Developing STEM toolkits for young children to improve spatial skills

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Abstract

This study aimed to develop STEM toolkits to improve spatial learning in the early years. The Pedagogical Play-framework was adopted as a conceptual framework to guide teachers in designing STEM toolkits to support children's spatial skills. Design-based research was applied to investigate in-service teachers' pedagogical practice. The results of the first stage showed that teachers' lack of confidence and pedagogical approaches to spatial learning were barriers to design effective toolkits. In the second stage, a professional development programme guided teachers to design STEM toolkits for young children's learning based on the teachers' pedagogical needs and children's learning interests. Navigation, map reading and map creation were the three types of spatial learning activities to improve children's spatial skills. Three pedagogical play types were adopted as pedagogical toolkits by the in-service teachers in designing spatial learning: 1) purposefully-framed play, 2) modelled play and 3) open-ended play. This study also investigated how to integrate digital technologies in STEM activities, including using digital maps, digital cameras, tablets and apps.

Keywords: STEM education, spatial skills, early childhood education, pedagogical-play types, digital technologies

1   Introduction

Internationally, Science, Technology, Engineering and Mathematics (STEM) education is regarded as critical to effectively prepare citizens for the twenty-first century (Early Childhood STEM Working Group, 2017; McClure et al., 2017). STEM-related learning can spur young children's interests through scientific inquiry (Kennedy & Odell, 2014). It also provides young children with opportunities to develop critical thinking, executive functioning and problem-solving skills (Simoncini & Lasen, 2018; Tippett & Milford, 2017). Research indicates that children are being increasingly exposed to STEM education during early childhood consistent with international trends in STEM education. The learning disciplines within STEM are not new concepts in early childhood education; however there is need for more emphasis on interdisciplinary connections (McClure et al., 2017) and greater provision of high quality learning experiences (Early Childhood STEM Working Group, 2017).

1.1   Spatial skills

Spatial skills are tools that have been recognized as essential abilities in daily tasks, assisting people to "visualize and navigate" the world (Uttal, Meadow, et al., 2013; Zimmermann, Foster, Golinkoff, & Hirsh-pasek, 2019). The ability to competently manipulate information about objects in space is increasingly important to everyday functioning and has been linked to success in a number of academic domains (Kell, Lubinski, Benbow, & Steiger, 2013; Lowrie, Logan, & Ramful, 2017; Wai, Lubinski, & Benbow, 2009). Similarly, spatial reasoning ability has been shown to predict the likelihood of success in science, technology, engineering, and math (STEM) fields beyond school (Lowrie et al., 2017; Uttal & Cohen, 2012; Uttal, Miller, & Newcombe, 2013). The link between mathematics and spatial reasoning in both children and adults has been repeatedly demonstrated (Cheng & Mix, 2014; Uttal et al., 2013; Wai et al., 2009). Researchers have found that children who perform better on spatial tasks consistently outperform their peers on mathematics assessments (Mix et al., 2016; Uttal et al., 2013). While there is a lack of consensus regarding the specific reasons for this relationship, it is generally believed that success in mathematics relates to the development of mental models, and the use of visualization and mental manipulation strategies to solve mathematics problems, including problems not inherently spatial in nature (Lowrie, 2012; Mix et al., 2016; Uttal, Miller, et al., 2013).

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Spatial learning experiences are vital for children to understand the world and spatial concepts can be prepared in young children's daily explorations. Newcombe and Shipley (2015), and Uttal et al. (2013) identified two aspects of spatial skills in a typological framework. The first aspect is "intrinsic and extrinsic", and the second is "static and dynamic". In the following Table 1, based on Newcombe and Shipley (2015), Okamoto, Kotsopoulos, Mcgarvey, and Hallowell (2015), Rule (2016), and Uttal et al. (2013), four categories of spatial skills are given a clear description and supported examples from which are in line with spatial relative researches in ECE STEM learning context. A comprehensive review related to spatial thinking about maps were targeted in STEM learning, which highlights the important areas of geography, earth and environmental sciences for improving spatial skills.

Table 1. Examples of Spatial Skills relate to STEM in ECE learning context

Category (Uttal et al., 2013)	Description (Hodgkiss,Gilligan, Tolmie, Thomas, & Farran, 2018; Rule, 2016)	Examples of Spatial Skills related to STEM in ECE learning contexts
Intrinsic-static Skill	The processing of objects or shapes with no further transformation	Shape recognition (Okamoto et al., 2015)
		Identifying rocks and their formations (Rule, 2016)
Intrinsic-dynamic Skill	The processing and manipulation or transformation of objects or shapes	Building blocks to exemplify items natural world (Mohan & Mohan, 2013; Okamoto et al., 2015)
Extrinsic-static Skill	The processing and encoding of the spatial relations between objects,without further transformation	Interpreting maps and designing routes (Okamoto et al., 2015)
		Plotting locations and combining what? to use landmarks in a map (Cheng, Huttenlocher, & Newcombe, 2013; Mohan & Mohan, 2013; Rule, 2016)
Extrinsic-dynamic Skill	Transformation or updating of the relationship between objects	Searching and locating hidden objects by using landmarks (Mohan & Mohan, 2013; Okamoto et al., 2015)
		Knowing multiple ways from place A, B, or C to place D (Okamoto et al., 2015)
		Understanding spatial language such as "near", "far", or "next to" and using the language of maps for navigating mazes (Mohan & Mohan, 2013)

As recommended by Mohan and Mohan (2013), the spatial concepts can be developed by four aspects, 1) identity and location, 2) magnitude, 3) relative distance and direction and 4) symbols, and the curriculum recommendation notice tactile, hands-on, active mapping activities for improving children's spatial thinking skills in family, schools and neighbourhoods. Digital maps as a powerful resource to include panoramic views for children to identify locations, and apply the zoom function to observe objects. Both teacher and children can practically apply magnitude functions to enlarge the imagery and symbols on the map through 2D version and 3D street view version.

1.2   Adopting the pedagogical play-framework to design STEM toolkits

Children are often considered as natural explorer, as they are curious to discover the world around them. However, curiosity is not by itself sufficient to ensure a high-quality STEM learning experience; children require adult guidance to fully explore and establish an understanding of scientific concepts (Early Childhood STEM Working Group, 2017). The Pedagogical Play-framework is a useful guide for EC teachers in developing a pedagogical approach to design STEM activities that include open-ended play, modelled play and purposefully-framed play (Edwards, 2013; Edwards, Cutter-Mackenzie, Moore, & Boyd, 2017). These three play types can be applied equally in the learning process. Open-ended play involves teachers providing children with STEM materials related to particular concepts and letting the children experience and explore with minimal teacher engagement. Modelled play involves teachers showing children how to use the materials to illustrate STEM concepts before allowing the children to use the materials themselves. Purposefully framed play involves teachers providing children with opportunities to use STEM-related materials and to participate in the modelled play, in addition to co-developing understandings of a concept. Teachers and children shift roles during exploration.

For example, children ask 'why' and 'how' questions during open-ended play activities, which may lead teachers to demonstrate how to use the materials in modelled play. In the purposeful-framed play, teachers help children search for and understand scientific concepts. These three types of play can guide children to learn, play, create and think about STEM subjects.

Developmentally appropriate STEM toolkits therefore require sufficient learning resources and appropriate pedagogical approach to allow children to explore and practice. They are characterised by immediacy, flexible participation, openness and adaptability (Conole & Fill, 2005; Conole & Oliver, 2002). Currently, the majority of STEM resources have not been specifically designed for young children's learning in school settings. STEM toolkits in this project include pedagogic toolkits and STEM learning resources, which expect to promote as practical resources for educators to become more engaged with new and challenging areas of teaching, particularly in the area of digital pedagogies (Burden & Kearney, 2018; Oliver & Conole, 2000).

The Early Childhood STEM Working Group (2017) broadly defines technology as any human-made used to solve problems or satisfy wishes STEM educators are urged to consider the ways and roles of integrating digital technologies into pedagogy, and assist children to move from technology users to technology creators. Many types of digital technologies have been introduced into early childhood education settings, including digital toys, digital cameras, video cameras, projectors, laptops, the Internet, CD players, portable interactive whiteboards, mobile phones, touch-sensitive tablets and digital toys (Hu & Yelland, 2019). Digital technology can provide meaningful support for spatial learning, and can also create a visual learning environment for children to understand abstract spatial concepts. Lowrie and colleagues (2018) demonstrated that digital games can create new learning spaces for spatial learning. They found that the digital game environment can provide learners with a dynamic way to learn and embed spatial knowledge. Kimmons, Graham, and West (2020) developed the new technology integration model named PICRAT, which is a student-focused, pedagogy-driven model. The model illustrates the children's relationship to technology in an educational scenario and the impact of the technology on a teacher's previous practice. PICRAT modal is constructed as children aspects (PIC) and educators' aspects (RAT) respectively. PIC is represented as Passive, Interactive, and Creative, which focuses on how children use technology. RAT is represented as Replacement, Amplification, and Transformation, which focuses on how teachers use of technology.

Research questions

1. What are the learning resources for spatial learning in STEM toolkits?
2. How should STEM toolkits be applied in the early years to support spatial learning?
3. What pedagogical approaches to spatial learning are effective?

2 Research design

Design-based research (DBR) was conducted to investigate how in-service teachers create and use STEM toolkits aimed at increasing spatial reasoning. Both qualitative and quantitative data were collected to understand the pedagogical approaches and how children learned during the process. Anderson and Shattuck (2012) defined DBR as 'a methodology designed by and for educators that seek to increase the impact, transfer, and translation of education research into improving practice' (p. 16). Grounded in both theory and the real-world context (Wang & Hannafin, 2005), DBR requires interactive collaboration between researchers and practitioners to identify needs and effective pedagogical approaches from teachers in preparing STEM activities. Design models provide prescriptive guidance about what a design should be to increase the likelihood that a desired STEM learning outcome will be achieved.

2.1   Participants

30 in-service teachers in their third year of a top-up Bachelor's of Early Childhood Education programme were invited to join this project. All of them had qualified Kindergarten Teacher Qualification before enrolling this programme as they completed the associate degree related to early childhood education. The professional development provided a 3-credit elective course titled *The Young in a Technology World*, which is related to the STEM learning context in the early years. As one part of the course, 12 hours of learning activities were designed to guide teachers in learning how to design and apply the STEM toolkits in the classroom.

Ethics approval to conduct this research was approved by the Education University of Hong Kong's Human Research Ethics Committee. Participants were invited to join this project and the research team explained the project information. The consent forms were collected at the beginning of the course from all participants.

2.2   Data collection and analysis

Data were collected from multiple sources, including classroom observation records, activity plans teachers' reflections and children's learning portfolios. The first stage involved teachers' pedagogical design and children's learning portfolios. In the second stage, teachers revised their design based on the research findings in the first stage and explored the way of adopting toolkits.

Participants were required to submit activity design packages two weeks after completing the course. The activity design packages include activity plans, reflective reports, all of which were submitted through the online learning platform. These together with analyses of the teachers' pedagogical design will be used to understand how STEM Toolkit was applied. In this study, three types of data analysis will be conducted to explore multiple data resources based on content analysis (Krippendorff, 2018).

Total 30 activity design packages were collected in this project. A coding scheme was designed to analyse the learning, including STEM resources, teacher's role, children's role, learning contents and pedagogical approaches. The children's learning portfolios were collected to record as the document to analyze the learning process. These included classroom observation audiovisual records, photographs taken by the children, and children's work samples. NVivo 12 was used to analyse the teachers' interviews and pedagogical designs, such as activity plans and the children's learning portfolios.

3 Research findings

3.1   What are the learning resources for spatial learning in STEM toolkits?

Learning resources were introduced in the course, and in-service teachers selected and applied in their schools. The project team collected 30 activity plans and analyse what kind of resources were included in their STEM toolkits after taking the course. The following table 2 shows the components of STEM toolkits and provides the fundamental functions of these selected toolkits.

Table 2 The components of STEM toolkits

STEM toolkits	Fundamental functions of toolkits	Examples of toolkit use
Digital maps (Google Earth and Google Maps)	Search for places Discover places at random Read map Find Street View Pegman	Children used digital maps to search places and create virtual trips. Children can zoom in and zoom out the imageries.
Digital camera	Take photographs Record videos	Children took photos with a designated digital camera during field trips.
Tablet/mobile phone	Take photographs Record voices Access websites and apps	Children used tablets/mobile phones to access Google Earth and other apps. The teachers used tablets/mobile phones to record pictures, audio and video.
Arts and crafts materials	Design and create items during learning	Children used arts and crafts materials to create maps.

3.2   How should STEM toolkits be applied in the early years to support spatial learning?

According to the collected data, teachers created sets of STEM toolkits to provide spatial learning for young children, and they particularly used digital technologies to prepare multiple playful activities. A web mapping tool was developed in this STEM toolkit to guide teachers to connect pedagogical approaches with spatial skills. The following figure 1 introduces the way of using the web mapping tool to as a pedagogical tool to guide in-service teachers to design activities. Three major categories of spatial learning activities were identified in the activities: 1) navigation, 2) map reading and 3) map creation. In the navigation category, children found locations and use inquiry tools to explore places on Google Earth. Children navigated the digital map using inquiry functions, including the relative location, such as relative spatial vocabularies "left, right, up and down". In the map reading category, teachers facilitated children in exploring the features and conditions of a place. Children could identify places on maps by using panoramic views. They applied the 360-degree street view to identify their school neighbourhoods. In the map creation category, the teachers printed the maps and integrated multiple resources to create 3D maps for the children based on their previous experience, such as combining pictures from a field trip.

In addition, children were guided to add real objects to the maps to make them 3D, such as animal toys, modelling clay and blocks. Children actively engaged in the process of making maps and creating relative symbols. The hands-on activities helped children to understand the basic concepts of distance and direction, such as they can begin to identify their neighbourhoods by using a digital map and explore the relative landmarks by using aerial photograph through 3D imagery.

Figure 1: Example of using a web mapping tool

C: Creating map
M: Map reading
N: Navigation
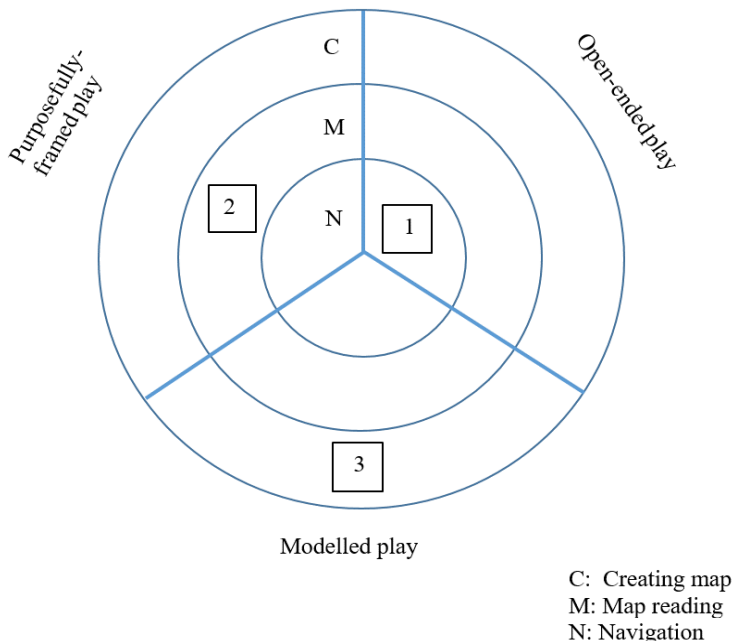
3.3   What are the effective pedagogical approaches to spatial learning?

In this project, the teachers used technology to amplify and transform traditional spatial learning in preschool settings. The children were not passive learners receiving an instruction to drill and practice, but active participants in interactive and creative learning scenarios. Children constructed STEM-related skills in real-life learning tasks by creating a map based on the virtual tour.

In-service teachers develop different pedagogy approaches to guide children in exploration. The following Figure 2 provides the categories of spatial learning and play types, which shows examples of pedagogical approaches in STEM learning activities.

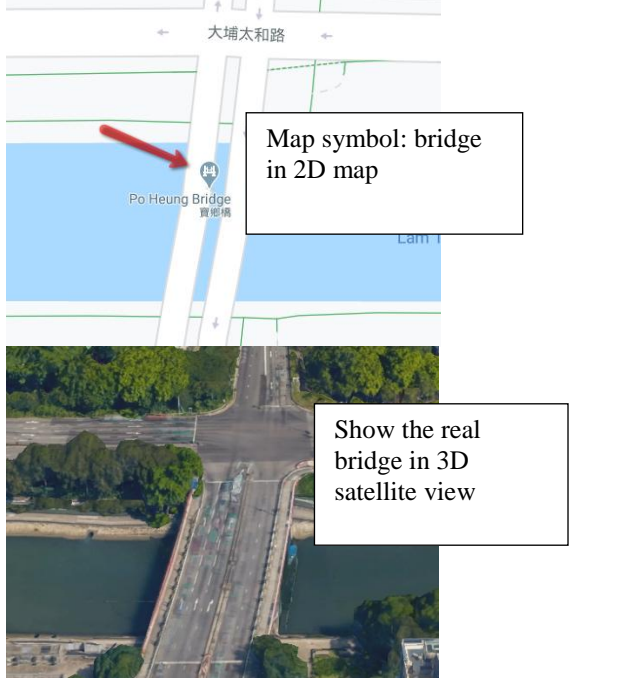Figure 2. Examples of navigation, map reading and creating a map

1.Opened-ended play: Navigation	2. Purposefully framed-play: Map reading
Children used Pegman to navigate Hong Kong	Teacher taught basic map symbols through 3D version to help children understand the bridge

3. Modelled play: Creating a map	4. Modelled play and purposefully framed-play: Creating a community map
Children used objects to make a map based on the virtual tour by using street view	Children collaboratively made a community map after the field trip. Teacher guided children to learn how to make map symbols.

Table 3 Spatial Learning Activities with Play Types

Spatial learning activities	Play types	Examples of spatial skills	Connect with spatial concepts(Mohan & Mohan, 2013)
1. Navigation	Open-ended play	• Exploring places on a map using virtual information • Relative location (left, right, up, down) • Zoom in/out	• Identity and location • Magnitude
2. Map reading	Purposefully framed-play	• Features and conditions identified at a place. • Using 2D version and 3D street view version to read the map (e.g. relative objects and symbols) • Zoom in/out	• Identity and location • Magnitude • Relative distance and direction • Symbols
3. Creating a map	Modelled play	• Comparisons between field trip and virtual trip with digital and non-digital resources • Creating a map (e.g. 2D and 3D maps)	• Identity and location • Magnitude • Relative distance and direction • Symbols

3.4 Opened-ended play: Navigation you need to specify that you are giving one particular example.

A teacher provided the children with an iPad with Google Earth during the free-choice time in a learning centre called exploration corner. Children used a street view panorama to explore various places across the planet. In this play type, children could decide where to navigate and how to use Google Earth. Teachers took the roles of observers and facilitators during the learning process and provided technical support. The following dialogue was collected in the teacher's classroom observation record.

Child 1: I want to go to Hong Kong today.
Child 2: You need to type 'Hong Kong'.
Child 1: No need, I can find it. You see it is on the left part of the ocean (pointing to the Pacific Ocean).
Child 2: Oh yeah, zoom out, let's fly.
Child 1: I found Hong Kong Island, and you see it is a very big island. My home is not there. It is too far from my home.

Child 2: Let me try. I want to find my school on the side, let me zoom it (Class1-Record 1-15)
The children then asked how to type their school name. The teacher wrote the words on paper, and one of the children put them into Google Earth to find the park on Hong Kong Island. Later, they applied the function of flying animation in Google Earth to visit their school and explored the street view of the school community. The flying animation provided children the feeling of virtual tour to navigate to a specific place by clicking a placemark. Children talked about what they observed on the images by using the Street View function, and they can use the zoom in and zoom out function to observe the features of the locations.

3.5 Modelled play: Creating Map this could potentially be both modelled and purposeful.

A teacher used Google Maps to create project-based learning where children were guided to highlight key locations on the map. The teacher assisted the children in typing the school's name and in finding locations in the local community, such as the market, the park, the hospital and the police station, which they may have had experience within their daily lives. During this activity, children learned multiple ways to connect locations and how to measure the distance between two places. For example, the distances could be represented as time by different modes of transport, such as walking, public transport and private car. The children were guided to observe the directions on the map and to personalise their own places.

The children were then guided to make their own maps and to create 3D objects based on their observations. The teacher printed out the map, highlighting the school building, and customised the view based on the street view and a real field trip. The teacher provided clay and other resources for a painting to enable the children to depict their walking routines on the map and to create other buildings and trees around the school. Before the field trip, the teacher printed out an enlarged map with a street view of the area around the school. During the activity, the teacher guided the children to observe the real street and the surroundings and then to compare them to the digital map. The children were thus motivated to engage in the exploration and to ask questions using spatial vocabulary in both the real field trip and the map reading process.

Teacher: Can you tell me what you have seen?

Child: I can see the building over there.
Teacher: Where is it?
Child: There! In the front of the bus station (pointing out the building).
Teacher: Can you tell me where it is on the map? (providing the street map)
Child: It is here, and you see it is on the right side of our school. There is a big building. I want to take a picture first.
Teacher: Okay, can you help to mark this building on the map and take a picture? (Class3-Record4-9)

3.6 Purposefully-framed play: Map reading

The teacher opened Google Earth and Google Map on the iPad and helped children enter the place to be found. When the target place was displayed, the child zoomed in and out on the map to observe and find other nearby locations. During the virtual tour, the teacher guided children to learn map symbols through 2D and 3D satellite map. Children asked the meaning of basic symbols before the field trip, which might help them build up the concepts of map. It was attractive for providing the school's community map since children had practical experience to visit those places, such as roads around the school, the river, and the wooded areas near to their school.

The map reading helped the learners to understand the information provided by digital maps. Especially the terrain and location in the 3D map helped the young children to explore and express their observations, and to determine destinations through operating the programme. As the following example, children learned to apply symbols on maps and spatial vocabularies in a small group activity.

Teacher: What can you see on the Google map?
Child: Buildings and roads.
Teacher: Good, there is a crossroad. Can you tell me the name of the road?
Child: It is Po Heung road, and I've known that there is a bridge beside the road.
Teacher: How do you know that?
Child: I can see a small river graph. Let me show you.
Child used zoom in function to explore the map and find the symbol of the bridge.
Teacher: Yes, that is a symbol of the bridge. Let's click the satellite map, you can see the real bridge on the map. (Class4-Record 6-21)

The teacher taught the children to apply the digital map to teach children the basic map symbols. Children showed interests to identify the symbols, such as road, building, gas station, fire station, or post office. Some children had limited geographic knowledge about the places and the relevant symbols, but they had real-life experience in approaching these places, leading to new learning scenarios and spatial vocabularies. The role of Google Map worked as a mediator to connect children's interests and the specific knowledge. The teacher guided children to design their own map symbols through hands-on activities.

3.7 The following table gives an overview of the types of learning involved

4   Discussion

The use of STEM toolkits in the classroom helps fulfil the Kindergarten Education Curriculum Guide in Hong Kong (Curriculum Development Council, 2017) in the learning areas of Mathematics, Nature and Living, which encourages schools to guide children in exploring their own living environment. Thus, the STEM toolkits could work as mediators to connect spatial learning in the STEM learning context.

Schools may encourage children to explore the physical world with multiple senses in order to discover the fascinating things and phenomena in nature and explore the way they relate to our everyday life. (Curriculum Development Council, 2017, p. 41)

When using digital maps, children were curious and eager to explore the world, and they learned how to acquire knowledge by using relative technologies, such as searching, zooming in to find their schools and landmarks. Lobben (2007) found that self-location was the most influential predictor of navigational map reading. In our study, young children could apply pegman to locate themselves. This child-directed navigation experience provided flexible spatial learning opportunities for children to develop self-location awareness. Both teachers and children had positive experiences with the digital map, as it was highly connected to their daily experiences. The manipulation of Google Maps provided evidence of how digital technologies could be integrated to enhance children's navigation. Teachers could use digital maps to amplify the virtual learning resources, showing children satellite and 360-degree street views. Students' spatial skills were improved through the navigation process because it scaffolded productive spatial vocabulary during learning, and children interacted with the digital maps to find locations and identify objects. The teachers felt comfortable explaining the locations, places, directions and movement of the digital maps as the information was clearly listed in digital maps.

The children showed interests in playing with Google Earth and Google Maps, especially during open-ended play in the learning centre. Their curiosity led them to discover various locations, in an experience that was different from the traditional paper-and-pencil spatial learning instruments. Children had the authority to decide the learning contents and direct the way of map reading.

Teachers' pedagogy approaches changed from delivering knowledge to scaffold children in the map reading process. The learning was dynamic and interactive since children asked questions based on their virtual exploration. These activities extended spatial learning from drills and practice with mazes and graphs in kindergarten as mentioned by Okamoto and her team members (Okamoto et al., 2015). The children's active engagement indicated that the STEM toolkits helped them think and create maps, which prepared children to observe 2D pictures and transform to 3D objects during the making process. The results thus show that children's spatial learning can be connected to real-life STEM learning activities with some interactive and creative experience.

STEM toolkits can help children understand those spatial concepts and vocabularies. For the children, our planet was an abstract concept, but the playful spatial learning enabled them to connect it to their everyday walking experience in their own communities. The children obtained practical spatial skills by navigating since it becomes a regular play activity for them to manipulate the tools to discover the world. Digital maps provided sufficient information for both learners and teachers to improve their spatial learning opportunities (Collins, 2018), which increased their motivation to explore during the daily playful activities.

These navigational and mapping activities also prompt science learning. The children ask questions such as about the shape of the planet and why there are differences between city life and natural environments. STEM toolkits include some everyday technologies related to children's and teachers' lives. According to the Curriculum Guide, it is important for children to gain a preliminary understanding of modern technology and the influence it has on them through everyday life experiences. Using appropriate technologies can support children in searching, applying and finding new ways to use spatial information. Integrating digital technologies in learning provides interactive and creative learning opportunities for young children.

The STEM Working Group paper provides general recommendations for selecting appropriate STEM resources; however, more specific guidance is required to support teachers and school leaders in establishing context-specific STEM classroom resources. Not all such resources need to be digital and high-tech; sometimes, the most effective resources are those that young children can touch and manipulate to obtain real-life experience. Individual school-level conditions may vary based on a school's vision, developmental plan or historical background. Without high-quality guidance, limited spatial classroom resources can be a sizable barrier for practitioners; moreover, searching for resources is a time-consuming process, and teachers often face a lack of support to find and adopt relevant appropriate resources. This study provides a practical example to integrate pedagogical tools and STEM-related resources in professional development, which integrate digital and non-digital resources to create dynamic spatial learning activities.

While our data provides evidence that the use of STEM toolkits can provide young children with the innovative spatial learning experience, the numbers of participants are limited, as only one class of in-service teachers and children in their classrooms have participated in this study. In the future, more combinations of spatial learning types can be identified with a larger group of participants.

5. Conclusion

STEM toolkits developed by teachers in this study explored innovative spatial learning in STEM learning activities, which may lead to the further design of interactive play activities for young learners in the classroom and beyond the school settings. Digital technologies should be adopted with the consideration of teachers' experience and should be appropriate for young learners' learning needs. Combinations of pedagogical play types can be helpful for teachers in reconstructing their pedagogical approaches and multiple roles, connecting children's authority and interest in open-ended play, and offering effective scaffolding in modelled and pedagogical-framed play.

6. Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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