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Lesson Study as a Professional Development Model for Teaching Spatial Ability in Primary STEM

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Abstract: This study explores the efficacy of a professional development (PD) model that employs lesson study to teach spatial ability skills in primary STEM education. The structure of the PD supported the 'Insights' mechanism by focusing on visualisation, mental rotation, construction and deconstruction, and spatial orientation, which are vital for nurturing students' spatial abilities. The 'Motivation' mechanism was addressed through goal setting in lesson planning, motivating teachers to integrate spatial tasks into their curricula. Continuous feedback and practical support facilitated the 'Technique' mechanism, embedding learned skills into everyday teaching practices. Last, the 'Embed in Practice' mechanisms, including action planning and prompts, were effectively translated into classroom practices, evidencing the model's operational efficacy.

Keywords: spatial ability; professional development; lesson study; primary school

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1. Introduction

In the ever-evolving landscape of education, cultivating spatial ability skills in primary STEM (Science, Technology, Engineering, and Mathematics) education is a pivotal endeavour [1]. The ability to visualise and comprehend spatial relationships is not only fundamental to achieving academic success [1,2] but is also essential for nurturing a generation of critical thinkers and problem solvers [3–6]. According to longitudinal and cross-sectional data, individuals with better spatial ability perform better in mathematics and science beginning in early childhood than those with inferior spatial ability [7–11]. Moreover, spatial transformation abilities improve during childhood, and interventions tailored to various age groups can significantly impact children's cognitive development [12].

Despite spatial ability being a fundamental aspect of intelligence [13], many young people across Europe, especially girls, fail to develop it to a level that enables successful engagement with STEM learning [14]. Given the multifaceted nature of spatial ability development—influenced by educational factors such as curricular design, institutional practices, classroom environment, teacher quality, and student characteristics—targeted interventions are essential for addressing these challenges [15]. Moreover, spatial ability is often relegated to the curricular periphery, thus posing significant challenges to the improvement thereof through changes in teaching practices. These challenges stem from several factors, including limited teacher knowledge regarding the impact and significance of spatial ability, insufficient experience in integrating it into lessons, time constraints, a dearth of instructional materials, and a lack of well-structured lesson plans [15,16]. Consequently, educators must engage in continuous professional development (PD) to surmount these hurdles effectively. In the context of PD aimed at giving educators the know-how to improve students' spatial ability, teachers can acquire the necessary skills to recognise and support students with varying levels of spatial proficiency. Furthermore, they can learn to seamlessly integrate spatial ability into the curriculum, transcending subject-specific boundaries.

For this reason, the current study aimed to develop a PD model that involves lesson study (LS) [17] as a mode of PD for teaching spatial ability in primary STEM education. Through the synergistic integration of theory and practical application, this study intended to shed light on the transformative potential embedded in the proposed approach. The study demonstrated the approach's ability to empower teachers, improve spatial cognition among young learners, and ultimately contribute to the overall progress of STEM education at the primary level. This investigation addressed the following research questions:

1. How do participants perceive the improvements in their understanding, integration of spatial ability into instructional practices, collaboration with colleagues, and adaptation of teaching materials following their engagement with the designed PD model?
2. What qualitative insights can be identified to assess the impact and effectiveness of the designed PD model?

2. Theoretical Framework

2.1. Spatial Ability and STEM

Defined as a multifaceted set of cognitive skills, spatial ability enables individuals to effectively organise, reason about, and manipulate spaces, whether tangible or abstract [18]. According to the National Research Council [1], these skills encompass a range of capabilities, including the ability to perceive and analyse the shape, size, orientation, direction, and trajectory of objects, as well as to understand the relationships between them. In addition, spatial ability involves the capacity to mentally visualise objects and their spatial relations, as well as to reason about these elements across both space and time [19]. Longitudinal research [20,21] indicates the importance of spatial skills for success in STEM fields. Moreover, a growing number of intervention studies [22–27] have demonstrated that enhancing students' spatial skills leads to improved STEM outcomes.

Extensive experimental research [5,23,25,26,28–35] has consistently underscored the pivotal role of spatial ability in students' comprehension of and reasoning about scientific phenomena. As emphasised by Gagnier et al. [36], students' ability to comprehend and analyse the spatial properties of objects is essential for effectively solving scientific problems. Furthermore, the utilisation of visualisations, such as maps, graphs, and diagrams, plays a crucial role in understanding and reasoning about spatial relationships that may not be directly observable. This reliance on visual aids for spatial reasoning is particularly prevalent within classroom settings, where educators employ various instructional tools to enhance students' understanding of complex spatial concepts and phenomena. Consequently, some have endeavoured to incorporate spatial ability into classroom interventions [37–41].

An increasing amount of research suggests that practicing spatial skills improves STEM outcomes. Students who underwent spatial training exhibited notable improvements in chemistry knowledge and skills [26], engineering [33,42], elementary and middle school mathematics [22,24], calculus [27], and physics [25]. In addition, studies [5,35,43,44] have investigated the connection between spatial ability and mathematics achievement, revealing a robust correlation across various educational stages. Particularly among primary school students, recent longitudinal studies have identified spatial ability as a significant predictor of mathematics performance [8,43].

Although commonly perceived as innate, spatial skills are indeed malleable. Research conducted by Uttal et al. [45] demonstrated that spatial ability exhibits a remarkable degree of malleability and can be cultivated through practice and experiences, especially during early developmental stages. This malleability, combined with a predictive and causal association with STEM education retention and accomplishment [46], makes spatial ability an especially advantageous cognitive ability to focus on for individuals interested in STEM education development.

2.2. PD Literature Review

PD refers to the ongoing process of enhancing the skills, knowledge, and abilities related to one's chosen profession [47]. In the context of education, PD for teachers is particularly crucial, as it directly impacts the quality of instruction and ultimately the learning outcomes of students. OECD [48] defined PD for teachers as 'the process of enhancing teachers' professional knowledge, skills, attitudes, and beliefs in ways that lead to improved student learning'. This definition underscores the multifaceted nature of PD, which encompasses not only the acquisition of new knowledge and skills but also the cultivation of attitudes and beliefs that support effective teaching practices. According to Sims et al. [49], the concept of PD can be approached from three different perspectives: programmes, forms, and mechanisms.

PD programmes are distinct sets of activities and resources associated with particular individuals or institutions. In established programmes, these activities are often documented in a manual, and materials may be readily available as part of a resource pack.

PD forms are broader categories or types of PD, defined at a higher level of abstraction compared to specific programmes. These forms are characterised by typical features that distinguish them. While they encompass a range of materials and activities, they are not tied to particular individuals or institutions. An example of a PD form is LS, as described by Lewis and Tsuchida [50]. Originating in Japan in the late 1800s, LS has emerged as a cornerstone of teacher PD in Japanese public education [51–53]. Unlike traditional forms of PD that focus primarily on teacher performance, LS prioritises student learning outcomes [54]. Many argue that LS not only enhances the quality of teaching over time [55] but also fosters collaborative opportunities for capacity building among educators. At its core, LS aims to place students' learning, participation, and engagement at the forefront of teachers' PD efforts [56]. A distinctive feature of LS is its emphasis on teaching live lessons, which is considered one of its main strengths [52,57]. Building upon the foundations of LS, Lewis et al. [58] presented a comprehensive model delineating the four key steps involved: studying, planning, conducting, and reflecting. This structured approach not only facilitates the investigation of teaching practice but also serves to enhance several critical inputs of instruction. Specifically, participation in LS has been shown to positively influence teacher knowledge, beliefs, and dispositions while also fostering a sense of community among educators and promoting curricular development [58]. Integral to this process is the cultivation of teachers' dispositions towards collaboration, reflective practice, and the exploration of curriculum and instructional strategies.

PD mechanisms refer to the entities and activities organised to enhance teaching and learning outcomes [59]. These mechanisms are integral to the design of PD programmes and are essential for achieving the desired impact. Removing a genuine mechanism from PD would alter its effectiveness. Mechanisms serve as the fundamental components of PD, shaping its structure and outcomes. For instance, one PD mechanism may involve the rehearsal of new teaching techniques in a realistic classroom setting, as suggested by Hobbiss et al. [60]. Having established a conceptual framework for PD in this manner, the next step is to theorise its effectiveness. The efficacy of PD initiatives hinges on a multitude of factors, including their alignment with teachers' needs and interests, the provision of ongoing support and follow-up, opportunities for active learning and reflection, and integration with school goals and priorities [61]. Understanding these key determinants is crucial for designing and implementing effective PD interventions.

2.3. Characteristics of Effective PD

The conceptualisation of 'effectiveness' remains a subject of contention, given that a pedagogical approach demonstrating efficacy within a specific PD milieu may not manifest commensurate success when transposed into an alternative contextual or educational paradigm. Numerous studies have been conducted to develop appropriate and successful PD programmes for maths teachers that enhance their ability to teach and learn. Garet et al. [62] identified three key components of effective PD that have significant and beneficial effects on teachers' knowledge, abilities, and classroom practices. These components include a focus on content understanding, opportunities for active learning, and consistency with previous learning experiences.

Guskey's five critical levels of professional development evaluation [63] offers a comprehensive framework for assessing the impact of PD on teachers and students. Ranging from participants' reactions to student learning outcomes, these levels provide a structured evaluation process. By instigating changes in instructional strategies, content knowledge, and pedagogical techniques, PD plays a pivotal role in narrowing achievement gaps and elevating overall educational standards. The collaborative efforts of educators also play a crucial role in enhancing the effectiveness of PD initiatives. In addition, the framework in Bubb and Earley's [64] comprises 12 levels, beginning with the baseline picture, goals, and planning, emphasising the crucial role of planning in enhancing student and teacher outcomes. This aligns with Guskey's notion that PD planning should take student outcomes into account.

The subsequent levels in Bubb and Earley's work [64] correspond to Guskey's [63] five levels, focusing on participants' reactions, learning, organisational support, change, and student outcomes. One notable distinction is that they explicitly incorporate attitudes, a component not present in Guskey's model.

King [65] incorporates Bubb and Earley's [64] extension of Guskey's [63] model of successful PD into a revised PD evaluation framework. This integrated framework considers systemic factors and diffusion, expanding staff outcomes to include personal, professional, and cultural impacts. In terms of staff personal impact, emphasis is placed on teacher attitudes and beliefs. Furthermore, the framework underscores the significance of collaborative practices, such as professional dialogue and participation in professional learning communities, within the category of staff cultural impact. According to Darling-Hammond [66], PD becomes effective when it is research-based and customised to address the specific needs of individual teachers, leading to improved student achievement and engagement.

Furthermore, a recent systematic review, namely Sims et al.'s work [67], highlighted the importance of a well-designed PD programme, emphasising the capability thereof to effectively address aspects such as instilling insights, fostering motivation, refining techniques, and integrating these changes into practical applications. The success of such a programme requires a thoughtful examination of the inherent causal components within a PD initiative, considered as mechanisms for transformative impact. Mechanisms, as defined by Illari and Williamson [59] (p. 14), encompass the entities and activities that causally contribute to the outcomes of a PD programme on teaching and learning. These mechanisms not only play a role in generating a causal effect but also contribute to understanding the process through which this causal effect unfolds.

The four components, along with the mechanism detailed by Sims et al. [67], hold significant relevance for the context of the present study.

2.4. Sims et al.'s (2023) IMTP Framework of Effective PD

In guiding the design and implementation of effective PD, this research drew up on Sims et al.'s conceptual framework of effective PD [67]. The framework emphasises connecting teacher learning with changes in classroom practice. The choice of this framework is rooted in its simplicity and comprehensiveness, utilising mechanisms that not only bring about a causal effect but also offer insights into the process of how that effect unfolds.

Sims et al.'s [67] proposed the hypothesis that changes in teaching might occur when PD follows four principles: instil insights, motivate, teach techniques, and support the embedment of innovation in practice. The authors framed this hypothesis based on a review of a large number of reports concerning effective PD, where certain mechanisms (or concrete actions that occurred throughout the PD) were identified; by grouping the mechanisms with their outcomes, Sims et al. [67] proposed the IMTP (insights, motivation, technique, and embed in practice) framework.

Insights (I): The work by Sims et al. [67] identified two mechanisms accordingly: (a) the first is managing cognitive load for participating teachers by concentrating on a single idea or task, eliminating excess information, or providing supportive inputs (examples) to prevent overload; (b) the second is revisiting material through techniques like reteaching or prompt recall of essential concepts on distinct occasions.

Motivation (M): Based on Michie et al. [68], three mechanisms have been identified for effective PD: (a) the first is a goal-setting process where teachers consciously establish objectives focused on changing specific aspects of their practice; (b) the second is presentation of evidence supporting the proposed change with empirical research findings from credible sources; (c) the third is reinforcement, which is achieved through praise or reiterating the value of a particular teaching practice.

Technique (T): Sims et al.'s [67] identified four mechanisms based on Michie et al. [68] model. (1) Practical social support, which involves organising guidance for implementing a practice from colleagues, who can offer practical assistance and advice. (2) Modelling, which entails providing an observable example of the targeted teaching practice to serve as a visual guide for subsequent implementation [69]. (3) Instruction, which involves offering direct advice on the implementation of a teaching method, reducing ambiguity, and providing clear guidance on successful procedure utilisation. (4) Feedback, which concerns providing evaluative guidance based on prior observation of the focal practice.

Embed in Practice (P): Based on the criteria of Michie et al. [68], Sims et al.'s [67] found four mechanisms. (1) Action planning specifies when and how a change in practice will occur in a future lesson, creating situational cues to trigger new practices. This has been proven effective in health, education, and lab settings [70]. (2) Context-specific repetition involves rehearsing the target practice in a realistic classroom setting, overwriting existing cue–response relationships (habits) by reassociating the classroom with the new practice [60]. (3) The use of prompts/cues introduces environmental stimuli to prompt the desired practice. (4) Self-monitoring establishes a method for individuals to record and review their practice.

Sims et al.'s [67] identified statistically significant correlations between the number of mechanisms realised in PD and changes in student learning outcomes; further, PD where mechanisms according to all four principles were implemented ('balanced PD design') demonstrated a higher impact on student learning outcomes than PD that lacked mechanisms according to any of the four principles ('unbalanced design'). Compared with previous studies [71] dedicated to the conceptualisation of effective PD, Sims et al. [67] took into account only quantitative studies where effects on student learning outcomes were measured.

3. Methodology

In this research endeavour, the focus was on the development of a robust PD model tailored to teaching spatial ability in primary STEM education. By employing a design-based research (DBR) methodology, this study represented the second cycle within the overarching design, with the specific aim of formulating a PD model conducive to teaching spatial ability in primary STEM through the implementation of LS. The utilisation of DBR allowed for an iterative and collaborative approach, emphasising the dynamic interplay between theory and practice.

3.1. Design

A qualitative research approach was employed to elucidate the practical impact and effectiveness of the developed PD model in teaching spatial ability. The rationale for opting for the qualitative design research approach was rooted in its capacity to describe, explain, report, and establish key concepts, as indicated by Cohen et al. [72]. Qualitative research, as suggested by Bryman [73], relies on the use of words rather than numbers due to the nature of the information acquired, which is predominantly expressed in the form of words and explanations rather than numerical data. The PD model design is derived from the framework proposed by Greitans and Namsone [74], incorporating key characteristics such as consistent input workshops coupled with continuous opportunities to apply the acquired knowledge in classroom settings, followed by analysis and reflection. In addition, it drew inspiration from the cycles of LS outlined by Lewis et al. [58].

3.2. Participants

The study involved the participation of a group of teachers from two different schools located in Latvia. The first school had a total of nine primary school teachers, with three in the 1st grade (N = 3), three in the 2nd grade (N = 3), and three in the 3rd grade (N = 3). The second school featured fifteen primary teachers, distributed as five in the 1st grade (N = 5), five in the 2nd grade (N = 5), and five in the 3rd grade (N = 5). All 24 participants were female, with teaching experience ranging from 4 to 47 years (M = 28.13; SD = 12.22).

3.3. Procedures

The PD programme comprised a series of workshops structured as follows: in the initial workshop, an overview of the research project was presented alongside a lecture on spatial ability, encompassing broad topics and delineating the significance of spatial ability and the associated rationales and methodologies. Over the subsequent month, participants engaged in refining these problems. In the second workshop, these refined problems were collectively discussed during a reflection session, which also included reflection on spatial ability. Each workshop adhered to a structured format consisting of four distinct phases: reflection (effective PD mechanisms: self-monitoring, practical social support, feedback, praise/reinforcement), input (effective PD mechanisms: credible source, revisit prior learning) + modelling (effective PD mechanisms: instruction, modelling, credible source), discussion, and the formulation of learning outcomes (in the form of lesson plans and effective PD mechanisms: action planning, self-monitoring; Figure 1).

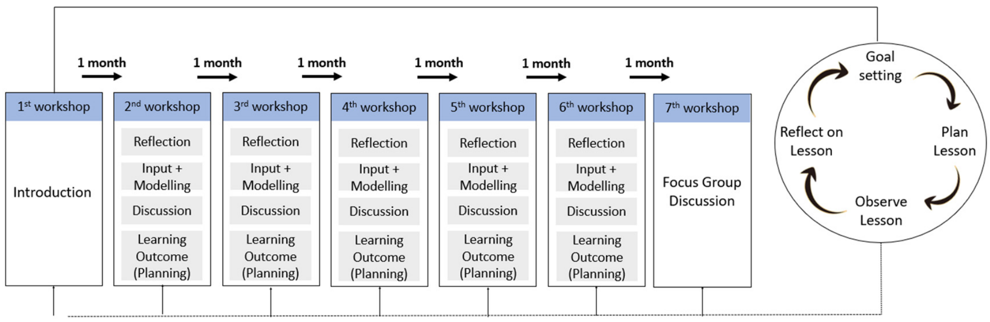


Figure 1. The design of the PD form is based on the framework proposed by Lewis, C.C. [58] and Greitāns, K. [74].

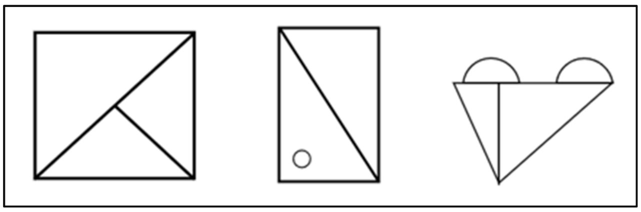
The reflection phase occurred at the beginning of the workshop, and participants elaborated and expressed their views on the triad and group of five. In addition, feedback was obtained from colleagues, as well as insights and recommendations for enhancement. In the input and modelling phase, the PD leader presented content related to the component of spatial ability, which was structured around the four core components outlined by Lowrie, T. [75]. Specifically, the second workshop focused on visualisation, the third focused on mental rotation, the fourth focused on construction and deconstruction, the fifth focused on orientation, and the sixth emphasised the importance of spatial ability in science, particularly in physics. During the modelling phase, the PD leader demonstrated a lesson, taking on the role of the teacher, and the participants acted as pupils. This approach allowed the participants to experience the lesson from the student perspective, thereby gaining a broader understanding of potential improvements and enhancements to the teaching method. Table 1 outlines the modelling task from the second workshop.

Table 1. Description of modelling lesson in second workshop.

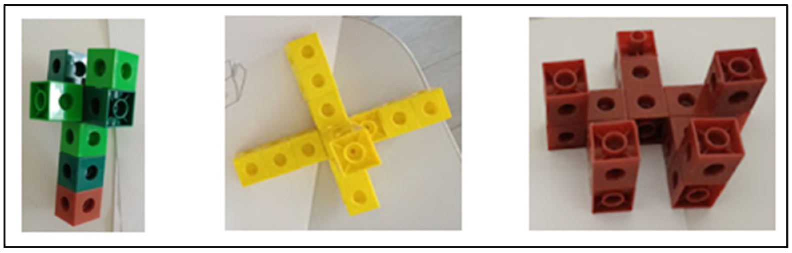
TOPIC: Visualisation of 2D and 3D objects.

Learning Outcome: To build an understanding of how one can visualise 2D and 3D objects.

Learning Activities And Organisation:
Figure-flashing task: The PD leader flashes an image and then asks the teachers to visualise the image in their 'mind's eye'; the leader then asks the teachers to draw it. Afterwards, a short discussion is facilitated regarding the different ways each person tried to remember the images (for making thinking visible).
Repeat with three images:



Three-dimensional object-flashing tasks: The PD leader flashes an object made from multilink cubes and hides it. The teachers try to recreate it with multilink cubes from memory. Afterwards, a short discussion is facilitated regarding the different ways each person completed the task.
Repeated with tree objects:



Describe your object to your friend: The teachers are paired up and sit with their backs together. One of the pair makes an object from the multilink cubes and then tries to describe it so that the other teacher can recreate it. The outcome is compared with the original. Switch roles. Afterwards, a short reflection is centred on the words used in the activity, the difficulties encountered, and the possible benefits of the task for students.
Imagine the figure if you see the shadows: You see the two shadows of an object (side view and back view):

Teachers are asked to carry out the following:

- Make an educated guess—how many cubes will you need to create what you see?
- Why do you think so?
- Create it and check whether you were right!
- Does everybody have the same figures?
- Are there some alternative ways to create a figure with the given shadows?

Create your own object: Teachers are asked to create an object and then draw it (visualise externally) so that others can create the exact object. The difficulties and advantages of the exercise are discussed and student examples of a similar task are explored.

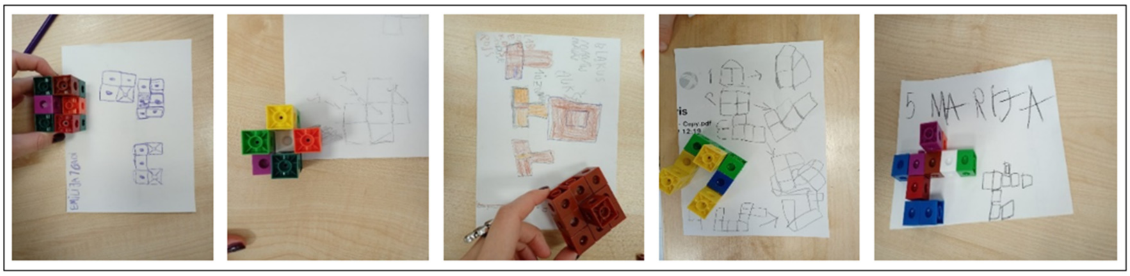


Table 1. *Cont.*

Cross-Curricular Link: Mathematic [76]: - How are figures described and formed? (Grade 1, topic 1.1) - How are figures formed and characterised? (Grade 2, topic 2.6) - How are spatial models created? (Grade 3, topic 3.7) Natural sciences [77]: - How can inanimate objects be studied? (Grade 1, topic 1.3) Design and technologies [78]: - How do you cut, tear, crumple, bend, and connect paper objects? (Grade 1, topic 1.1)

At the end of the modelling phase, a comprehensive discussion was initiated involving all participants. This conversation focused on potential improvements and suggestions, recommendations for future sessions, detailed explanations of the methodologies used, and strategies for better lesson organisation. The dialogue was designed to collect diverse perspectives to refine and enhance the teaching approach to equip teachers with insights and experience to handle various scenarios that they might encounter when designing their lessons. The final phase of the workshop focused on learning outcomes; participants were divided into groups, including triads and groups of five. Together, they specified the learning outcomes for topics in mathematics, science, and technology. The objective was to incorporate and enhance the lesson plans by emphasising the spatial ability insights gained from earlier inputs. This collaborative effort was aimed at integrating these new competencies into teaching strategies, thereby enriching the educational experience with a stronger focus on spatial reasoning. In the context of the IMTP framework, the workshop phase largely adhered to three principles: first, insights about teaching spatial ability were instilled through input and modelling; second, goals for teachers were motivated through reflection and discussions; and third, techniques were fostered through the formulation of lesson plans and reflection. After each workshop, participants in the PD programme engaged in a structured process of LS according to the framework proposed by Lewis et al. [58]. In one school, teachers formed triads comprising three members, whereas in the other school, due to a larger number of teachers, groups of five were formed (as illustrated in Figure 2).

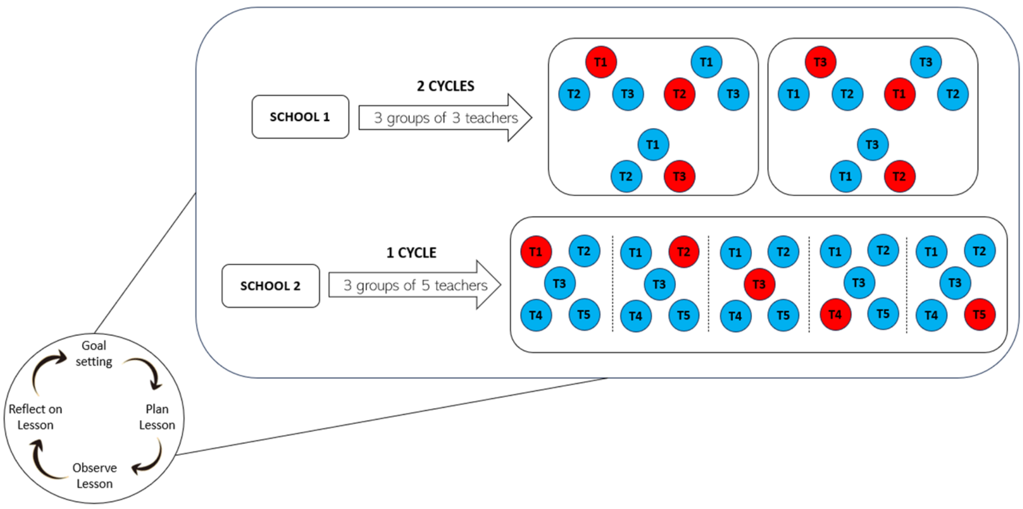


Figure 2. Organisational structure within the LS framework. Note: The "arrow" represents the number of groups and enrolled teachers in each school's group. The color red indicates the teacher's assuming the position of leader, while the color blue represents the other teacher being observant.

The LS framework involves four phases, described in the following:

(a) Goal Setting: Teachers in triads and groups of five created goals and learning objectives for each lesson, aiming to incorporate more spatial skills based on the modelling input obtained during the workshops; (b) Lesson Planning: In this phase, teachers within the triads and groups of five collaborated to create the lesson plan, aiming to include more activities that improve students' spatial skills. The lesson plans were designed to address topics related to mathematics, science, technology, and design; (c) Lesson Observation: This phase involved applying the planned lesson in practice. While one teacher took on the role of the leading teacher in the class, the other two teachers (in a triad) or four teachers (in a group of five) observed the lesson. The role rotation was systematic for each new lesson; (d) Lesson Reflection: In this phase, the teachers discussed the observed lesson from the perspective of the observers. They highlighted necessary improvements, assessed the level of engagement of the students, and evaluated which aspects of the lesson went well and which could be improved.

In the context of the IMTP framework, the LS phase largely adhered to two principles of the IMTP framework: one, teacher techniques were fostered through lesson observation and reflection, and two, implementation of new practices was achieved through lesson planning and rehearsal of planned lessons in a real classroom context.

3.4. Ethical Considerations

In adherence to ethical principles, particular emphasis was placed on obtaining informed consent, ensuring anonymity, and maintaining confidentiality throughout the study [79]. Participants were fully informed about the research process and were provided with detailed explanations regarding their participation. Transparency and respect for participant autonomy were prioritised, and informed consent was obtained, allowing individuals to make informed decisions regarding their involvement in the study.

4. Findings

The findings are discussed in accordance with the dual research questions, namely one examining changes in teachers' gains and beliefs based on specified criteria, and the other focusing on the impact and effectiveness of the devised PD model. The data underlying this discussion were collected through various modalities, such as questionnaires, focus group discussions, lesson plans, artefacts, and classroom observations.

4.1. Assessing Changes in Teacher Gains and Beliefs Using Specific Criteria

Two general questions were posed to the participants in the questionnaire before the intervention, focusing on the concepts of teaching spatial ability and the definition of spatial ability. In response to the question concerning teaching spatial ability, most participants offered generic answers. Some emphasised the need to create situations that prompt students to explain their thinking in depth (T1). Others highlighted the importance of critically evaluating information (T4). One participant (T8) provided a comprehensive perspective, stating that teaching spatial ability involves guiding children to express and justify their thoughts, recognise patterns, explore diverse solution paths, and generate innovative ideas. Another participant (T11) mentioned that teaching spatial ability entails expressing a conclusion, and another (T15) emphasised the incorporation of personal knowledge, examples from experience, and imagination when thinking spatially. Overall, the responses touched on various aspects of spatial ability, but an in-depth and specific understanding seemed to be lacking. To evaluate the progress of the enhancement of the concepts involved in teaching spatial ability through the PD model, a set of criteria (refer to Table 2) was employed to identify any noticeable improvements.

Table 2. Criteria for assessing changes in improvements following PD enrolment.

Criteria	Description	Teacher Response
Depth of understanding	Evidence of a deeper understanding of the various facets of spatial ability, including its theoretical underpinnings, cognitive processes involved, and practical applications.	T1: "I've gained a much deeper understanding of spatial ability, realizing it's not just about imagery but involves complex cognitive processes". T10: "Spatial ability isn't just about pictures and videos; it's about integrating activities like board games and manipulatives, which I hadn't fully appreciated before". T4: "I now see the importance of spatial ability in math and science, especially in areas like numbers and geometry".
Integration into instructional practices	Demonstrated ability to integrate spatial ability concepts into day-to-day teaching practices across different subjects, showing a practical application of the knowledge gained from the workshops.	T2: "I've started incorporating spatial ability concepts into my lessons, making them more engaging and relevant across subjects". T6: "I'm now using spatial ability strategies in my teaching, which has improved student engagement and understanding". T3: "Spatial ability is now a regular part of my instruction, with activities that connect it to real-life situations".
Recognition of multifaceted nature	Acknowledgment and articulation of the multifaceted nature of spatial ability, showcasing an awareness of its diverse components, such as visualisation, problem-solving, and the connection to mathematics and science.	T9: "I've come to recognize the diverse aspects of spatial ability, from visualization to problem-solving, and its connections to math and science". "Spatial skills involves more than just imagination; it's about allowing students to express their thoughts and reach conclusions".
Application beyond traditional approaches	Application of spatial ability beyond traditional methods, with evidence of incorporating innovative and varied instructional strategies, such as hands-on activities, manipulatives, and interactive learning experiences.	T14: "I've been using innovative methods like hands-on activities and manipulatives to teach spatial skills, which has made a significant difference in student learning". T10: "Through interactive learning experiences, I've been able to apply spatial ability in ways that go beyond traditional approaches".
Increased awareness of student learning	Recognition of the impact of spatial ability on student learning outcomes, with examples of improved understanding, engagement, and problem-solving skills observed among students.	T1: "I've noticed a remarkable improvement in student understanding and problem-solving skills since integrating spatial ability into my teaching". T22: "Students are more engaged and motivated, and their problem-solving abilities have significantly improved".
Connection to real-world contexts	Ability to articulate connections between spatial ability and real-world contexts, demonstrating an understanding of how spatial skills are relevant beyond the classroom environment.	T6: "I now see how spatial ability connects to real-life situations like orientation at school and home, which has made it more relevant for students". T3: "Spatial skills are crucial beyond the classroom; they're applicable in various real-world contexts, and I make sure to highlight this to my students".
Adaptation of teaching materials	Adaptation or creation of teaching materials that specifically incorporate spatial ability concepts, showcasing a practical translation of theoretical knowledge into tangible resources for students.	T15: "I've adapted my teaching materials to include spatial concepts, providing students with resources that help them develop these skills". T22: "Creating teaching materials with spatial skills in mind has allowed me to translate theory into practice effectively".
Collaboration and knowledge sharing	Engagement in collaborative activities, discussions, or knowledge-sharing sessions with colleagues, indicates a broader impact of the workshops within the school or educational community.	T2: "Collaborating with colleagues in triads and groups of five has been invaluable; we've exchanged information, refined definitions, and created collaborative activities together". T14: "The knowledge-sharing sessions with colleagues have broadened our understanding and expanded the impact of the workshops within our school community".

By working through the PD model, participants realised newfound insights concerning the importance of spatial ability, recognising its connection to an improved understanding of various subjects and enhanced problem-solving skills (T1, T10, T4). Some teachers expanded their initial views on spatial ability, realising that it goes beyond the use of images and videos and includes activities like board games and manipulative items (T10). Others acknowledged the significance of spatial ability in mathematics and science, particularly in areas like numbers and geometry (T4). The PD programme also contributed to a deeper understanding of the connection between spatial ability and imagination (T22, T15). Teachers recognised the malleability of spatial ability and its potential for improvement through practice (T3). Several stated that spatial ability involves more than just imagination—it includes allowing children to express their thoughts to reach conclusions (T9). Some teachers linked spatial ability to real-life applications, such as orientations at school and home (T3, T6). Furthermore, through the LS, working in groups of triads and groups of five provided participants with additional insights, as they learned from each other through the exchange of information, refinement of definitions, and collaborative activity creation (T2, T3, T9, T14). Moreover, the prompts obtained during the lesson from the teachers created an environmental stimulus that prompted the desired practice. As stated by T10, 'Most of the students started to articulate their thought processes while solving spatial problems'. T7 vividly explained the experience, likening it to students finding a path, talking loudly about it, and others joining in, sparking a dynamic conversation among them. T1 added, 'When I asked my students questions, I observed a positive atmosphere because the student was elaborating on his thoughts and the way he reached that decision'.

4.2. Evidence of IMTP Mechanisms Presence

In terms of Insights (I), two mechanisms were identified. First, the group of teachers focused on a single task during each workshop, such as visualisation, construction/deconstruction, mental rotation, and spatial orientation. Second, supportive inputs were consistently provided to the participants in each workshop to prevent information overload and to emphasise the importance of each piece of information.

In terms of Motivation (M), three proposed mechanisms were discovered. First, the goal-setting process was accomplished when participants, at the beginning of each workshop, set goals for each of the lesson plans. They carried this out through substantial incorporation of spatial ability skills. The second mechanism, the presentation of evidence, was evident in the lesson plans provided by the teachers, where the inclusion of more spatial content was observed in every lesson. The third mechanism, in which the materials were revisited from one workshop to another to prompt recall of essential concepts and recognition of the differences between each component of spatial ability, was also evident.

In terms of Technique (T), two out of the five mechanisms proposed by Darling-Hammond and Richardson [47] and Sims et al. [67] were identified: practical social support and feedback. These two mechanisms were observed in the participants' answers during the focus group discussions.

In terms of Embed in Practice (P), two out of four mechanisms were observed: action planning and prompts/cues. Throughout the classroom observations in the triads or groups of five, participants observed situations that could be changed in practice in the next lesson based on the pupils' reactions and responses. Such evidence was obtained during the focus group discussions; for instance, T6 mentioned that, during the first observation, including some questions for the students made them more engaged in the topic. In addition, T12 stated that, in creating the symmetry lesson plan, their group discussed and considered how to encourage students to reflect on their thought processes and the steps taken to arrive at solutions by using tangram puzzles. Figure 3 illustrates the creation of the LS on symmetry using tangram puzzles.

Figure 3. Teachers constructed lesson plans collaboratively in groups of five (**Left**) or three (**Right**).

Table 3 represents the mechanisms discovered through our designed PD programme compared to those in Sims et al.'s [49].

Table 3. Mechanisms identified using information supported by evidence.

[49] Mechanisms		Mechanisms Identified in Our Study	Evidence
Insights (I)	(a) Managing cognitive load (b) Revisiting material	(a) Managing cognitive load (b) Revisiting material	T1: "I've gained a much deeper understanding of spatial ability, realizing it's not just about imagery but involves complex cognitive processes". T10: "Spatial ability isn't just about pictures and videos; it's about integrating activities like board games and manipulatives, which I hadn't fully appreciated before". T4: "I now see the importance of spatial skills in math and science, especially in areas like numbers and geometry". T9: "I've come to recognize the diverse aspects of spatial ability, from visualization to problem-solving, and its connections to math and science". "Spatial ability involves more than just imagination; it's about allowing students to express their thoughts and reach conclusions". T6: "I now see how spatial ability connects to real-life situations like orientation at school and home, which has made it more relevant for students". T5: "Working with my colleagues in the group of five was very helpful, as each one of us provided insightful ideas on how we can improve and what we did wrong and correct during the lesson".
Motivation (M)	(a) Goal-setting process (b) Presentation of evidence (c) Reinforcement	(a) Goal-setting process (b) Presentation of evidence (c) Reinforcement	T2: "I've started incorporating spatial skills concepts into my lessons, making them more engaging and relevant across subjects". T3: "Spatial ability is now a regular part of my instruction, with activities that connect it to real-life situations". T3: "Spatial skills are crucial beyond the classroom; they're applicable in various real-world contexts, and I make sure to highlight this to my students". T15: "I've adapted my teaching materials to include spatial ability concepts, providing students with resources that help them develop these skills". T22: "Creating teaching materials with spatial skills in mind has allowed me to translate theory into practice effectively".

Table 3. *Cont.*

[49] Mechanisms		Mechanisms Identified in Our Study	Evidence
Technique (T)	(a) Practical social support (b) Modelling (c) Instruction (d) Feedback (e) Rehearsal	(a) Practical social support (d) Feedback	T6: "I'm now using spatial strategies in my teaching, which has improved student engagement and understanding". T14: "I've been using innovative methods like hands-on activities and manipulatives to teach spatial skills, which has made a significant difference in student learning". T10: "Through interactive learning experiences, I've been able to apply spatial ability in ways that go beyond traditional approaches".
Embed in Practice (P)	(a) Action planning (b) Context-specific repetition (c) Prompts/cues (d) Self-monitoring	(a) Action planning (c) Prompts/cues	T2: "Collaborating with colleagues in triads and groups of five has been invaluable; we've exchanged information, refined definitions, and created collaborative activities together". T14: "The knowledge-sharing sessions with colleagues have broadened our understanding and expanded the impact of the workshops within our school community". T6: "The modeling phase of the workshop equipped us with a variety of prompts and cues tailored to different learning styles, enhancing our ability to effectively guide students through complex tasks". T18: "As a result of the PD, we've adopted consistent prompts and cues across our curriculum, creating a more cohesive and supportive learning environment for our students".

5. Discussion

5.1. Theoretical Contributions and Fit with the PD Mechanism

This study introduced a theoretically robust PD model that leverages LS as a means of enhancing spatial ability in primary STEM education. Grounded in the theoretical framework proposed by Sims et al. [49,67], the model effectively aligns with the principles of effective PD mechanisms. According to the findings, the PD framework catalysed meaningful engagement and fostered collaborative learning environments among primary teachers. By focusing on spatial ability—an essential skill in understanding and solving complex problems in STEM—our PD model facilitates a deeper comprehension and integration of these critical skills in teaching practices. Specifically, the PD model's structure supported the Insights (I) mechanism by concentrating workshop activities on enhancing visualisation and spatial orientation skills, critical components in developing students' spatial ability. The Motivation (M) aspect was adeptly addressed through structured goal setting in lesson planning, thus ensuring that teachers were motivated to integrate enhanced spatial tasks into their curricula. Furthermore, by enabling continuous feedback and practical support, the Technique (T) component was well served, highlighting our model's capacity to embed learned skills into everyday teaching practices effectively. Finally, the Embed in Practice (P) mechanisms, such as action planning and the use of prompts/cues, were evident in teachers' classroom applications, suggesting a seamless translation of workshop insights into classroom environments.

5.2. Practical Implications

The practical implications of this PD model are significant for primary education, particularly in terms of the enhancement of teachers' PD activities aimed at boosting students' spatial abilities. The application of this model in real-world educational settings has shown promising results, suggesting that it can be a valuable asset to add to primary teachers' PD repertoire. Not only does the model encourage the adoption of innovative teaching strategies but it also promotes a culture of reflective practice among teachers, as evidenced by the collaborative discussions and feedback mechanisms embedded within the lesson study format. The iterative nature of this design-based research study allowed for continuous improvements to the PD model. Each cycle provided opportunities to refine and enhance the model based on direct feedback and observed classroom implementations.

This adaptability is crucial for sustaining the model's effectiveness and ensuring that it remains responsive to evolving educational needs and challenges.

5.3. Reflection on PD Mechanism

Reflecting on the implementation of the PD model, we notice that integrating the theoretical frameworks with practical, actionable strategies can profoundly impact teaching effectiveness and student outcomes. The model's alignment with Sims et al.'s [49] PD mechanisms not only fortified the theoretical underpinnings but also enhanced its practical efficacy. The teachers' newfound insights and expanded perceptions of spatial ability highlighted the model's impact on enhancing subject understanding and problem-solving skills among students. Moreover, the study's findings underscore the importance of flexibility and responsiveness in PD models. As the educational landscapes evolves, so too must our approaches to teacher development, ensuring that they remain relevant and impactful. By fostering an environment of continuous learning and adaptation, the PD model not only supports current educational needs but also prepares educators and students for future challenges.

5.4. Limitations

While our study offers valuable insights into the use of the LS method for enhancing the teaching of spatial ability in primary STEM education, it is important to acknowledge several limitations that may affect the interpretation and applicability of our findings.

- Sample Size and Diversity: The study's conclusions are drawn from a limited sample size, which may not represent the wider population of primary school teachers. The lack of diversity in our sample in terms of geographical location, teaching experience, and educational background might limit the generalisability of our findings to other settings.
- Duration and Longitudinal Impact: The relatively short duration of the study represents another limitation. As such, it precludes the examination of the long-term effects of the LS method on teacher practices or student performance. Longitudinal studies would be needed to assess the sustainability and lasting impact of PD.
- External Validity and Scalability: Our study focused on a specific method of PD within a controlled environment. Therefore, the results might not hold true in different educational contexts or when scaled up to a broader range of schools or districts.
- Economic and Resource Constraints: Finally, the feasibility of adopting the LS method broadly may be limited by economic and resource constraints within schools. The cost, time, and staff required to implement such an intervention might not be feasible for all schools, particularly in under-resourced areas.

6. Conclusions

The implementation of this PD model provided significant insights into the transformative power of targeted PD initiatives. Teachers participating in the study reported an enhanced understanding and integration of spatial ability into their instructional practices, which are vital for fostering students' comprehension and problem-solving skills in STEM fields. The collaborative nature of the LS approach fostered a reflective and supportive teaching community, enhancing the professional growth of participants, and promoted a culture of continuous improvement and innovation in teaching strategies. Furthermore, the iterative cycles of the design-based research approach employed in this study allowed for ongoing refinement of the PD model, ensuring that it remained responsive to the teachers' needs and educational contexts, and clearly revealed how to improve the PD to have more impact on teaching STEM in the classroom and facilitate greater student gains. This adaptability is a critical feature of effective PD and underscores the model's potential for broader application. By continuing to refine and evaluate such models, educators and researchers can better understand and enhance the mechanisms through which teacher development can positively impact student learning outcomes, particularly in the crucial fields of STEM education. The findings from this study underscore the importance of well-structured and theoretically informed PD programmes that are closely aligned with effective teaching practices. Future investigations are addressed in the next DBR cycle in order to elucidate how to improve the PD programme to have more impact on teaching STEM in the classroom and foster student gains.

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Abbreviations

PD	Professional Development
LS	Lesson Study
T1	Teacher 1
I	Insight
M	Motivation
T	Technique
P	Practice

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