [3]. Early math instruction has been shown to positively impact children's math skills [12], underscoring the need for effective preschool math interventions.

2.1. Spatial Thinking for Preschoolers

Spatial thinking, particularly spatial orientation, is an important skill closely linked to mathematics and STEM success [13]. Spatial thinking involves understanding spatial relationships, using maps and models for navigation, and employing spatial vocabulary [3]. It is essential for navigating environments, interpreting diagrams, and solving mathematical problems across geometry, algebra, and calculus [14]. Early spatial skills correlate with later math achievement and STEM career choices [15,16], with evidence showing that spatial abilities develop early and can be improved through targeted educational interventions involving teachers and parents [17,18]. Despite its significance, spatial thinking is often neglected in early education curricula, and many teachers lack confidence or awareness in teaching these concepts [19,20]. Gender differences in spatial skills emerge over time but are minimal in early childhood, suggesting early intervention may help reduce disparities [21,22]. Research shows spatial skills improve with effective training, including technology-based approaches like augmented reality [23]. Overall, fostering spatial thinking in preschool is critical to support children's readiness for mathematics and STEM learning.

2.2. Technology to Foster Spatial Learning

Technology has a growing potential, particularly digital tools and augmented reality (AR), to foster spatial learning in preschoolers. While early concerns existed about technology negatively impacting young children's social skills [24], recent evidence shows that preschoolers can effectively use technology to collaborate and enhance their learning experiences. Effective technology integration requires evidence-based design with embedded scaffolds and opportunities for engagement, supported by targeted professional development for teachers [25, 26]. Digital tools promote mathematical learning by enabling repeated practice, immediate feedback, and exploration through simulations [27]. AR, as an emerging technology, blends real-world and virtual content to create interactive, student-centered, and playful learning experiences that increase motivation and interactivity [28,29,30]. Studies have shown AR's effectiveness in teaching mathematics, reading, language acquisition, empathy, and pretend play [31,32,33,34]. Specifically for preschoolers, successful use of AR to teach geometry and spatial concepts has involved integrating 2-D and 3-D representations, which assists children in overcoming difficulties with mental transformations [35, 36, 37, 38]. Meta-analyses indicate that AR interventions with scaffolding and game elements significantly boost spatial knowledge and skills [23]. However, successful implementation requires addressing usability challenges and providing adequate scaffolding, as observed in classroom studies where children needed adult support to navigate AR tasks (this study). Overall, technology, especially AR, holds unique promise for enhancing spatial learning in early childhood when thoughtfully designed and integrated into curricula.

3. METHODS

This paper describes the development and testing of a supplemental preschool spatial thinking curriculum. The goal was to create a connected intervention with both home and school components with rich, play-based activities that used books, hands-on materials, movement, and technology to introduce and foster spatial orientation learning. To accomplish these objectives, we engaged in a Design-Based Implementation Research (DBIR) approach that used findings to iteratively revise and develop the intervention. This began with co-design meetings with teachers, a user study, and a pilot study, the findings of which are described in this paper. The final intervention underwent further testing and revision in a subsequent study [1].

3.1. Design-Based Implementation Research

Our design process leveraged a DBIR approach, which seeks to improve education and learning via an iterative design and research cycle. DBIR focuses on understanding the complexities of classroom environments and aims to improve educational practices through continuous feedback and adaptation based on teacher and student experiences [39]. By engaging teachers in co-design processes, the research seeks to create resources that are not only effective but also relevant and feasible for everyday use in classrooms [40]. By continuously cycling through analysis, design, development, and implementation, the digital tool and instructional strategies are refined to effectively address the needs of young learners and their educators [41].

Our DBIR process started with interviews of preschool teachers, during which we shared our initial design plans and gathered their feedback to revise the first version of the tool. In addition, we created a "learning blueprint" [42] (Vahey et al., 2018), which articulated learning goals and task features, as our grounding document to ensure that all design decisions helped achieve the outcomes of interest. These learning goals were derived from learning trajectory research in the field of early mathematics education [3]. The DBIR process served as a theoretical framework for our design process. The learning trajectory describes the theory of learning key spatial content, while the learning blueprint served as a theoretical tie between the learning outcomes we strived for and the curriculum activities.

3.2. Research Questions

Our research questions focus on the following:

1. *Usability and Comprehensibility*. Which design elements or scaffolds in the classroom and home learning activities contribute to their usability and comprehensibility?
2. *Instructional Supports*. Which instructional activity components and teacher or caregiver scaffolds are linked to successful engagement in spatial orientation activities with preschool children? What are the observed challenges to successful engagement?
3. *Potential for Augmented Reality*. What affordances and challenges do the AR experience present for preschoolers?

3.3. Participants

Participants included preschool classroom teachers (n=4 user study; n=10 pilot study) and families (n=4 user study; n=10 pilot study).

3.4. Instruments

Co-Design Focus Group Protocol (Co-Design Study). Starting with an overview of the project goals, this protocol then presents teachers with examples of classroom activities focused on spatial navigation, map use, and spatial vocabulary, followed by prompts to gather their feedback on these activities. It also introduces AR technology through an example app called “Measure! Everything!” and describes a proposed AR app featuring a character named Gracie who navigates real-world environments created by children based on spatial directions. Throughout the protocol, prompts encourage teachers to share their thoughts, suggest improvements, consider classroom feasibility, and brainstorm additional ideas for both hands-on and AR-based spatial learning activities.

Teacher Interview (User and Pilot Study). At the conclusion of both the user study and pilot study, interviews were conducted with the participating teachers. The interview protocol was a semi-structured series of questions to gather teachers’ feedback on classroom activities they have tested with children. The protocol covers various aspects, such as overall experience, what worked well, challenges faced, materials used, learning goals supported by the activity, and suggestions for improvement.

Teacher Survey (Pilot Study). Each participating teacher was asked to complete a pre- and post-survey at the beginning and end of the user and pilot studies. The survey is designed to take 15-20 minutes and aims to improve educational tools for preschool spatial learning. The pre-survey gathers background information about the school setting (urban, rural, suburban), student demographics (including socioeconomic status and dual language learners), classroom technology use, and teacher personal demographics such as race/ethnicity, language spoken, gender identity, years of teaching experience, and education level. The post-survey also asks about teachers’ overall experience with program implementation, attitudes toward mathematics and technology, feedback on educational books used, and detailed reviews of weekly activities, specifically the activities' educational benefit, engagement level, length appropriateness, format, material accessibility, and likelihood of future use. The survey also gathers teacher opinions on professional development sessions, modifications made to activities, and suggestions for improving learning goals. The goal is to assess the program's components for effectiveness and usability to guide improvements that support preschool spatial learning.

Parent Interview (User and Pilot Study). Parent interviews were conducted at the end of the user study and pilot study with participating parents and/or caregivers. It includes two parts: Part 1 gathers detailed feedback from parents or caregivers about ten specific activities, asking what worked well, challenges faced, engagement and difficulty ratings, materials used, learning outcomes, and any additional comments. Part 2 is a brief math attitudes questionnaire where parents rate their child's interest and self-perception in math across five statements using a Likert scale from Strongly Agree to Strongly Disagree. The overall goal is to assess both the effectiveness of the activities and children's attitudes toward math.

Parent Survey (User and Pilot Study). Each participating parent was asked to complete a short survey at the beginning and end of the user and pilot studies. The pre- and post-surveys asked parents to assess various aspects of their child's relationship with math, including interest in becoming a mathematician, self-perception of math ability, enjoyment of using math to solve problems, belief in the importance of math, and excitement about math. The post-survey also asked whether parents started or completed specific activities, how engaging those activities were for their child, the appropriateness of the activity length, the difficulty level for the parent to do the activity with their child, and the degree to which parents agreed that each activity contributed to their child's learning. These questions were repeated across multiple activities throughout the survey.

3.5. Learning Activities

The classroom pilot study used the thirty classroom activities, including one collaborative digital game and one augmented reality game (Table 1). The classroom intervention is an eight-week comprehensive program designed to enhance preschoolers' spatial orientation skills through a combination of hands-on classroom activities, read-aloud stories, and digital experiences, including tablet-based games and augmented reality (AR) apps. It focuses on building spatial vocabulary, understanding and using maps, navigating routes, and creating spatial models. The curriculum is organized into four two-week topics: spatial language, introduction to maps, navigating maps, and making maps. Teachers receive professional development and resources such as a detailed digital guide, books, materials, and tablets to support implementation.

Table 1. Classroom Study Activity Descriptions

Activity	Description
Piggies in the Pumpkin Patch	This activity involves reading the story "Piggies in the Pumpkin Patch" to children while emphasizing spatial language and movements, followed by exploring a farm map to reinforce understanding of spatial vocabulary through interactive discussion and actions.
Story Map	This activity involves children using a printed or digital map of Piggies Farm to follow and mark a specific route through various farm locations, either independently or with a partner.
Meet Me at the Lemonade Stand!	This activity involves printing, cutting out, and assembling a Lemonade Stand-themed die and character pieces for an interactive game or craft.
Block Party	This activity involves using cards to guide participants in building towers in various spatial relationships around an existing tower, promoting understanding of positional concepts.
Where's Gracie?	This activity involves learning and practicing spatial vocabulary by identifying the position of Gracie relative to a robot using descriptive phrases such as "under," "above," "behind," and "next to."

Activity	Description
Freeze Dance	This outdoor freeze dance activity helps children learn and practice spatial vocabulary by having them stop dancing and describe the positions of their peers using spatial terms.
Move Right-Left Song	This activity is a circle-time movement song designed to help children learn and practice the spatial concepts of right and left through singing, body movements, and interactive participation.
Table Moves	This activity involves using cards to engage participants in a hands-on, interactive game that combines spatial awareness and physical movement around a table.
Map the Classroom	This activity guides children to create a large, bird's-eye-view map of their classroom using landmark cutouts, helping them learn spatial relationships and map-reading vocabulary.
Friends on the Map	This activity involves children placing their face or name labels on a classroom map near landmarks, then locating those spots in the real classroom to develop spatial vocabulary and understanding of spatial relationships.
All Around the Classroom	This activity engages children in identifying and drawing classroom landmarks on individual maps to develop their understanding of spatial relationships and vocabulary.
Henry's Map	This activity involves reading the book "Henry's Map" by David Elliot with children to help them understand how maps represent real places by comparing drawings to actual landmarks on a farm and encouraging map-based navigation skills.
Amazing Maps	This activity challenges children to help Gracie navigate through city mazes while developing spatial thinking skills.
Walkable Map	This activity guides children to create a physical, walkable map of Henry's farm from the book by taping landmark and animal drawings around the classroom to develop their understanding of maps, navigation, and spatial relationships.
Find the Shortest Route	This activity engages children in using a classroom map to collaboratively plan and navigate the shortest route between landmarks marked with stars.
To the Rescue!	In this activity, children use a classroom map to identify and compare two routes to get the paper towels, then physically test and count steps to determine the shortest path.
Mapping My Day	This activity involves reading a story about a girl named Flora who draws maps of her daily places.
Map Making on a Grid	This activity guides children to create a map of a miniature scene using a 4-panel grid to help them accurately place and represent objects.
Priscilla's Obstacle Course	This activity guides children to create and navigate a miniature obstacle course for toy animals, using spatial vocabulary and map-drawing to connect real-world obstacles with their diagrammed representations.
Classroom Obstacle Course	This activity involves children taking turns navigating a classroom obstacle course by following and giving spatial language directions.
Draw an Obstacle Course	Children create and share maps of their obstacle courses, using spatial vocabulary to describe routes and navigate.
Lucy in the City	This activity guides children through reading "Lucy in the City," encouraging them to explore navigation by comparing perspectives, tracing routes, and identifying landmarks to help Lucy find her way home.
Landmarks in the City	This activity guides children to reread "Lucy in the City," collaboratively adding characters and landmarks to a city map while tracing Lucy's route home.
Different Kinds of Maps	This activity engages children in comparing different types of maps—from a bedroom to the world—by identifying landmarks and understanding how maps represent real places at various scales.
Neighbourhood Map	Children work together to create a neighbourhood map on the floor using felt pieces and paper landmarks, while learning spatial vocabulary and concepts through play and discussion.

Activity	Description
Map Treasure Hunt	This activity guides children to use a map with landmarks to plan and follow routes outdoors in a treasure hunt, helping them develop spatial vocabulary and map-reading skills.
Map Adventure App	This collaborative digital map game is played in pairs, where they plan routes and identify landmarks during gameplay.
AR Adventures	This augmented reality activity allows children to see digital characters and objects overlayed on their real world, then they engage in tasks such as picking apples, feeding cows, helping a mama duck find her chicks, and exploring a county fair.

The family study included ten activities that were tested (Table 2). The home-based activities with the caregiver are intended to complement the classroom activities and reinforce learning.

Table 2. Family Study Activity Descriptions

Activity	Description
Rosie's Walk	This activity involves reading the book "Rosie's Walk" twice—first indoors and then outdoors—while acting out spatial vocabulary words with imaginative physical movements to reinforce learning.
Bug Dance	This activity helps children learn and practice the spatial directions left, right, forward, and backward through reading, movement, and interactive play using stickers and dance steps.
Albert's Amazing Snail	This activity encourages children to practice spatial vocabulary through reading, interactive discussions, and acting out words using a story about Albert's Amazing Snail and a stuffed animal.
Take a Right, Robot!	This activity helps children practice spatial vocabulary and directions (left, right, straight) by role-playing as robots following guided movements around the home to find a hidden prize.
Gracie Says: Left!Right!	This activity is a fun, interactive game designed to help children practice distinguishing and using their left and right sides through simple commands and movements.
Freeze Dance	The Freeze Dance activity involves dancing to music, freezing when it stops, and using spatial words to describe your location relative to objects, helping children practice spatial language.
Which Way to the Treasure?	This activity involves hiding stars and a treasure around the home or outdoors and using spatial language to give children directions to find them, helping reinforce and teach spatial vocabulary.
Shape-to-Shape Game	This game is an interactive movement activity where players navigate a board of shapes by verbally describing and physically moving left, right, forward, or backward to reach target shapes either indoors on a printed board or outdoors on a chalk-drawn grid.
Move Around Challenge Course	This activity involves creating a simple obstacle course, drawing a map to navigate it using spatial vocabulary, and taking turns completing the course while following and giving directions.
Kitchen Gadget Matching	In this matching game, players match aerial-view cards of kitchen gadgets to their corresponding ground-view pictures on a game board, helping children understand different perspectives.

3.6. Digital Activities

In addition to the classroom activities, the intervention also included two digital apps. *Map Adventure* is a collaborative app in which preschoolers visit landmarks and navigate farm and city maps. As a two-player game, children can play with peers or adults as they collect move from place to place and solve spatial challenges. Engaging activities were crafted to resonate with children’s diverse interests, such as popping bubbles, skateboarding, running a lemonade stand, dressing up for imaginative play, and exploring farms and cities.

Within the *AR Adventures* app, children engage in two distinct spatial thinking games. In *Around the Farm*, they navigate a farm map displayed on the screen to reach an apple tree, where they pick apples and feed them to hungry animals by lifting their tablet. When the tablet’s camera activates, children can look left and right to see AR apple trees surrounding them. A small white circle composed of stars at the center of the screen enables interaction with the AR environment. Using this, they grab an AR basket and pick apples from the virtual trees. After collecting all the apples, children navigate the map again to reach the cow pasture. The tablet’s camera activates once more, displaying a virtual cow pasture in their environment. They follow spatial directions and visual cues to feed cows located on the grass, between corn stalks, and in front of a yellow sign. In the *Map the Fair* game, children create a map of an AR fair. Given tickets, they are tasked with finding specific rides using spatial instructions such as “between the balloons,” “to the left of the roller coaster,” or “in front of the trees.” Upon locating a ride, the child pays the ticket, triggers an animation of the ride, and earns a sticker representing it. They then place the sticker on the correct spot on their map corresponding to the ride’s location in the AR environment.

3.7. Analysis

Leveraging both qualitative and quantitative data, a mixed-methods analysis was conducted. First, we analysed qualitative data from teacher and parent interviews by coding responses by themes, such as successes, challenges, perceptions of learning, and experiences preparing to use and implement activities with children. These themes were then summarized to identify the range of responses and summarize the overall response related to that theme. Starting with transcriptions of interview audio, we summarized the responses around these key themes to generate patterns within participants' verbalizations. Second, we conducted a descriptive analysis of quantitative responses from teacher and parent surveys. Specifically, frequencies for closed-ended survey responses were run and reported. These qualitative and quantitative findings were triangulated to identify where they overlapped and concurred with one another. Within each theme, we examined that them, such as successes, to determine what successes were identified by both sets of participants (teachers, parents) and data sources (interview, survey). This allowed us to leverage the data to generate recommendations for revision, as part of an evidence-centered approach to DBIR [42]. Third, we created composite scores for items that were part of a larger scale and conducted paired-samples t-tests to compare the findings from pre- to post-data collection time points.

4. Results

4.1. Co-design Feedback from Teachers

The teacher's feedback reveals positive engagement and practical connections for all three activities. For the first activity focused on navigating from one point to another in the classroom, teachers appreciated it as a “great idea, open/flexible enough to build on throughout the year,” highlighting its hands-on nature and opportunities for children to predict, test, and use spatial language. For the second activity using maps, teachers found maps intriguing but sometimes challenging to introduce; one said treasure maps are effective because “the more game-like the better,” while another noted child “love maps” and that mapping prepares them for kindergarten. The third activity focused on spatial language and position, which the teacher viewed as “good” at helping vocabulary development and child ownership, with one teacher saying it could be used during transitions and meals, and another likening it to “Where’s Waldo.” Overall, teachers connected these activities to existing classroom practices and valued their potential to engage children in spatial reasoning and language.

Teachers anticipated that preschoolers would respond with strong interest and engagement to the activities. They believed children would be curious and motivated, enjoying hands-on challenges like predicting routes or finding objects using maps. Preschoolers were expected to appreciate opportunities to explore spatial concepts through familiar contexts such as classroom routines, treasure hunts, and looking at pictures of themselves. Overall, teachers saw these activities as effective ways to capture children’s attention and encourage active participation in learning spatial language and reasoning.

Teachers generally felt that the activities fit well within classroom routines and structures. For Activity 1, feedback included that it “fits in circle time, small group, large group, centers,” with a suggestion to “introduce in larger group, then workshop in small group.” Activity 2 was seen as adaptable to different parts of the day, lasting “15-20 minutes,” working both indoors and outdoors, and fitting into large/small group combinations; one teacher noted, “Each child could have their own map,” and another suggested using maps with intentional mistakes for learning. For Activity 3, teachers said it “would be a good activity for the beginning of year,” helping with introductions and learning names. Overall, the activities were viewed as flexible and compatible with various classroom settings and schedules.

Teachers identified several benefits across the activities. For Activity 1, benefits included that it “fits into routines,” pairs language with visuals, offers “hands-on problem-solving,” and allows children to “practice estimating,” making it versatile for different uses. Activity 2 was praised for helping children “develop map-making skills,” learn new vocabulary like “next to, in front of, behind, closer, farther,” enhance spatial awareness, and practice counting. For Activity 3, benefits included using “cards with pictures and words” to help children understand spatial concepts and providing “good tips for how to fit spatial vocabulary into the day.” Overall, teachers valued these activities for promoting spatial language, reasoning, and engagement through interactive, hands-on learning.

Teachers viewed the app as a promising tool for home and classroom use, appreciating its potential to extend spatial learning through interactive play. They liked the idea of following up on activities like the “Bear Hunt” song with a “Spatial Hunt” in the app and suggested incorporating features such as a compass or directional arrows to help children understand movement and directions. Teachers were interested in the character Gracie, discussing how she could either be controlled by the child or act as a helpful guide, with one noting that moving the tablet to move Gracie might be safer. They recommended using the app in pairs, with one child navigating and another acting as a spotter to ensure safety and support collaboration. Challenges anticipated included engaging dual language learners (DLL), accommodating families without English proficiency through translations, addressing the needs of hearing-impaired children, and managing classroom distractions. Safety and classroom management were emphasized, with suggestions to designate specific spaces for app use and start with small groups or individual children. Teachers also mentioned that children enjoy games like hot/cold and would be motivated by celebrating successes, choosing characters (especially animals), and seeing how differently sized units affect measurement. Suggested destinations for Gracie included places like the zoo, water park, castle, jungle, playground, school hallways, beach, and storybook settings. Overall, teachers saw the app as engaging but highlighted the importance of thoughtful implementation to address practical challenges.

Teachers noted several challenges with the activities. For Activity 1, challenges included that "children might rush/run" and need reminders to stop and observe, difficulty with "using correct terminology: right, left, forward, backward," and that it "might be challenging as a whole group, better as a small group." For Activity 2, no specific challenges were directly quoted, but teachers implied complexity by noting it is "more difficult than the paper towels activity" and suggested starting simple. For Activity 3, a challenge mentioned was the time needed to produce photos ("take them, print, cut, laminate"), suggesting having a ready set of pictures would help. Regarding the app, challenges included engagement difficulties for DLL children, accommodating families without English proficiency, hearing-impaired children, safety concerns, classroom management, and ensuring children are not distracted while others use the tablet.

Teachers offered various suggestions to improve the activities. For Activity 1, they recommended creating "accompanying spatial language cards," especially early in the year, and using "arrow/word cards" laminated and placed on the floor so arrows don't get turned the wrong way. They also suggested extending the activity by adding obstacles or challenges, timing routes, or having a character like a frog travel the route. For Activity 2, suggestions included leading children to envelopes with spatial cards like "go left," making the map interactive by moving pieces daily, and incorporating hot/cold scavenger hunts. For Activity 3, teachers proposed taking headshots of children, attaching them to sticks or body printouts for arranging according to positional words, and previewing the activity by physically practicing the vocabulary. Regarding the app, suggestions included adding a compass or directional arrows on screen, partnering children as user and spotter, and starting with teacher-led navigation to teach directions.

4.2. User Study Feedback

4.2.1. User Study Feedback: Teacher Interview

The key takeaways from the teacher interviews on the seven classroom activities are that the activities filled an important curricular gap by providing spatial learning resources, which teachers appreciated and plan to reuse. Spatial concepts and language, especially perspective-taking, were new and challenging for many children, leading some teachers to suggest breaking activities into smaller parts and using small groups or one-on-one settings for better scaffolding. Teachers noted progress in children's understanding of spatial language over time but recommended clearer sequencing of activities (e.g., practicing left/right earlier). Overall, the activities were well-received, with specific feedback highlighting areas for improvement such as simplifying instructions, using more engaging materials, and providing additional practice opportunities. The key takeaways are:

1. The activities filled a needed curricular gap. The teachers do not generally have a lot of spatial activities/resources on hand, so these activities filled a curricular gap for them. Teachers liked the activities and plan to use them again.
2. Spatial concepts and language were new and challenging: Spatial concepts, including spatial language and perspective taking (especially perspective taking), were new to the children and tended to be challenging for some. Some teachers felt that certain activities needed to be divided into two smaller activities to allow for heavier scaffolding.
3. Adaptations in group size helped: Some activities that were envisioned as being full groups were run as small groups, and some small group activities were run as 1:1s, which helped manage complexity.
4. Sequencing might improve ease of learning: If some of the activities currently in the works came before some of this batch of activities (e.g., the ones that practice left and right), some of this batch might have been a little easier.

5. Children’s understanding improved over time: Children’s understanding of spatial language progressed throughout the activities, will use them again.

While the overall feedback was positive, it emphasized the importance of scaffolding, clearer sequencing, and occasionally more engaging or suitable materials.

4.2.2. User Study Feedback: Parent Interview

The parent interview feedback from a user study involving four families who tested various spatial vocabulary activities designed for children. Overall, parents found some activities too easy, with mixed engagement levels reported by children across different tasks. Activities like the Treasure Hunt, Right-Left-Forward-Backward Game, Move Around the Challenge Course, and Bug Dance (see Table 2) were generally well-liked and considered fun and educational, helping children learn spatial terms such as left, right, under, above, forward, and backward. Some challenges included confusing instructions, difficulty with drawing symbols or maps, and limited materials at home. Parents suggested improvements like simpler directions, printable symbols, more images, and better graphics. The books used (e.g., Rosie’s Walk, Albert’s Amazing Snail) were often engaging but sometimes too short or familiar to children. Physical activities like Freeze Dance were fun but less effective for learning new concepts. Overall, the study highlighted the value of hands-on, interactive spatial language activities while identifying areas for refinement in materials and instructions.

Children learned a variety of spatial vocabulary and concepts through the activities, including terms like left, right, under, above, forward, backward, near, far from, around, and behind. They gained new words such as “through,” “forward,” and “backwards,” and improved their understanding of spatial relationships by practicing directions, mapping routes, recognizing shapes, and connecting symbols to real-world objects. The activities also helped children develop skills in counting with one-to-one correspondence, drawing, matching different perspectives of objects, and understanding multiple routes between places. Some children deepened their comprehension by acting out spatial terms or relating them to familiar contexts, while others enhanced their ability to use spatial language quickly and accurately during play. Overall, the children solidified their grasp of spatial awareness and vocabulary in engaging, practical ways.

4.3. Pilot Study Feedback

4.3.1. Teacher Pilot Study Feedback

Overall. The unit on spatial orientation was generally well received and considered successful, though with some challenges. Teachers noted that kids were engaged and learned a lot, especially older children who excelled more than younger ones. For example, one teacher said, “the kids were really engaged… they started to really grasp the ideas,” but also observed that left and right were abstract concepts for many: “I never really realized that at this age, they just don’t understand left from right as much as I thought they would.” Several teachers highlighted the value of hands-on activities like creating maps and obstacle courses, which helped children apply spatial vocabulary such as “next to,” “between,” and directional terms. One teacher remarked, “They loved the whole grid idea,” and another noted, “They were using the spatial words not even realizing it.” Challenges included maintaining attention during some activities and difficulty with abstract concepts like cardinal directions or aerial views, with one teacher saying, “Some of the books… talked about north, east, west. That threw them totally off.” Overall, the unit provided meaningful learning experiences in spatial awareness, vocabulary, and map skills, with repeated emphasis on the importance of scaffolding and adapting activities to children’s developmental levels.

Books. The overall experience with the books was generally positive across teachers, with many highlighting that the books were engaging and effective for teaching spatial concepts. One teacher said, “They liked them,” especially appreciating how the kids connected with the stories like *Piggies in the Pumpkin Patch*. Another teacher described the books as “really great” and noted how each book offered different spatial learning angles, saying, “I liked the fact that all of the stories had different twists to it,” and she would not remove or replace any. A third teacher observed that older kids understood more complex vocabulary while younger ones struggled with some books, particularly those involving cardinal directions, noting, “Some of the books… talked about north, east, west. That threw them totally off. I think that was too advanced for this age group.” Overall, the books were seen as valuable tools for introducing spatial vocabulary and concepts, with repeated readings helping reinforce learning, though pacing and complexity sometimes posed challenges.

Teachers also rated the educational value, engagement, length of activity, and activity format. The majority of teachers rated each book’s educational value as very educational or educational. The engagement level for each book (Figure 1) was rated, with most books either very engaging, engaging, or somewhat educational. Three of the books were rated by a minority of teachers as not engaging at all. The length of the book was overall “Just right,” with the last two books rated by 1-3 teachers as too long. The most common format for using the books was with the whole group, followed by small groups or pairs of children.

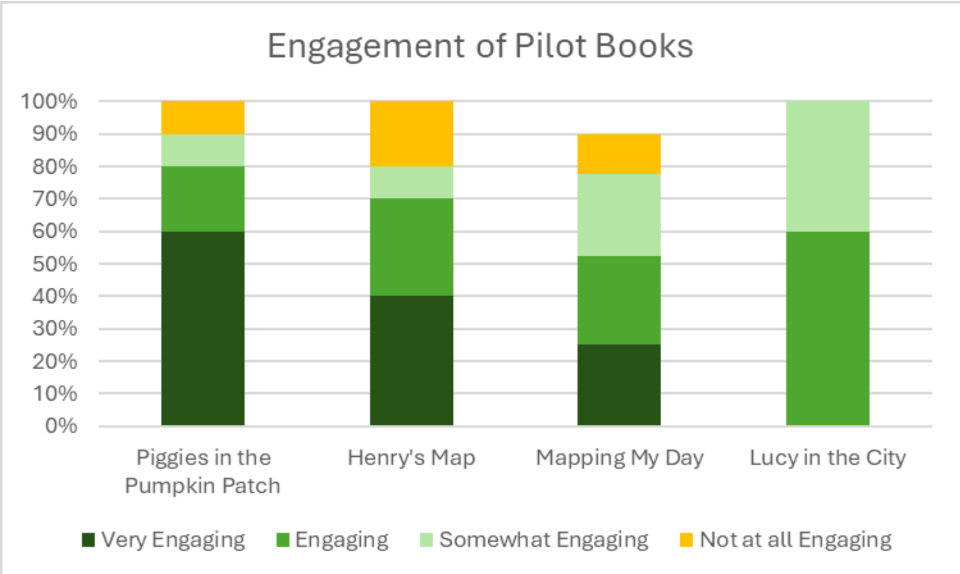

Figure 1. Teachers Percent Rating of Children’s Engagement in Books

Hands-on activities. The overall experience with the activities was generally positive, but highlighted challenges related to time constraints, pacing, and managing groups. Teachers appreciated the hands-on nature and engagement of the kids, especially with obstacle courses. One teacher noted, “I feel it went well. The kids were really engaged with it,” while another said, “It was a really awesome experience… I totally recommend it.” Teachers also valued the vocabulary learning opportunities, with one stating, “Vocabulary is my favorite part,” and another noting how the activities opened their eyes to students’ spatial language development. Overall, the materials were seen as valuable and effective, though many suggested spreading out the activities over a longer period for better assimilation.

Regarding what worked well, teachers consistently highlighted the engagement and learning benefits for children. For example, one teacher noted that older children “did really well” with spatial language and activities like mapping the classroom, where landmarks helped them understand different areas. One teacher appreciated the vocabulary development opportunities, saying, “I liked that it was hands-on… gave me an opportunity to give them lots and lots of vocabulary words.” Another teacher mentioned that certain books and games were enjoyed, such as “The Piggy Book” and the lemonade game, which supported vocabulary and spatial concepts. Teachers also valued hands-on and physical activities, with one stating, “They liked the physicality, again, that they were able to actually do something while learning.” Collaboration and teamwork were noted as positive outcomes in activities like obstacle courses and map-making.

On challenges, time constraints and pacing were frequently mentioned; a teacher said, “It just seemed like a big bulk of content and learning goals, and not really enough time,” and “It’s just time constraints, planning, and then other requirements.” Some activities were too advanced or abstract for younger children, especially concepts involving cardinal directions (“north, east, west”), which a teacher found “too advanced for this age group.” Managing group dynamics and keeping children’s attention was sometimes difficult, with comments like needing to do some activities “one on one” due to behavior or focus issues. Technical difficulties with apps and devices were also noted, such as registering inputs in AR adventures. Lastly, some teachers felt the volume of activities was overwhelming, with a teacher reflecting, “it was just a lot of activities…it was complicated for them,” and another suggesting simplification: “Just simplify.”

The best-supported learning goals across activities consistently focused on spatial vocabulary and spatial awareness. For example, a teacher emphasized vocabulary as the key learning outcome: “Vocabulary. I think any of those opportunities for any of the activities, with making a map or even the books, I think you can get so much vocabulary out of them, all of them.” Another teacher highlighted directionality and understanding maps: “I feel this was more so direction and kind of understanding, 'Hey, things make up a map and this map just happens to be split into the grids.’” Other teachers noted that children learned concepts like left and right, following directions, categorizing objects, and spatial recognition, often stating these were challenging but important skills gained through the activities. Overall, spatial language (e.g., next to, behind, over), map comprehension, and perspective-taking were seen as the primary learning goals effectively supported by the activities.

Ipad. Children responded positively to the Map Adventure app overall. Engagement levels were high, as many children expressed excitement about the game and a desire to play repeatedly, with comments such as “they just wanted to play it more and more each day” and “they loved them.” Collaboration occurred both individually and in pairs or small groups, sometimes pairing younger and older children to support navigation. Learning-wise, especially older children demonstrated understanding of spatial concepts, using spatial language like “go right,” “go left,” and recognizing different paths: “My older friends would say, 'No, you have to go down.’” Interaction with technology was generally smooth; most children had the necessary motor skills and familiarity with tablets, though younger kids sometimes needed help: “my older group, absolutely… my younger group, they are still working on a lot of their fine motor skills,” and “I think it’s easy enough for a teacher to navigate.” Classroom behavior challenges were minimal, mostly related to sharing iPads and waiting turns: “The only hard thing was just telling them, you just got to wait your turn,” but management was not a significant issue. Overall, the app was seen as engaging, educational, and manageable within classroom routines.

Children’s responses to the AR Adventure app showed mixed engagement and collaboration experiences. One teacher noted, “a lot of them worked together a lot more just because it was a little bit challenging," and that children "were using [spatial] words when they were doing the activity," indicating positive collaboration and vocabulary use. However, navigating the app was "really hard with… making the scenery pop up as we were moving it," which posed some challenges. Technologically, many kids were "very technologically savvy," especially older ones, which helped their interaction with the app, though younger children needed more support. Classroom behaviour was generally positive, described as "really engrossed," with no major management issues, but physical movement required by the AR feature sometimes caused disorganization ("it kind of got a little discombobulated"). Some teachers felt the app opened their eyes to children's spatial language skills and inspired them to incorporate these lessons more broadly. Overall, while the AR Adventure fostered engagement, collaboration, and learning, technical and physical navigation challenges affected ease of use, particularly for younger children.

4.3.2. Family Pilot Study Feedback

Parents provided detailed feedback from interviews and surveys about ten spatial vocabulary activities designed for preschoolers. Families generally appreciated the engaging and imaginative nature of the activities. Many children enjoying movement, pretend play, and interactive elements. For example, Rosie's Walk was praised for its illustrations and humour, with children enjoying acting out parts of the story. Bug Dance was a favourite for many due to the dancing aspect, while Albert's Amazing Snail was noted for focusing on vocabulary like "near" and "far." Take a Right Robot was popular because of its interactive pretend play and use of masks. Gracie Says Left/Right was well-liked for being fun, familiar (like Simon Says), and easy to play anywhere. Freeze Dance engaged children who enjoyed dancing and music, often sparking spatial language use. Which Way to the Treasure appealed to children motivated by finding objects or prizes. The Shape-to-Shape Game attracted competitive children who liked the board game format, though engagement varied. Move Around the Challenge Course was successful in encouraging map creation and route planning, and the Kitchen Gadgets Matching Game was positively received, especially when using physical objects to explore perspectives. Overall, successes centered on enjoyment, engagement (Figure 2), and learning through active, playful activities.

Parents reported high levels of child interest and participation. Activities like Rosie's Walk, Bug Dance, Take a Right Robot, Gracie Says Left/Right, Freeze Dance, and Move Around the Challenge Course were frequently described as fun, interactive, and involving physical movement or pretend play, which helped maintain engagement. Some variability in engagement was noted for activities such as Bug Dance (due to repetitive nature and lack of music) and Shape to Shape Game, where some children struggled to understand the game goals, leading to lower engagement. Overall, families appreciated activities that combined movement, imagination, and clear instructions, though a few children showed less interest or had difficulty sustaining attention in certain tasks.

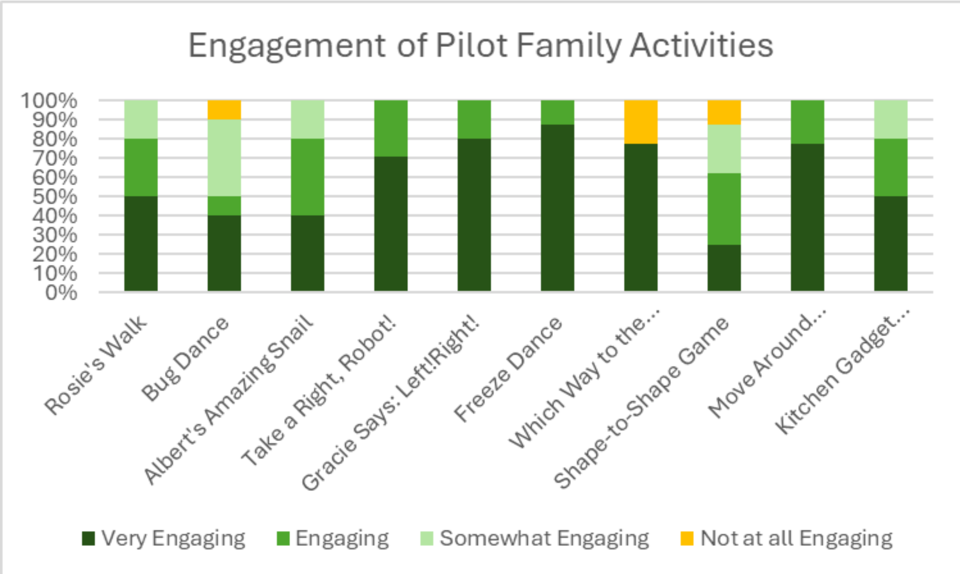

Figure 2. Parent Percent Rating of Children's Engagement in Books

The learning (Figure 3) sections reveal that most activities effectively supported children's acquisition and practice of spatial vocabulary, particularly concepts like left/right, near/far, and positional words such as in front of, behind, and on top of. Many parents noted improvements in their child's understanding and use of these terms through the activities. Some activities also helped with listening skills, following directions, map reading, and comprehension of spatial relationships. However, learning outcomes varied depending on the child's prior knowledge and engagement level; some children already knew the vocabulary or found certain concepts challenging, especially verbal responses or multi-step instructions. Activities involving physical movement and pretend play were often highlighted as beneficial for reinforcing spatial language and cognitive skills. Overall, parents generally agreed that the activities contributed positively to their child's learning.

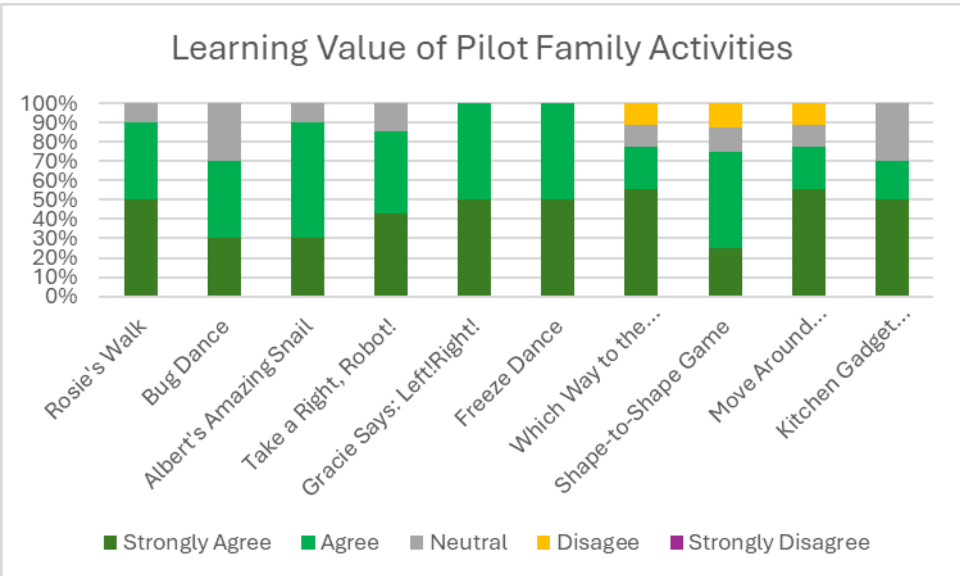

Figure 3. Parent Rating of Activity's Learning Value

Parents responded to five questions about their child's mathematics confidence (My Child: (1) wants to become a mathematician, (2) views themselves as good at math, (3) likes to use math to solve problems, (4) thinks math is important, (5) gets excited about using math. Analysis was conducted before and after completing these ten activities at home. While the mean increased from pre- to post-survey, there was not a significant difference in the scores for pre-survey (M=16.8, SD=3.22) and post-survey (M=18.3, SD=3.53) conditions; $t(9)=1.61$, $p = 0.14$.

The activity length (Figure 4) sections indicate that most families found the duration of the activities to be appropriate and manageable, often describing them as "just right" or good for maintaining their child's engagement. A few parents noted some activities felt slightly too long, such as Bug Dance, Freeze Dance, and Which Way to the Treasure, though these were generally still acceptable due to the inclusion of movement or engaging content. Some families mentioned that certain activities took less time than expected because children moved quickly through them or lost interest. Overall, the activity length was considered appropriate for preschoolers, and the flexibility to adjust sessions for shorter or longer playtime was valued.

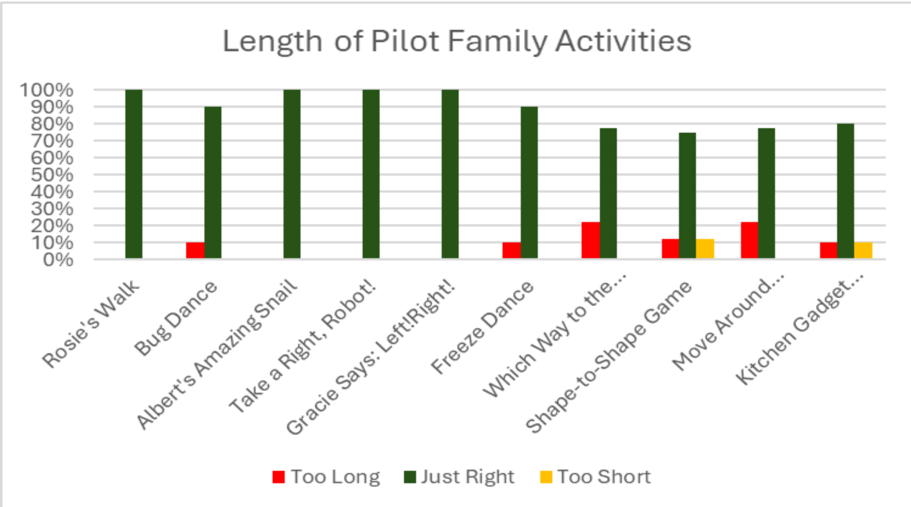

Figure 4. Parent Percent Rating of Activity Length

While most activities were well-received, several common difficulties emerged. Many children struggled with understanding and applying spatial vocabulary, especially left and right, with some finding stickers or prompts confusing or unhelpful. Following multi-step directions and verbal instructions posed challenges for some children, particularly in activities requiring listening skills or map comprehension. Engagement issues arose when activities were too long, repetitive, or lacked motivating elements like music. Parents often adapted activities to support their child's understanding or engagement.

Families generally found the materials for the activities easy to find and use, with some activities requiring minimal or no materials (e.g., Gracie Says Left/Right, Freeze Dance). In a few cases, parents adapted materials using items they already had at home. Some challenges were noted, such as not using certain provided items like the stuffed animal in Albert's Amazing Snail or difficulties with specific components like mask ribbons in Take a Right Robot. For activities involving cards or visuals (e.g., Kitchen Gadgets Matching Game), parents emphasized that physical objects were more effective than pictures alone for helping children understand concepts. Overall, materials were seen as accessible and adaptable, supporting the successful implementation of the activities.

The suggestions for improvement across activities focused on enhancing clarity, engagement, and support for spatial learning. Families recommended adding questions or prompts to guide interaction, providing lists of similar books or activities, and including specific learning goals to help parents understand the purpose. Some parents advised clearer instructions or additional supports to aid children struggling with vocabulary or verbal responses. Visual aids like arrows or stickers were proposed to help children better grasp directions. A few families wanted more adaptable materials or easier-to-use props, such as improved mask designs. Overall, suggestions aimed to make activities more accessible, engaging, and supportive of children's spatial language development.

5. DISCUSSION

The findings from this study highlight the promise and challenges of implementing a comprehensive spatial orientation curriculum for preschoolers that integrates hands-on activities, storytelling, and digital tools, including augmented reality. Teachers and parents generally valued the intervention's focus on spatial vocabulary, map skills, and navigation. They also noting improvements in children's engagement and understanding over time. The iterative design-based implementation approach allowed for meaningful refinements based on user feedback, emphasizing the importance of scaffolding, clear sequencing, and developmentally appropriate materials. While the AR app showed potential to enhance motivation and collaboration, technical and usability challenges underscored the need for further optimization to support younger children and diverse learners effectively. The mixed responses regarding activity complexity and pacing suggest that tailoring interventions to individual developmental levels is critical. This research provides valuable insights into fostering early spatial thinking through combined classroom and home experiences, emphasizing technology's role as a supportive aid rather than a standalone solution.

5.1. Limitations

This study has several limitations that should be considered when interpreting the findings. First, the sample size for both teacher and family participants was relatively small, which may limit the generalizability of the results to broader preschool populations or diverse educational settings. Second, the intervention was tested over a limited time frame, restricting insights into long-term impacts on children's spatial skills and sustained engagement. Third, variability in implementation fidelity across classrooms and homes, including differences in teacher experience, group sizes, and parental involvement, may have influenced outcomes and introduced inconsistencies. Fourth, challenges related to technology use, particularly with the augmented reality app, such as usability issues and the need for adult support, could affect scalability and accessibility, especially for younger or less tech-savvy children. Finally, some activities involved complex spatial concepts that were difficult for younger preschoolers, suggesting that developmental readiness may moderate effectiveness.

5.2. Broader Impacts

The intervention holds significant broader impacts by addressing a critical gap in early childhood spatial orientation education, particularly benefiting underserved communities with limited access to high-quality STEM resources. By combining hands-on activities, storytelling, and technology such as augmented reality, the program offers an engaging, developmentally appropriate approach that can enhance foundational spatial skills essential for later academic success in mathematics and STEM fields. To scale this intervention effectively, partnerships with educational organizations and policymakers could facilitate its integration into existing preschool curricula at district or state levels, supported by professional development for teachers to ensure fidelity and adaptability across diverse classroom settings. Additionally, providing freely accessible digital resources and comprehensive guides for both educators and families can promote widespread adoption and sustained use. System-level integration would enable consistent reinforcement of spatial learning both in classrooms and homes, fostering equitable opportunities for all children to develop critical cognitive skills from an early age.

5.3. Future Research

To overcome these limitations, future research should include larger and more diverse samples, extend the duration of interventions, and improve technological tools to increase usability and inclusivity. Future work should continue to explore scalable strategies that balance innovation with accessibility to maximize impact on early STEM readiness.

6. CONCLUSION

This study demonstrates the feasibility and value of a design-based implementation approach to developing a preschool spatial orientation curriculum. The positive feedback from teachers and families affirms the importance of fostering spatial vocabulary, navigation skills, and map understanding in young children as foundational components for later STEM success. Despite ongoing challenges with technology use and developmental readiness, the iterative process facilitated continuous improvement and adaptation to more effectively address the needs of diverse learners. By providing accessible resources for both classroom and home environments, this intervention on offers a promising model for enhancing early childhood spatial thinking. Ongoing research and refinement are crucial for broadening the intervention’s reach and effectiveness, ultimately helping to create more equitable opportunities for all children to develop essential spatial and mathematical skills.

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REFERENCES

[1] A. E. Lewis Presser, E. Braham, and R. Vidiksis, “Enhancing preschool spatial skills: A comprehensive intervention using augmented reality and hands-on activities,” *Education Sciences*, vol. 15, no. 6, p. 727, 2025, doi: 10.3390/educsci15060727.

[2] T. Bartell et al., “Toward a framework for research linking equitable teaching with the standards for mathematical practice,” J. Res. Math. Educ., vol. 48, no. 1, pp. 7–21, 2017, doi: 10.5951/jresematheduc.48.1.0007.

[3] D. H. Clements and J. Sarama, Learning and Teaching Early Math: The Learning Trajectories Approach. Routledge, 2020.

[4] D. Dumas, D. McNeish, J. Sarama, and D. H. Clements, “Preschool mathematics intervention can significantly improve student learning trajectories through elementary school,” AERA Open, vol. 5, no. 4, pp. 1–5, 2019, doi: 10.1177/2332858419879446.

[5] G. J. Duncan et al., “School readiness and later achievement,” Dev. Psychol., vol. 43, no. 6, pp. 1428–1446, 2007, doi: 10.1037/0012-1649.43.6.1428.

[6] J. Preskitt, H. Johnson, D. Becker et al., “The persistence of reading and math proficiency: the benefits of Alabama’s pre-kindergarten program endure in elementary and middle school,” ICEP, vol. 14, p. 8, 2020, doi: 10.1186/s40723-020-00073-3.

[7] National Mathematics Advisory Panel, Foundations for Success: The Final Report of the National Mathematics Advisory Panel. Washington, DC: U.S. Department of Education, 2008. S. Hyun Lee and M. Na Kim, “This is my paper,” ABC Transactions on ECE, vol. 10, no. 5, pp. 120-122, 2008.

[8] J. Aldemir and H. Kermani, “Integrated STEM curriculum: Improving educational outcomes for head start children,” Early Child Dev. Care, vol. 187, no. 11, pp. 1694–1706, 2017, doi: 10.1080/03004430.2016.1185102.

[9] C. T. Cross, T. A. Woods, H. A. Schweingruber, and National Research Council (U.S.), Mathematics Learning in Early Childhood: Paths Toward Excellence and Equity. Washington, DC: National Academies Press, 2009.

[10] H. P. Ginsburg, “Mathematical play and playful mathematics: A guide for early education,” in Play = Learning: How Play Motivates and Enhances Children’s Cognitive and Social-Emotional Growth, D. Singer, R. M. Golinkoff, and K. Hirsh-Pasek, Eds. New York, NY: Oxford University Press, 2006, pp. 145–165.

[11] C. Tofel-Grehl, B. L. MacDonald, and K. A. Searle, “The silent path towards medical apartheid within STEM education: An evolving national pedagogy of poverty through the absenting of STEM-based play in early childhood,” Educ. Sci., vol. 12, no. 5, p. 342, 2022, doi: 10.3390/educsci12050342.

[12] H. P. Ginsburg, J. S. Lee, and J. S. Boyd, “Mathematics education for young children: What it is and how to promote it,” Soc. Policy Rep., vol. 22, no. 1, pp. 1–24, 2008.

[13] N. S. Newcombe, “Picture this: Increasing math and science learning by improving spatial thinking,” Am. Educator, vol. 34, no. 2, pp. 29, 2010.

[14] M. Krakowski, K. Ratliff, L. Gomez, and S. Levine, “Spatial intelligence and the research—Practice challenge,” in Learning in the Disciplines: ICLS 2010 Conf. Proc., vol. 1, Chicago, IL, USA, 2010, pp. 556–563.

[15] J. Buckley, N. Seery, and D. Canty, “A heuristic framework of spatial ability: A review and synthesis of spatial factor literature to support its translation into STEM education,” Educ. Psychol. Rev., vol. 30, pp. 947–972, 2018, doi: 10.1007/s10648-018-9432-z.

[16] D. H. Uttal and C. A. Cohen, “Spatial thinking and STEM education: When, why, and how?,” in Psychology of Learning and Motivation, vol. 57, Academic Press, 2012, pp. 147–181.

[17] G. A. Borriello and L. S. Liben, “Encouraging maternal guidance of preschoolers’ spatial thinking during block play,” Child Dev., vol. 89, no. 4, pp. 1209–1222, 2018, doi: 10.1111/cdev.12779.

[18] D. S. Fox et al., “Diversity of spatial activities and parents’ spatial talk complexity predict preschoolers’ gains in spatial skills,” Child Dev., vol. 95, no. 3, pp. 734–749, 2023, doi: 10.1111/cdev.14024.

[19] K. E. Bates et al., “Practitioners’ perspectives on spatial reasoning in educational practice from birth to 7 years,” Br. J. Educ. Psychol., vol. 93, pp. 571–590, 2023, doi: 10.1111/bjep.12579.

[20] M. Krakowski, K. Ratliff, L. Gomez, and S. Levine, “Spatial intelligence and the research—Practice challenge,” in Learning in the Disciplines: ICLS 2010 Conf. Proc., vol. 1, Chicago, IL, USA, 2010, pp. 556–563.

[21] J. E. Lauer, E. Yhang, and S. F. Lourenco, “The development of gender differences in spatial reasoning: A meta-analytic review,” Psychol. Bull., vol. 145, no. 6, pp. 537–565, 2019, doi: 10.1037/bul0000191.

[22] D. Reilly, D. L. Neumann, and G. Andrews, “Gender differences in spatial ability: Implications for STEM education and approaches to reducing the gender gap for parents and educators,” in Visual-Spatial Ability in STEM Education, M. Khine, Ed. Springer, 2017, doi: 10.1007/978-3-319-44385-0_10.

[23] H.-Y. Chang et al., “Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate impact,” Comput. Educ., vol. 191, p. 104641, 2022, doi: 10.1016/j.compedu.2022.104641.

[24] M. M. McClelland and F. J. Morrison, “The emergence of learning related social skills in preschool children,” Early Child. Res. Q., vol. 18, no. 2, pp. 206–224, 2003, doi: 10.1016/S0885-2006(03)00026-7.

[25] K. Hirsh-Pasek et al., “Putting education in ‘educational’ apps: Lessons from the science of learning,” Psychol. Sci. Public Interest, vol. 16, no. 1, pp. 3–34, 2015, doi: 10.1177/1529100615569721.

[26] A. E. Lewis Presser, J. M. Young, D. Rosenfeld, L. J. Clements, J. F. Kook, H. Sherwood, and M. Cerrone, “Data collection and analysis for preschoolers: An engaging context for integrating mathematics and computational thinking with digital tools,” *Early Childhood Research Quarterly*, vol. 65, no. 4, pp. 42–56, 2023, doi: 10.1016/j.ecresq.2023.05.012.

[27] S. Liu, W. Wei, Y. Chen, P. Hugo, and J. Zhao, “Visual-spatial ability predicts academic achievement through arithmetic and reading abilities,” Front. Psychol., vol. 11, p. 591308, 2021, doi: 10.3389/fpsyg.2020.591308.

[28] P. J. Ponners and Y. Piller, “The reality of augmented reality in the classroom,” in Cognitive and Affective Perspectives on Immersive Technology in Education, R. Z. Zheng, Ed. IGI Global, 2020, pp. 51–66, doi: 10.4018/978-1-7998-3250-8.

[29] B. Dewi, “Augmented reality for young learners,” presented at iTELL Conference, Bogor, Indonesia, Feb. 2020.

[30] N. Jamiat and N. F. N. Othman, “Examining kindergarten students’ motivation on augmented reality apps: A survey using emoticons,” ASM Sci. J., vol. 13, no. 3, pp. 39–42, 2020.

[31] M. Y. F. Aladin, A. W. Ismail, M. S. Salam, R. Kumoi, and A. F. Ali, “AR-TO-KID: A speech-enabled augmented reality to engage preschool children in pronunciation learning,” in IOP Conf. Ser.: Mater. Sci. Eng., vol. 979, Nov. 2020.

[32] K. Atit et al., “Examining the relations between spatial skills and mathematical performance: A meta-analysis,” Psychon. Bull. Rev., vol. 29, no. 3, pp. 699–720, 2022, doi: 10.3758/s13423-021-02012-w.

[33] Z. Bai, A. F. Blackwell, and G. Coulouris, “Exploring expressive augmented reality,” in Proc. 33rd Annu. ACM Conf., Seoul, Republic of Korea, Apr. 2015, doi: 10.1145/2702123.2702250.

[34] N. Zamin, F. A. Khairuddin, D. R. A. Rambli, E. N. M. Ibrahim, and M. S. A. Soobini, “Building empathy in young children using augmented reality,” Int. J. Eng. Technol., vol. 7, no. 2.28, pp. 191–192, 2018, doi: 10.14419/ijet.v7i2.28.12909.

[35] N. I. N. Ahmad and S. N. Junaini, “Augmented reality for learning mathematics: A systemic literature review,” Int. J. Emerg. Technol. Learn., vol. 15, no. 16, pp. 106–122, 2020, doi: 10.3991/ijet.v15i16.14961.

[36] R. Andrea, S. Lailiyah, F. Agus, and Ramadiani, “’Magic Boosed’ an elementary school geometry textbook with marker-based augmented reality,” Telkomnika (Telecommun. Comput. Electron. Control), vol. 17, no. 3, pp. 1242–1249, 2019, doi: 10.12928/telkomnika.v17i3.11559.

[37] Z. Gecu-Parmaksiz and Ö. Delialioğlu, “The effect of augmented reality activities on improving preschool children’s spatial skills,” Interact. Learn. Environ., vol. 28, no. 7, pp. 876–889, 2020.

[38] H. C. K. Lin, M. C. Chen, and C. K. Chang, “Assessing the effectiveness of learning solid geometry by using an augmented reality-assisted learning system,” Interact. Learn. Environ., vol. 23, no. 6, pp. 799–810, 2015, doi: 10.1080/10494820.2013.817435.

[39] W. R. Penuel, B. J. Fishman, B. H. Cheng, and N. Sabelli, “Organizing research and development at the intersection of learning, implementation, and design,” Educ. Res., vol. 40, pp. 331–337, 2011, doi: 10.3102/0013189X11421826.

[40] B. DiSalvo, C. DiSalvo, J. Yip, and E. Bonsignore, Eds., *Participatory Design for Learning: Perspectives from Practice and Research*, 1st ed. Routledge, 2017, doi: 10.4324/9781315630830.

[41] J. W. Creswell and V. L. Plano Clark, Designing and Conducting Mixed Methods Research, 3rd ed. SAGE Publishing, 2017.

[42] P. Vahey, D. Reider, J. Orr, A. E. Lewis Presser, and X. Dominguez, “The evidence-based curriculum design framework: Leveraging diverse perspectives in the design process,” Int. J. Designs Learn., vol. 9, no. 1, pp. 135–148, May 2018.