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Mishra, R., Klapwijk, R. M., de Vries, M. J., & Spandaw, J. G. (2025). Storybook driven design for enhancing spatial ability in early childhood: A lesson study approach. *International Journal of Technology and Design Education*, *36*(1), 7-40. https://doi.org/10.1007/s10798-025-09986-x

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International Journal of Technology and Design Education
https://doi.org/10.1007/s10798-025-09986-x

Storybook driven design for enhancing spatial ability in early childhood: a lesson study approach

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Accepted: 17 April 2025
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Abstract
This study investigates the integration of spatial thinking into early childhood education through story-driven design activities and the use of a Lesson Study approach. Conducted in six Irish junior and senior infant classrooms across two schools with ten teachers, this research aimed to address the following research question: How can the Lesson Study approach support early childhood teachers in deepening their knowledge of their pupils, changing teaching practices, and impacting teacher self-efficacy, particularly in relation to spatial reasoning during story-based design activities? Qualitative data from classroom observations and teacher discussions indicate that teachers adapted their lesson strategies based on deeper insights into their students' spatial thinking. They improved the development of spatial design assignments and demonstrated enhanced self-efficacy in conducting spatialized design lessons. Lesson Study dynamics enhance teacher awareness related to design and technology projects, foster creative task identification, and challenge teacher perceptions. Our findings suggest that the Lesson Study processes implemented in this study could motivate teachers to integrate spatial thinking into their classrooms while still adhering to their curriculum. This approach effectively integrates spatial thinking into the curriculum, providing authentic design scenarios for pupils to develop spatial reasoning. These outcomes underscore the potential of Lesson Study for teacher professional development in early childhood spatial and design education.

Keywords Spatial thinking · Teacher professional development · Early-childhood education · Lesson study · Design and technology education

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Introduction

In early childhood classrooms, children engage in various activities that foster spatial thinking, such as constructing towers, navigating mazes, and creating prototypes with toys (Pritulsky et al., 2020; Tian et al., 2023). Spatial thinking plays a critical role in facilitating young learners'achievement in Science, Technology, Engineering, and Mathematics (STEM) fields (Wai et al., 2009, p. 827). Spatial thinking involves understanding the locations, shapes, and relationships of objects, as well as their movement through space (Newcombe, 2010). It relies on spatial abilities such as perceiving spatial properties, recognizing relationships, and mentally visualizing objects (Farran et al., 2024). In this study, we define spatial thinking as the application of these abilities in storybook-driven design tasks facilitated by teachers. Our work examines how educators can actively support children's spatial thinking through intentional teaching practices. This aligns with Pritulsky et al. (2020), who, building on Chatterjee's (2008) Framework of Spatial Thought and Language, offer strategies for integrating spatial language and gestures into everyday activities, as well as providing spatial classroom activities.

Research underscores the significance of early spatial development, highlighting that spatial skills exhibit greater mellablity in younger children (Yang et al., 2020). This highlights the substantial impact of early spatial intervention. Over the past decades, numerous studies have underscored the malleability of spatial thinking abilities, indicating that they can be trained and enhanced through targeted interventions (Cheng & Mix, 2013; Hawes et al., 2017; Lowrie et al., 2017; Sorby, 2009; Uttal et al., 2013).

Storytelling and open-ended spatial task design for young learners

It is crucial to recognize that spatial thinking is not employed in isolation but often in conjunction with content knowledge, necessitating the design of educational interventions in real-world learning tasks (National Research Council, 2006; Newcombe, 2017; Zhu et al., 2023a, b). Design practices inherently involve interdisciplinary knowledge integration and the use of spatial representations, particularly in envisioning and creating solutions to authentic problems (Klapwijk & Stables, 2023; Schon & Wiggins, 1992). However, not all children are motivated by spatial activities like construction. In a qualitative study conducted in two Dutch schools, Sonneveld et al. (2024) observed that some children prefer role-playing and imaginative play with toys, such as small dolls or chairs, rather than construction activities. To engage children with varying play preferences in spatial tasks, integrating design and construction assignments linked to storybooks can be more effective for developing spatial thinking (Kharbanda & Khunyakari, 2025; Sonneveld et al., 2024). The stories provide four essential elements for effective learning of any kind: meaning, context, relevance, and empathy (Haven, 2007). In England, for instance, design and technology lessons have long used stories as a framework for designing and making, with examples such as *The Lighthouse Keeper's Lunch* (Armitage & Armitage, 1977) and resources like *Moving Pictures* and *Winding Up* units for young learners (Qualification and Curriculum Agency, 2000a, b). In addition, researchers at the University of Surrey in the UK[1] and the University of Canberra in Australia[2] have curated a collection of narratives tailored for

[1] https://earlymaths.org/spatial-books/

[2] https://elsaprogram.com.au/wp-content/uploads/2022/02/STEM-Booklist_Publishing-040518.pdf

integrating STEM education, particularly emphasizing spatial skills. Nevertheless, there remains a research gap concerning the application of these narratives in developing design and construction tasks aimed at enhancing children's spatial abilities.

Teachers' professional development through lesson study for spatial thinking

Storytelling is a fundamental part of early childhood education, yet its potential for engaging children in spatialized design tasks remains underexplored (Fleer, 2022). Open-ended design tasks challenge students to explore multiple solutions, encouraging creativity and spatial reasoning while offering valuable insights for teachers (Watkins et al., 2018). However, effectively integrating spatial design tasks into storytelling requires teachers to identify spatialized design challenges within stories, recognize varying levels of spatial thinking among pupils, and adapt their instructional strategies accordingly. To support teachers in this process, professional development (PD) is essential. PD can help teachers learn to frame spatialized design challenges in ways that foster problem-solving, recognize different levels of spatial reasoning, and develop strategies to support diverse learners. However, for PD to be effective, it must go beyond theoretical instruction and provide opportunities for teachers to engage in reflective practice within their own classrooms.

Lesson Study has been shown to deepen teachers'understanding of their pupils (Moss et al., 2015), lead to changes in teaching practices (Dudley, 2013; Vermunt et al., 2019), and enhance teacher self-efficacy (Schipper et al., 2018). Building on this evidence, we designed a PD program in collaboration with a teacher training institute in Ireland to help teachers incorporate spatialized design activities into their storytelling practices. The program included an initial workshop on fostering spatial thinking, followed by two Lesson Study cycles in six classrooms, and concluded with a final meeting where teachers shared their insights.

Study overview and research questions

This study investigates how Lesson Study supports early childhood teachers in implementing story based spatialized design tasks. Specifically, we explore:

1. How can Lesson Study help teachers deepen their understanding of their pupils' spatial thinking?
2. What changes occur in teachers' instructional strategies to better support pupils' spatial reasoning?
3. How do teachers perceive changes in their self-efficacy regarding the implementation of spatialized design activities and STEM instruction?

Ten female in-service teachers (4–15 years of experience) from two Irish schools participated in the study. They taught Junior and Senior Infant classrooms (ages 4–6), with class sizes ranging from 20 to 25 pupils.

To address our research questions, the literature review first presents the rationale for using Lesson Study as a professional development tool. It then introduces the theoretical framework for identifying teachers'learning, structured around three key themes derived from the research questions. Next, we discuss the subject matter knowledge required for early childhood teachers to develop spatial design activities and the essential skills for designing spatialized lesson plans.

Literature review

Lesson study as professional development (PD) strategy

While design and technology education has been implemented in numerous countries globally, focusing on enhancing spatial thinking through open-ended design assignments is a relatively recent development (Sonneveld et al., 2024; Zhu et al., 2023a, b, 2024), underscoring the need for a deeper understanding of effective PD strategies. PD strategies can encompass a variety of methods, including workshops and courses with instructional coaching (Joyce & Showers, 1981, p.170), teacher learning communities(Chow, 2016, p.288), and Lesson Study (Cerbin & Kopp, 2006; Lewis et al., 2006, p.3). Although workshop and course-based PD help educators acquire new knowledge, the transition to applying this knowledge in practice often poses a significant challenge. Instructional coaching, a personalized support system aimed at fostering individual growth for educators, is often hindered by its high cost and the potential lack of peer support, given its predominantly one-on-one nature. Therefore, our focus in this paper is on PD strategies that are especially effective in supporting teachers in integrating new teaching techniques into their everyday practice. International review studies (De Vries et al., 2017; Huang & Shimizu, 2016; Xu & Pedder, 2015) underline Lesson Study's impact on teachers'knowledge, behavior, attitudes, and its influence on student learning. At its core, Lesson Study involves the observation of live classroom lessons by teachers who collect data on teaching and learning and collaboratively analyze the findings to drive instructional improvements (Lewis et al., 2006, p.3; Dudley, 2013). Its collaborative nature fosters sustainable professional growth among teachers, with evidence suggesting significant shifts in teachers'learning patterns (Vermunt et al., 2019).

Lesson Study is characterized by five key principles ('big ideas') (de Vries et al., 2023; Goei et al., 2021): 1) fostering teachers'understanding of pupils, 2) combining personal and external knowledge, 3) examining their own practices, 4) engaging in collaborative discussions, and 5) following a cyclical process for continuous improvement. In Lesson Study's cyclical approach, a particular focus on 'case pupils' (Dudley, 2013), representing certain learner groups based on their ability or other characteristics is present. All Lesson Study phases involve these case students, which might be a promising strategy to teach teachers to identify and support diverse spatial thinking processes present in a classroom. Lesson Study continuously challenges teachers to anticipate their students' responses and design lessons to cater to the needs of different ability or interest groups, ideally guided by a facilitator or'knowledgeable other'(Takahashi & McDougal, 2016). The'knowledgeable other'is an external experts, who may also act as facilitators, introduce new knowledge to the group. The benefits of Lesson Study include enhanced pedagogical content knowledge (Dudley, 2013; Goh & Fang, 2023; Schipper et al., 2017), deeper teacher understanding of students (Moss et al., 2015), improved teacher learning patterns (Vermunt et al., 2019), strengthened professional identity (Vermunt et al., 2019), and increased self-efficacy (Chong & Kong, 2012; Schipper et al., 2018). LS is not without its criticisms. Wiliam (2016) in his book 'Leadership for teacher learning' points that LS is time-consuming and requires significant commitment from teachers and administrators. Adapting LS for small schools and rural settings presents unique challenges but also opportunities for innovation. By tailoring LS processes to meet the specific needs of teachers and students—such as using smaller groups, teacher duos, or online reflection sessions—LS can be made more accessible and practical for educators in these settings.

Thoretical framework of lesson study outcomes

International review studies (Benedict et al., 2021; De Vries et al., 2017; Huang & Shimizu, 2016; Xu & Pedder, 2015) highlight three key outcomes of Lesson Study in teacher learning: (1) a deeper understanding of their pupils, (2) instructional changes to better support children's learning, and (3) an increase in teachers'self-efficacy. These themes align with prior research demonstrating how Lesson Study fosters teacher reflection and adaptation in response to student needs (Lewis et al., 2019). Specifically, Moss et al. (2015) provided a practical example of how adapted Lesson Study can support changes in teaching practices and enhance teachers'understanding of students'spatial thinking. Building on this foundation, our study applies these three themes to analyze teacher learning in early-childhood STEM education, particularly in the context of spatialized design tasks.

The following sections define each theme by reviewing relevant literature, establishing the theoretical basis for identifying evidence of teacher learning in our study.

Defining teachers' learning and change in (mis)understanding of pupils' spatial ability

Teachers'knowledge and beliefs about students encompass various aspects, including their understanding of student learning goals, beliefs about students'abilities, awareness of diverse learning styles, students'funds of knowledge, and processes of understanding (Lee Bae et al., 2016). These perceptions profoundly influence teachers'instructional practices (Bandura, 1993; Fishman et al., 2003; Lumpe et al., 2000; Pajares, 1992; Savasci & Berlin, 2012). It is essential for professional learning opportunities to enable teachers to unearth and articulate their deeply ingrained beliefs about students and critically evaluate the alignment of their practices with evidence of student learning (Lewis et al., 2006; Savasci & Berlin, 2012; Wilson & Berne, 1999). Analysis of teacher discourse over time provides valuable insights into how teachers deepen their knowledge through participation in Lesson Study (Benedict et al., 2021; Murata et al., 2012). Moss et al. (2015) explore the adaptation of Japanese Lesson Study to improve the teaching and learning of geometry and spatial reasoning in early years classrooms. The unit of analysis in this study was the Professional Learning Team (PLT). When data sources were relevant to multiple categories, they were repeated and cross-listed accordingly. The study identified three major changes: (1) altered perceptions of geometry and spatial reasoning, (2) revised views on children's thinking and mathematical development, and (3) modified pedagogical approaches to teaching and learning. The final teacher discussion post-lesson study of the professional development (PD) process was most important in highlighting these key themes, as it involved teachers sharing, discussing, and reflecting on their overall PD experiences. Examination of post-lesson study discussion leads to a nuanced understanding of the changes in teachers'understanding of their pupils.

Defining change in instruction to spatialize the lesson plan

Teacher learning and changes in instruction during Lesson Study involve iterative cycles of experimenting with instructional practices, refining these practices, and testing the effectiveness of different pedagogical strategies against students' learning outcomes (Cobb et al., 1990; Darling-Hammond, 1998; Dudley, 2013; Tripp & Rich, 2011; Wilson & Berne, 1999). This process is not merely an outcome of participating in lesson

study but occurs throughout the different stages of lesson study as teachers investigate, plan research lessons, observe students' learning, and analyze evidence of student growth to improve instruction. Teacher learning and change in lesson study are viewed from a social constructivist perspective, emphasizing cooperative interactions and exchanges of language and tools among teachers to develop new knowledge (Clarke & Hollingsworth, 2002; Vygotsky, 1986). Collaborative discourse during Lesson Study meetings facilitates application of change in instruction codes (Dudley, 2013). Lee Bae et al. (2016) introduces a comprehensive coding tool designed to systematically capture various facets of teacher learning and change within lesson study contexts. The tool encompasses dimensions such as teachers' subject matter and pedagogical content knowledge, their beliefs and attitudes toward students, engagement in professional learning communities, and their use of evidence-based decision-making processes. Additionally, it facilitates the examination and development of curriculum and instructional materials, including the critical analysis, revision, and enactment of such resources.

Defining teachers' increase in their self-efficacy of teaching spatialized design activity and STEM instruction

Teacher self-efficacy, as defined by Bandura (1997, 1986), pertains to individuals' beliefs or convictions regarding their ability to successfully execute tasks and influence outcomes within the educational context. Specifically, it encompasses teachers' perceptions of their capabilities to perform professional tasks, regulate classroom dynamics, engage students effectively, and navigate organizational processes (Friedman and Kass, 2002; Tschannen-Moran and Woolfolk Hoy, 2001). This belief system extends beyond personal competence to encompass social interactions and environmental conditions (Bandura, 1997); thus, it is useful in the Lesson Study context, which is a collaborative and socially shared learning space for teachers. Chen et al. (2021) define STEM self-efficacy beliefs as"the extent to which a teacher feels capable of teaching STEM to preschool children"(p. 138). Teachers with high self-efficacy are more inclined to utilize innovative teaching approaches and adeptly manage diverse classroom settings, even when faced with challenges such as off-task behavior or student disengagement (Zainal and Mohd Matore, 2021). In a lesson study setting, where teachers encounter pupils with varying abilities, their self-efficacy plays a pivotal role in effectively supporting all students. Lesson study provides an opportunity for teachers to engage in observational learning and receive constructive feedback, thereby nurturing their self-efficacy. In summary, an increase in teacher self-efficacy in context of Lesson study provide insights on strengthening of teachers' beliefs in their capacity to positively impact student learning across diverse abilities and navigate the multifaceted demands of teaching integrated STEM subjects within lessons, thereby fostering professional growth and instructional effectiveness.

Lesson Study's effectiveness in developing various aspects of teachers' professional capacity makes it a valuable form of PD for spatialized design assignments. Earlier, Moss et al. (2015) and Hawes et al. (2017) employed Lesson Study to train teachers in spatializing the math curriculum, and this year-long intervention resulted in enhanced spatial thinking in four to seven-year-olds, including improved 2D mental rotation and visual-spatial geometry. Rohaan et al. (2012) emphasize that subject matter knowledge is essential for developing self-efficacy in teachers. They recommend that teacher training should prioritize enhancing subject matter and pedagogical content knowledge, as this boosts

teachers'confidence and positively influences their attitudes towards teaching design and technology education.

Subject matter knowledge for teachers of early-childhood classrooms in developing spatial design activities

Various elements of spatial thinking play essential roles in children's developmental processes both at home and in educational settings. In a meta-analysis focused on early childhood spatial skills training, Yang et al. (2020) highlighted that activities such as hands-on exploration, use of visual aids, incorporation of spatial language, and training in spatial gestures were found to substantially improve spatial abilities in young children. Gilligan-Lee et al. (2023) highlight the potential of spatial activities, particularly those that use physical materials, for improving children's mathematics skills. They found that hands-on embodied (Pallasmaa, 2017) spatial training using physical manipulatives leads to larger, more consistent gains in mathematics and greater depth of spatial processing than non-embodied training. Furthermore, Cartmill et al. (2010) and Kısa et al. (2019) suggested that educators integrate spatial vocabulary and gestures (Ehrlich et al., 2006) into their teaching methods, as these approaches have proven advantageous in cultivating spatial cognition in children aged four to seven years old. Studies have highlighted the significance of construction activities in early childhood classrooms. Uttal et al. (2013) and Hawes et al. (2022) proposed various spatially demanding tasks, such as replicating block structures, crafting number lines through block play, and devising pathways within the classroom. These activities should be purposeful and involve guided play to effectively capture young children's attention (Klapwijk & Rodewijk, 2018). Since spatial thinking skills develop from a young age and throughout childhood (Newcombe & Huttenlocher, 2000), providing children with opportunities to engage in spatial activities within formal, informal, and non-formal learning environments has the potential to enhance their spatial abilities (Newcombe & Stieff, 2012; Newcombe & Frick, 2010).

Our study focuses on story-driven design tasks where children engage with a narrative and solve embedded design challenges. Research suggests that open-ended design tasks, which encourage multiple solutions, are particularly effective in fostering spatial and design thinking (Klapwijk & Stables, 2023). In structured design activities, spatial thinking is crucial for visualizing ideas, iterating on prototypes, and assessing real-world functionality (Julià & Antolì, 2018; Zhu et al., 2024). However, many early childhood educators are unfamiliar with such open-ended spatialized design tasks, necessitating professional development to equip them with the necessary pedagogical strategies.For topics unfamiliar to participants, introductory workshops (see Sect. 3.2.2) are often used in Lesson Study PDs to convey new pedagogical content knowledge before teachers begin lesson planning (Benedict et al., 2021; de Vries et al., 2023).

Methodology

This section outlines the context, including adaptations made to the Lesson Study structure. It details the introductory workshop setup, which incorporated five spatial tools to foster spatial thinking and support teachers in creating spatialized lesson plans for story-based design. Lesson Study is then used to guide teachers in developing, implementing, and refining these lesson plans through peer collaboration and focused observation of case pupils.

Context: spatial thinking in Irish early childhood curriculum (Aistear)

In order to design a PD trajectory, it is essential that it matches the context and curriculum (Van den Akker et al., 2006). This study builds on the integration of spatial thinking into the Irish curriculum, presenting a unique opportunity to utilize the existing foundations provided by the curriculum. In Ireland, Aistear serves as the curriculum framework (2009) for children aged from birth to six years old. Key points related to spatial thinking and exploration are outlined in the framework under"exploring and thinking"(Page 43). Although the term"spatial thinking"is part of the curriculum, its presence does not guarantee a focus on the spatial element in the classroom.

Adapted lesson study structure for integrating spatial thinking in curriculum

Kager et al. (2023) propose a conceptual model of continuous professional development (PD) through Lesson Study, outlining key outcomes at multiple levels. The initial level involves teachers'satisfaction and acceptance of PD, followed by enhancement in knowledge, beliefs, and attitudes (level two). Subsequent stages include changes in teaching practice (level three), organizational changes (level four), and finally, sustained enhanced student performance. Our study's Lesson Study structure aligns with these outcomes, incorporating a preparation phase, implementation phase, and retrospective evaluation, as recommended by Kock et al. (2015).

The Adapted Lesson Study structure followed eight key steps, described below and summarized in Table 1:

Step 1: Work-Shadowing to Understand Current Practices
The first author observed classroom practices to understand how teachers were already using storytelling, spatial language, and gestures. For instance, in a junior infant classroom, a teacher used directional cues when teaching letters, such as"around up, down and tick"for 'a' and"down from the top, up and around"for 'b'. This highlighted that spatial language and gestures were already embedded in existing pedagogical content knowledge. Similarly, teachers were familiar with storytelling and hands-on construction materials, providing a strong foundation for integrating spatial design tasks.
Step 2: Workshop on Spatial Thinking in Early Childhood Education
A 1.5-h foundational workshop introduced teachers to spatial thinking in Science, Technology, Engineering, Art, and Math (STEAM), incorporating hands-on design and construction activities. The workshop built on research from Pritulsky et al. (2020), who, drawing from Chatterjee's (2008) Framework of Spatial Thought and Language, emphasized spatial language and gestures in classroom activities. Additionally, Cross (2006) identified gestures, conversations, drawings, and models as the"language of design".
The workshop covered five spatial tools to enhance early childhood spatial thinking:

1. Utilization of spatial language
2. Incorporation of gestures
3. Integration of manipulatives using a"think then do!"approach to encourage cognitive engagement
4. Implementation of story-based design tasks utilizing construction toys
5. Adoption of the Lesson Study approach to evaluate students' spatial learning

Table 1 The Lesson Study structure for each classroom (Table 1) adapted from Dudley (2013)

Steps of PD	Key activities	PD Conceptual model (Kager et al., 2023)	Outcomes
1	Work shadowing by first author to know the current practices in classrooms	Input	Understanding baseline practices
2	Workshop on fostering spatial thinking	Input	Teachers'acceptance of PD
3	Collaborative lesson planning and selection of case pupils	Emergent stage	Developing spatial tasks
4	First Lesson Study Cycle – implementing the research lesson (includes pupil observation and interviews)	Mediating mechanism	Gathering data on teaching practices
5	Post-lesson discussion with facilitator	Collective and individual development stage	Reflecting on teaching practices
6	Second Lesson Study Cycle – implementing the adapted lesson	Collective and individual development stage	Improved lesson plan implementation
7	Second post-lesson discussion	Emergent stage of shared cognition	Reflecting on teaching practices
8	Final meeting of 10 participants – sharing Lesson Study insights	Collective feedback and knowledge sharing	Proposing changes in school structures for LS implementation

To support teachers, the Spatial Reasoning Toolkit from the Early Childhood Mathematics Group (ECMG) was introduced (Gifford et al., 2022). This toolkit provided posters, videos, guidance materials, and a learning trajectory from birth to age seven, focusing on key spatial reasoning skills: Movement and navigation, Shape properties and Shape composition and construction.

Step 3: Collaborative lesson planning and selection of case pupils
Following the workshop, teachers participated in a 1-h collaborative lesson design session (See 3.5 for more details). Teachers planned their research lessons and identified three case pupils based on their observed spatial abilities. These case students were chosen based on the teachers'professional judgment of pupils' spatial abilities.
Step 4: First Lesson Study Cycle – Implementing the lesson and Observing the case pupils
Teachers implemented their lesson plans in both junior and senior infant classrooms, working in pairs—one teacher led the lesson while the other observed designated pupils. Observation sheets (Appendix A), adapted from Dudley et al. (2013), guided teachers in recording children's use of spatial language, gestures, and engagement in design tasks. This observation sheet was adapted to focus on spatial tools. The observation sheet included five tools aimed at fostering spatial thinking in the early childhood classroom, derived from the workshop, enabling teachers to observe students'use of spatial language, gestures, and progress in design tasks. To gain deeper insights, teachers conducted short interviews with the case pupils during the activity (Fig. 1). This real-time assessment helped address the challenge that young learners often struggle to recall and articulate their experiences after a lesson.



Fig. 1 Observing teacher interviewing case pupil during the testing of design

Step 5: Post-Lesson Discussion and Reflection
After the lesson, teachers engaged in a 30-min facilitated discussion. This session allowed teachers to analyze classroom observations, compare insights across junior and senior infant classes, and refine their understanding of how pupils engaged with spatial tasks.
Step 6: Second Lesson Study Cycle – Adapting and Re-Implementing the Lesson
Using feedback from Step 5, teachers modified their lesson plans and conducted a second implementation. This allowed them to test adapted strategies and assess improvements in pupil engagement and spatial task performance.
Step 7: Second Post-Lesson Discussion
Following the second lesson, teachers held another reflective discussion to evaluate changes made, discuss observed improvements, and refine strategies for future lessons.
Step 8: Final Cross-Team Reflection and Knowledge Sharing
The program concluded with a 1-h online reflection session involving all ten teachers. Following Dudley & Vrikki (2019) the meeting was focused on analysing how the lesson enabled pupils to learn and how future teaching or research lessons should benefit from reporting of learning (Dudley & Vrikki, 2019) which is an essential part of lesson study cycle. As small rural schools often have fewer participants, this cross-team discussion provided an opportunity for schools to exchange insights without requiring in-person visits. In the absence of public research lessons, Dudley (2013) suggests using final reports, posters, or group discussions to document learning outcomes and ensure sustainable instructional improvements.

This approach ensures that the PD model is comprehensive, addressing essential aspects of teacher development and improving educational practices in a meaningful and sustainable way.

Research design

We employed a design-based research (DBR) approach (Van den Akker et al., 2006) combined with a case study methodology to gain in-depth knowledge of the Lesson Study approach.The Lesson Study approach developed in this research, detailed in Sect."Adapted lesson study structure for integrating spatial thinking in curriculum", was inspired by two pilot projects: one involving international pre-service students in the Netherlands working on story-based design assignments and another with pre-service students focusing on spatializing inquiry corners. We followed the approach described by Gravemeijer and Cobb (2006), which consists of a sequence of a preparation phase, an experimental phase, and a retrospective evaluation, to develop the Lesson Study approach for the Irish teachers in this study. During the preparation stage, information from literature and Irish educational practice was collected. A key element in design research is the creation of an educational innovation that considers the complexity of the context. In our case, with the assistance of the training institute, we studied the Irish context and visited schools and classrooms to inform and inspire the Lesson Study design presented in Sect."Adapted lesson study structure for integrating spatial thinking in curriculum".

Participants and school context

Participants

The study involved ten female in-service teachers with 4–15 years of experience, teaching Junior and Senior Infant classrooms (ages 4–6) in two Irish schools. Class sizes ranged from 20 to 25 pupils. Participants were recruited with the assistance of a teacher training institute in Ireland. Out of five schools invited, two schools chose to participate in the study.

School context

School A: A small school where only two teachers formed a Lesson Study group along with the facilitator (first author).

School B: Teachers worked in pairs, attending the spatial thinking workshop together before implementing Lesson Study cycles.

During the final post-lesson discussion, all ten teachers participated in an online reflection session to share insights.

Lesson study implementation

In each classroom, teachers worked in pairs, collaboratively developing spatialized lesson plans. The study presents findings from six classrooms involving ten participant teachers.

Ethical considerations

Ethical approval was obtained from the Human Research Ethics Committee, TU Delft, The Netherlands. Informed consent was secured from all participants before data collection.

Spatialized lesson plan created by teachers using story-based design assignments

Teachers in group chose a story and Identify a target group (character of story) and problem from a story. For example: In a story, a kite is stuck on a tree and Floyd (the character) wants to get his kite back.This is the moment in story where pupil can be given a design task to make or build something which helps Floyd to get the kite back. Make sure the design challenge is:Open to multiple solutions, Positive in its formulation and Relevance is important for young pupil, Short and as clear as possible (Klapwijk et al., 2024, p.40). Each research lesson began with the teacher narrating a story with attention to spatial language and using gestures. Next, pupils were tasked with creating a design to solve a problem in a story, beginning with sketching out their ideas and then building their design with materials. In each classroom, teachers selected stories during step 3 (Table 1) of the PD for creating their lesson plans. During the workshop, teachers were given a list of stories that focused on spatial language; however, they were free to choose the stories that fit well with their curriculum and catered to their pupils' spatial thinking development needs. Table 2 below shows the stories and the design tasks designed by teacher-duo and given to pupils in each of the six classrooms. These teachers worked in pairs, with one observing the case pupils and how they reacted to the activities during the research lesson (Table 1).

Table 2 Story selection and design tasks given to pupils by the teacher duo in each classroom

School A		School B			
Classroom 1 (Senior infants)	Classroom 2 (Junior Infants)	Classroom 3 (Junior Infants)	Classroom 4 (Senior infants)	Classroom 5 (Junior Infants)	Classroom 6 (Senior infants)
Ms Cassidy Ms Nelly	Ms Nelly Ms Cassidy	Ms Aine Ms Michelle	Ms Jane Ms Rose	Ms Mary Ms Lisa	Ms Katherine Ms Grainne
Selection of story: We're Going on a Bear Hunt by Michael Rosen **Design task for pupil:** Construct a bear trap using manipulatives **Spatial Elements:** Direction and descriptive language (e.g., big, deep, thick)	**Selection of story:** We're Going on a Bear Hunt by Michael Rosen **Design task for pupil:** Construct a bear trap using manipulatives **Spatial Elements:** Direction and descriptive language (e.g., big, deep, thick)	**Selection of story**: Stuck by Oliver Jeffers **Design task for pupil:** Design a solution to assist Floyd in retrieving his stuck kite from the tree **Spatial Elements:** Understanding height, depth, and object manipulation	**Selection of story**: We're Going on a Bear Hunt by Michael Rosen **Design task for pupil**: Create a design to navigate across the mud and river without soiling or wetting their feet **Spatial Elements:** Navigating through different terrains (over, under, through), perspective-taking and physical exploration	**Selection of story:** Room On The Broom by Julia Donaldson **Design task for pupil:** construct a broom long and strong enough to carry all animal and the witch **Spatial Elements:** Length, weight, balance, and stability, weight distribution, and the properties of different shapes	**Selection of story**: Goldilocks and the Three Bears; by Robert Southey **Design task for pupil:** design a preventive solution to secure the house so Goldilocks can't get inside the house **Spatial Elements:** concept of closure spaces, barriers, and spatial planning including perspective-taking, and navigation

Data collection

Data collection occurred during both the facilitated teacher meetings and in classrooms. All teacher meetings and the workshop were audio-recorded as video recording was not allowed from participating school. Discussion on lesson plans and adaptations after the post-lesson discussion were collected. The first author and the teachers observed the case pupils in classrooms and took photos of the intermediate and final designs by the pupils. The first author transcribed the audio data from all sessions. Pupil A, Pupil B, and Pupil C are three case pupils chosen by classroom teachers, each representing – an expert, developing, and beginner in spatial skills. In identifying the case children as experts, developing, or beginners in spatial skills, teachers relied primarily on teachers' professional judgment. Teachers'experiences and beliefs informed this process about their pupils and their understanding of what defines spatial design capabilities.

Data analysis

In selecting the focus themes for this study, we aimed to address crucial aspects of teacher professional development identified in the Lesson Study literature, specifically teachers deepening their knowledge of their pupils, changes in teaching practices and instruction, and teachers' self-efficacy. These themes were chosen based on frameworks by Lee Bae et al. (2016) and Moss et al. (2015). To analyze the data, we employed Clarke and Braun's (2013) thematic analysis, which defines a theme as "a coherent and meaningful pattern in the data relevant to the research question" (Clarke & Braun, 2013, p. 121). The first author identified relevant episodes that aligned with the three predefined themes. Out of the identified episodes, both authors coded them independently. Through multiple rounds of discussion, the authors refined and named the themes to ensure they accurately captured meaningful patterns in the data and engaged in discussions on the analysis. To enhance reliability, a researcher external to the study independently coded the episodes, with only two discrepancies emerging. Upon discussion, it became evident that these two themes—teachers knowing their pupils and changes in instruction—were closely intertwined in one episode, illustrating how understanding pupils influenced instructional adjustments. This thematic analysis approach provided a structured yet flexible framework to examine how teachers applied their learning in practice.

Findings

Below, we present representative episodes from data that illustrate teacher learning in alignment with the three key themes guiding our analysis, as detailed in the literature review and directly addressing our research questions. First, we examine teachers' learning and changes in (mis)understanding of pupils' spatial abilities, highlighting shifts in their perceptions based on classroom observations and reflections. Second, we explore changes in teaching instruction to support pupils' spatial reasoning, demonstrating how teachers adapted their strategies based on their evolving understanding of pupils'needs. Finally, we discuss teachers' perceived increase in self-efficacy in teaching spatialized design activities and STEM instruction, focusing on how participation in the Lesson Study process influenced their confidence and instructional approaches.

Teachers' change in understanding and misunderstanding of pupils' spatial ability

In the subsequent post-lesson discussion below, the teachers discussed the challenge faced by the pupil, who was perceived as expert spatial ability by the teacher in classroom 3.

Episode 1:

Ms Michelle*: Going to the three children that we picked, the most abled child; we thought that she would be much more of a planner and organizer and knowing what she was doing, but she was totally lost. She had no plan she couldn't fix on anything. She was unable to adapt materials. I was with her for a while, and she had a straw and the problem she struggled that it was too bendy. We had a long discussion on what would be better, and she needed something more rigid/stronger. We found a lollipop stick. She wasn't happy as it wasn't long enough. I gave her the idea of taping them together like I tried to get her to do but she couldn't adapt it.*

Ms Aine*: She's capable in all the other areas but maybe not spatially.*

Ms Michelle*: (she) was very lost in this one*

Ms Aine*: She kind of taught us a lot about her that she does find maybe that whole area of spatial thinking quite difficult so while she has strength in other areas of the curriculum maybe that's an area that we do need to help her develop actually. So, it's good, it's good for me to know.*

Ms Michelle reflects on the challenges encountered by one of the case pupils, initially perceived as an expert pupil. Despite expectations of strong planning and organizational skills, the pupil struggled significantly during the design activity. Ms Michelle recounts the pupil's difficulty in adapting materials, exemplified by her struggle with a bendy straw. Through discussion and experimentation, they attempted to find a suitable alternative, ultimately settling on a lollipop stick to get the rigidity wanted by the pupil. However, the pupil still faced difficulties in adapting the solution to her needs, indicating a challenge with spatial thinking to Ms Michelle. Ms Aine acknowledges this observation, recognizing that while the child may excel in other areas of the curriculum, spatial thinking appears to be a developmental area. Here the teachers do not explore enough what has caused the difficulty that pupil faced; it could have been use of material and underdeveloped motor skills instead of spatial thinking. However, this insight prompts a realization of the need for targeted support in this domain, emphasizing the importance of identifying and addressing individual learning needs. The exchange underscores the value of post-lesson discussion in revealing insights into pupils' strengths and challenges, guiding teachers in tailoring instructional approaches to better support pupils' learning.

Post-lesson discussion after a second lesson in classroom 3, below sheds light on the gender dynamics observed in the classroom by teachers, particularly in relation to expert pupils'interests, abilities, and opportunities for engagement in design activities. Ms Michelle expresses regret over her previous assessment of the case pupil as the expert based solely on academic performance, overlooking the influence of gendered socialization on the pupil's interests and skills.

Episode 2:

Ms Michelle: Something that is terrible to say but I definitely noticed it last week we picked a girl as our top girl because she's academically brillent and has a very good language and ability. She'd be a great child to have as the top child but reflecting back on it, I think she is the oldest girl of two girls in her house and that there are no construction toys or anything like that; and that gender imbalance that you hear is

aloud and alive that she is used to only playing with dolls and with toy houses. She couldn't build and make.
Ms Aine: With her partner, he was always going to make an elephant because he loves elephant and straight away they were making an elephant. She couldn't in any way say what about something else you know maybe we could try a different design. I watched the two of them interact and they were making an elephant and that was it. You know she very easily got talked into making an elephant and at the end she decided maybe a rocket would be better.
Ms Michelle: I'd like to have seen if she could have made it though, because I don't think she could. She's not very good at the Lego pieces
Ms Aine: I also think she didn't have time today. I wonder if she worked on her own?
Ms Michelle: last time she worked her own and she made the butterfly because it was a butterfly shape.
Ms Aine: OK yeah (smiled)

At the start of the conversation, Ms Michelle reflects on the girl's struggle with construction tasks, attributing it to a lack of exposure to such activities at home, where gendered norms might influence the types of toys available. This observation prompts a critical look at how home environments and societal expectations shape pupils' skills and interests. Ms Aine points out the influence of gender expectations on the girl's design choices, noting her tendency to follow her partner's preferences without asserting her own ideas. This interaction illustrates how gender stereotypes can subtly impact children's engagement in activities, potentially limiting their creativity and confidence in exploring alternative designs. The conversation underscores the importance of recognizing and addressing implicit biases in educational settings. Ms Michelle doubts about the girl's ability to construct with Lego pieces; however, Ms Aine's acknowledgement of the girl's independent engagement in a previous design task suggests that with appropriate support and opportunities, the pupil could demonstrate her capabilities. Ms Michelle's disagreement, pointing to the girl's previous design (second last sentence), provided evidence to Ms Aine about the struggle of this specific case pupil. In summary, the dialogue between the teachers highlights the complex interplay of gender, socialization, and educational practices. It suggests that addressing these issues requires a conscious effort to provide diverse resources and opportunities, allowing all students to explore and develop their skills without the constraints of gender stereotypes. The Lesson Study process, with its focus on case pupils, created space for this critical reflection, which might have gone unnoticed without this structured approach. This highlights the importance of Lesson Study in uncovering and addressing subtle yet significant issues in educational practice.

In Classroom 6, where Ms Katherine and Ms Grainne teach, the discussion of teacher beliefs regarding the grouping of pupils emerged during the post-lesson analysis of the first lesson plan. They observed that Pupil A, who is perceived as having high ability in the class, did not engage as much as anticipated during the construction activity. Ms Grainne noted minimal interaction between Pupil A and his partner, suggesting that a different pairing might have led to more active participation. Ms Katherine pointed out that if Pupil A had been paired with another boy, the results might have been different.

Episode 3:

Ms Katherine: I thought Pupil A (expert pupil) might have got more into it.
Ms Katherine: He actually would have preferred to finish his sketch I kind of nearly needed to take the sketch from him and say, 'ok we're going to start now' and I thought he might have got more interested.

Ms Katherine: He's the top boy.
Ms Grainne: It was very little conversation between him and his partner. I wonder if it was a different partner.
Ms Katherine: He sits with other boys and they do their own things. I wonder, if it was the two boys together it could have been something completely different.

The above discussion of teachers highlights the influence of peer dynamics in the classroom and teacher perceptions on pupil engagement and collaboration in group activities in the context of spatial task and design activity.

For classroom 6 during step 7 of Table 1, teachers discussed in more details about their expert ability pupil. They discussed details of pupils behavior and approach to the given task (Fig. 2).

Episode 4:

Ms Katherine: yeah now that the higher boy his sketch was beautiful but he was really lucky because in one of the in one of the boxes towards the already made airplane so he didn't make the plane
Ms Grainne: no and I was kind of a disappointed because he was finished so soon but that's that was all. He didn't had any interest in making going further with it and then he was like well this is Goldilocks and she's got a parachute but he didn't think of making the parachute he was like well it's going to come out of her helmet you know, it was all in his imagination. He didn't actually think of
Ms Katherine: of I could do more here…
Ms Grainne: yeah, to do more here. He would just nearly wanted to play with the adding things onto the airplane but wasn't adding (to his design)
Ms Katherine: It would have been more interesting if he had to actually use Lego to make an airplane. There was one little girl who made a helicopter didn't look like a helicopter but she said it was a helicopter so it was a helicopter that had a balcony where she could stand and look out so yeah that's our helicopter.
Ms Grainne: So, if we were to do it again we might remove the airplane (from the LEGO box)
Ms Katherine: Yeah I'm surprised because he's very into creation you know he's into LEGOs. I'm surprised that he did take the easy option.

Ms Katherine initially noted the quality of the sketch made by the pupil but highlighted an element of luck involved due to finding a pre-made aeroplane in a Lego box. This observation suggests that while the end result may seem impressive, there's a question of

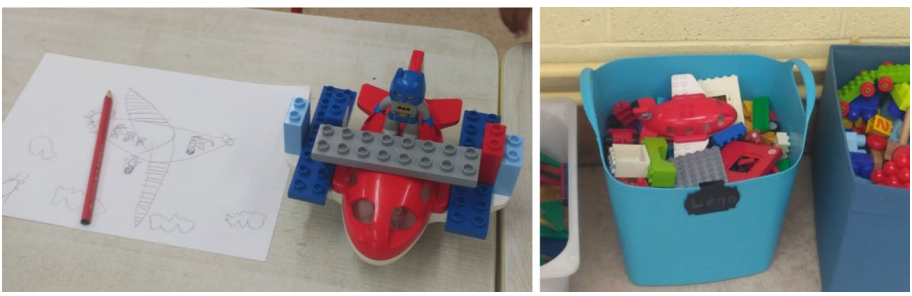

Fig. 2 Case pupil's use of readymade airplane from the LEGO box for completing his design

genuine effort and creativity. Ms Grainne expresses disappointment in the pupil's lack of further engagement with the task. Despite completing it quickly, there's a sense that he didn't fully invest himself in the process. She mentions his reliance on imagination without translating it into tangible effort, such as the absence of a parachute in his design. Ms Katherine used other case pupils' example to show that it would have been better if this pupil have made the airplane. Ms Grainne suggest to remove the plane from the LEGO box for the next session so pupil can use their design skills. In summary, the teachers'discussion reflects a critical assessment of the student's behavior and the underlying factors contributing to it. They highlight issues of effort, engagement, and follow-through, indicating a deeper understanding of the pupil's approach to tasks and areas for potential growth.

Episode 5: In classroom 4 post-second lesson discusison, Ms Jane and Ms Rose discuss the significant progress of their pupils, focusing on Pupil C (perceived low spatial ability pupil).

Ms Jane: and I even found that with my student C you know with the blocks and the boat. Because originally I said that what he is going to make is it like a mommy and a daddy? Do you know what I mean? But then next thing he was building a boat, that's like Oh my God he's really come on (a long way)
Ms Rose: and even his language from last week.. like he was you know using a lot of the language while last week he wasn't.
Ms Jane: I really do think they (pupils in general) improved hugely since the last time
Ms Rose: they seemed more focused I was so delighted with my Pupil C that he built something on his own like last time he didn't open his mouth at all so even to speak
Ms Jane: that was shocking
Ms Rose: and his language,
Ms Jane: his language was brilliant

Initially, teacher expected traditional pretend-play, but Pupil C's construction of a boat surprised both. Ms Rose also highlights Pupil C's improved language skills from the previous week, showing learning in the use of language provided by the design task. Ms Jane notes the general improvement, while Ms Rose is particularly pleased with Pupil C's newfound confidence and participation in construction/design tasks. This discussion underscores their deepening understanding of the pupils'capabilities and the positive impact of providing tools and resources that foster spatial thinking and development through design tasks.

In addition to the representative examples above, we provide below an overview of teachers' change in understanding (and misunderstanding) of pupils' spatial ability in different classrooms. Based on all episodes, the following changes in teachers' understanding of their pupils' spatial abilities were observed.

Classroom 1 and 2: Teachers were surprised by the lower ability pupils' detailed designs in senior infant classroom. Interviewing the case pupil during the desing process helped the observing teacher in understanding the detailed design made by the pupil. Teachers also learned more about lower spatial ability pupils, who remained on task and fostered their imagination through the design task related to the story. One teacher noted,"just that he had an interest in the topic and then he used his imagination and that kept him on task."The Lesson Study process, including predictions, observations, interviews, and reflections, deepened teachers'knowledge of pupils'capabilities during spatialized design assignments.
Classroom 3:

Teachers changed their perception of different levels of spatial thinking present in the classroom. They recognized the importance of allowing young learners to create multiple designs, as they are not likely to prototype at this age. This approach helps pupils use a variety of language and spatial transformations, which is beneficial for their development. Teachers found the intervention fitting for early childhood settings and supported its regular implementation.

Classroom 4:

Teachers initially thought pupils might copy each other's designs, but this was not the case, leading to a clarified understanding. They also changed their conception that boys are better at spatial thinking than girls, learning that gender stereotypes can impact children's engagement and creativity. Teacher post-lesson discussions led to exploration of the complex interplay of gender, socialization, and educational practices.

Classroom 5:

Teachers gained insight into expert spatial ability pupil's 'engineering mind'. Teachers noted his struggle to collaborate and atributed it to his independent play with Legos at home. However, when his design didn't work, he persevered. In this class, the teacher also observed that the pupils who could not complete there design failed to use spatial language and gestures to showcase their spatial thinking. Thus, teachers learn the importance of sharing designs made by pupils at the end of the session to improve the use of spatial language and gestures in the classroom.

Classroom 6:

Teachers learned that the arrangement of groups, such as pupils who know each other together could help in improving the use of spatial language. Teachers also observed that for expert spatial ability, pupils finding a readymade design from the lego box led to design fixation, hindering improvement. They critically examined their assumptions and expectations regarding pupils'abilities and interests as discussed in episode 2 and 4.

Change in instruction to support pupils' spatial reasoning

Below, we provide a number of representative episodes that show how teachers changed their instructions. In the post lesson discussion below teachers discussed the challenge of visualisation their pupils faced during the first lesson implementation and suggested change in presenting the design problem using 3D model of a tree. Conversation below highlights the design considerations and scaffolding teachers are discussing for pupils' development of spatial understanding and design skills effectively.

Episode 6: (Classroom 3)

Ms Michelle: You know, what they (pupils) we're lacking? In my head they were lacking the tree, the perspective of a tree. The tree was flat on the ground (sketch of tree on A3 paper) and that's fine but the perspective of what you make is actually going to raise me (was Missing)

Ms Aine: So, I think the next time we need a tree

Ms Michelle: like something at a hight and they need to really work and not just use the magic wand (smiling)

Ms Aine: and to test it

Ms Michelle: yes

Ms Michelle identifies a key gap in the students'understanding from the session: the lack of perspective of height while creating design to get the kite from the tree. She observes that while the students can depict a tree on a flat surface, they struggle to grasp the perspective of how the tree would appear in a three-dimensional space (sentence 1). Ms Aine agrees with this assessment, indicating the need to incorporate activities that encourage students to consider perspective in their designs (sentence 2). Ms Michelle emphasizes the importance of providing opportunities for students to actively engage in constructing their designs rather than relying on shortcuts like a"magic wand"(sentence 4). Teachers then took the 3D model of the tree (Fig. 1) and test it with pupils in the next lesson. After the lesson study cycle completion, Ms Aine explained how the 3D model of a tree helped in testing design ideas for pupils by giving an example during the lesson study discussion (Step 8 of PD) (Fig. 3).

Episode 7:

Ms Aine: On the second day decided that we'd actually have a 3D life model of a tree so that they would come and like test to see if they're creation worked. Here in the last picture she created a dinosaur but when she came over to the tree she couldn't figure out how it would actually help Floyd to get his kite down from the tree. So I said does that work? and she was like no that's rubbish. But she was able to kind of use; she could see for herself very clearly when there was a 3D life model (of tree). These children I think especially that young, they need that kind of something very realistic for them to to see if it's a good design or not.

Ms Aine's comment underscores the importance of providing tangible, realistic models to support young pupils in understanding spatial concepts and evaluating their designs effectively. She highlights how the 3D life model of a tree enabled students to grasp the practicality of their designs, as evidenced by one student's realization that her design wouldn't effectively retrieve a kite stuck in the tree. This emphasizes the necessity for hands-on, experiential learning experiences that allow pupils to visualize and test their designs in a realistic context. By incorporating such models, teachers can scaffold



Fig. 3 First lesson teachers used sketch of tree (left side) to show problem while in second lesson they used 3D model of tree (right side) with a small sized character

students'spatial understanding and encourage critical thinking in design processes, aligning with the broader goal of enhancing students'spatial skills development.

Ms Aine also explained a pedagogical strategy that both teachers used to enhance pupils'engagement. They combined empathy in a storytelling-based design task with 'role play' to improve pupils' engagement.

Episode 8:

Ms Aine: We decided on the second day that they (pupils) would become inventors that we gave them a title for their roles. In the first lesson we were hoping they'd be more empathetic that they would be saying poor Floyd' kite suck in this tree but actually they forgot about that when they saw the materials, they didn't really care about Floyd anymore. But then on the second day we said right they need a role. They need to kind of become inventors. It's kind of all about them as they are 5 years old. They were really excited that they were going to be adventurous and invent something that would help Floyd"

Ms Aine reflects on the initial approach on day one, where pupils were expected to empathize with a character named Floyd, whose kite was stuck in a tree. However, she observed that the students'empathy diminished when they were presented with materials for the task. To address this, Ms Aine and Ms Michelle decided to incorporate role-play by assigning pupils the role of inventors. This shift in approach aimed to personalize the task for pupils, making it more relevant and engaging. By assuming the role of inventors, pupils were encouraged to think creatively and were motivated by the prospect of solving a problem and helping Floyd. This strategy highlights the importance of integrating storytelling and role-play to foster empathy and active engagement in young learners.

Change in instruction to support case pupils in their design activity: During teachers' post lesson discussion in classroom 3 (episode 9), one structured approach to design instruction emerged from the teachers'discussion on their initial teaching practices. They observed that on the first Lesson Study cycle, students freely created designs without adhering to their initial sketches. For example, during the sketching process, a pupil might sketch a helicopter, but while designing, he/she changed the idea completely and starts making something totally different. Recognizing the need for more focused guidance, the teachers implemented a change for the second day and chose the method of scribing. Through scribing they instructed students to adhere strictly to their initial designs, providing a clear directive by writing down the design idea along with a list of required materials. This approach aimed to prevent students from getting distracted by other available resources, ultimately leading to a more effective and focused design process. Ms Michelle's point below during post lesson discussion shows how this change in instruction helped teachers keep track of different designs made by pupils and also explains why the techniques of scribing are particularly helpful for young pupils (Fig. 4).

Episode 9:

Ms Michelle: In literacy anyway we do this thing called scribing, where they (pupil) tell us and because they can't write yet, so we do scribe. They're used to that where we go around and write their words. From a teacher point of view scribing was very useful because you weren't trying to remember 10 or 12 inventions and what they (pupil) thought. You had written (all those thought) so I could go back and ask, but you said you were making a helicopter and you said you were making a trampoline. Will that work? and how can you plan? how can you improve it?

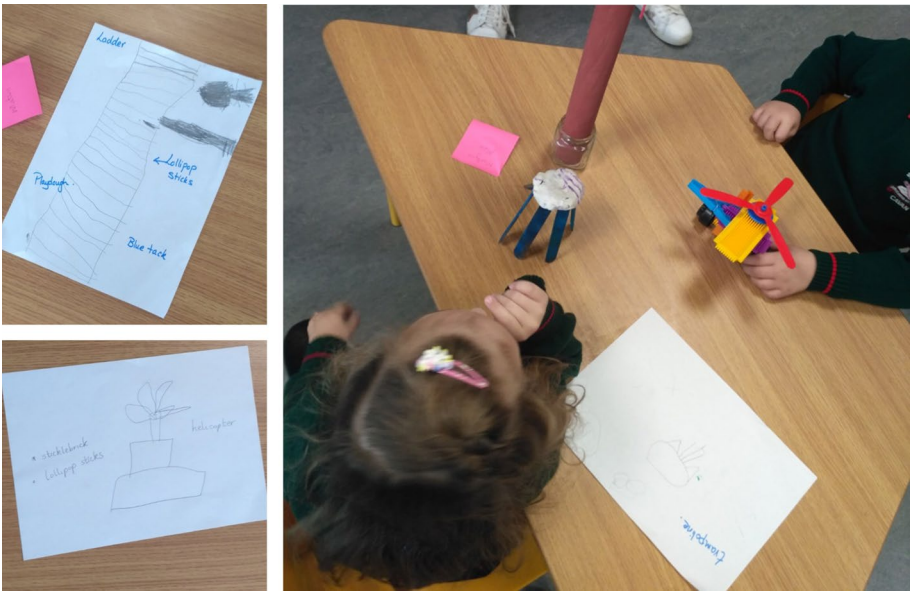

Fig. 4 Teacher using the method of Scribing to annotate sketches made by pupils by writing down the name of the design and list of materials so pupils stick to their design ideas

In Episode 10, similar to Episode 3, teachers realise that some of the pupils might have difficulty with visualising a house and context before they think of a solution to the design task given to them. However, here the teachers' duo went a step further and realise what change in instruction could have helped their pupils. First Ms Katherine noticed that some pupils were overly focused on building the house in the story of Goldilocks and Three Bears, indicating a potential difficulty in visualizing the broader context of the narrative. Ms Katherine suggested providing students with a contextual model, drawing from the example in another classroom (as mentioned in episode 4) where a tree prototype was used to aid visualization.This realization highlights the importance of context in facilitating students'understanding and problem-solving abilities. By providing a tangible representation of the setting, such as the three bears'house, students could better grasp the spatial relationships within the story and approach the design task more effectively (Fig. 5).

Episode 10: (Classroom 6)

Ms Katherine: I don't know if this is a bad thing but some of the girls over on this side were focusing so much on building the bears house saying "oh building the house","we building the house"
Ms Grainne: You don't need to build the house
Ms Katherine: I kind of said, If I want you to build this house, how Goldilocks is going to get across river. But they wanted to have a setting the house and then the river and the details wanted the whole context.
Ms Grainne: Yeah, I know in in junior infants teacher was saying that they actually made a tree. So maybe you could have the house made out or something and then you could let them

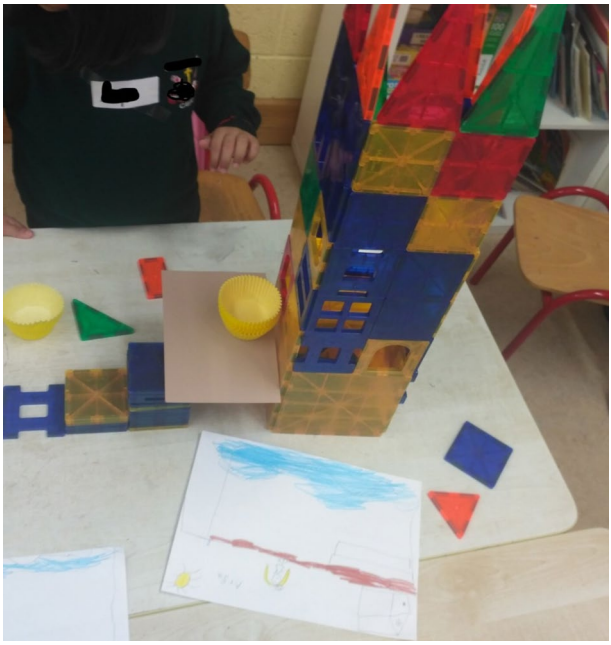

Fig. 5 Pupils making elaborative house design while addressing a problem of bridge to cross the river around the house

Ms Katherine: yeah, I have the three bears house in my class, I should have brought that with me and allowed someone to try to build their thing around.
Researcher: That's a very nice thing because I was about to give the same example
Ms Grainne: Oh sorry I crossed you (laughing)
Researcher: No problem, I think that's very nice, that's the idea of the lesson study anyway is when you have multiple groups within a school doing similar kind of activities you can learn from each others idea
Ms Grainne: yeah we're talking about at lunchtime and everything!

Moreover, the conversation underscores the collaborative nature of Lesson Study and its potential for learning from each other's ideas among teachers. Ms Grainne mentioned informal discussions during coffee breaks or lunchtime where teachers share insights and learn from each other's experiences. This informal exchange of ideas enhances the collective learning within the school community, showcasing the strength of Lesson Study in fostering professional growth and innovation. Overall, this conversation illustrates how Lesson Study encourages teachers to critically reflect on their instructional practices, draw inspiration from colleagues, and continuously refine their approaches to better support student learning.

In addition to the representative examples above, below we provide an overview of teachers' change in understanding (and misunderstanding) of pupils' spatial ability in different classrooms. Based on all episodes, the following changes in teachers' understanding of their pupils' spatial abilities were observed:

Classroom 1–2:

Removal of Junk Art: Teachers realized young learners could better complete designs using Legos, Duplo, and Knex instead of straws, cardboard, and cups, which resulted in Missed opportunities to use spatial language.
Cosmic Yoga: Used to help junior infants practice spatial words in a story context before the design task.
Use of sketch while designing: Teacher leave sketch with their pupils in the second session so pupils could relate their sketches with their design.
Classroom 3:
Scribing: Employed to ensure pupils stick to their design choices and materials. This structured way of instruction allowed teachers first to record and track number of design made by their pupils, secondly, if helped pupil in choosing matrials for their design and provided more opportunity for the use of spatial language.
Role Play: Pupils were made"inventors"to increase engagement. This role play allowed pupils to empathise with the character more as discussed in episode 8.
3D Prototypes: A 3D model of a tree was used to help pupils test their designs, addressing issues like understanding height perspective.
Engagement Strategies: Combined empathy in storytelling-based design tasks and role play to give pupils a sense of purpose.
Group Size Reduction: Changed from groups of 3 to 2 to increase engagement and focus.
Classroom 4:
Resource Management and Mixed Ability Grouping: Teachers provided fewer resources and mixed ability groups.
Design Location Change and testing of prototype: Moved from wet to muddy areas and allowed pupils to test their ideas in a second lesson, possibly inspired by strategies from Classroom 3.
Classroom 5:
Story Choice Dilemma: Struggled with choosing between long and strong as the deisgn assignment in the story.
Engagement with Spatial Language: Noted that Pupil C was engaged and using a lot of spatial language, which was surprising given her initial lack of clarity on the design task.
Future Instruction Planning: Considered strategies to better engage Pupil C by adding more visual clue, cards explainig the spatial words.
Classroom 6:
Context Design: Inspired by other classrooms, teachers proposed having a pre-made house for pupils to build around.
Explicit Use of Spatial Language: Teachers proposed explicitly teaching spatial words to help children explain their designs better.
Discussing Design Problems: Planned to address design problems in the last lesson to support struggling pupils.

Teachers perceive changes in their self-efficacy regarding the implementation of spatialized design activities and STEM instruction

Teachers' dialogue, during the final reflection on the Lesson Study cycle (Step 8, Table 1.)
Episodes 11: Teachers' discussion during post lesson study discussion

Ms Katherine: It (lesson study experience) gave me…. (taking a short pause) like I wouldn't be the best teacher I feel in design and making myself but that has given me a bit of confidence
Ms Grainne: *I too think so, because I really like it. If someone said to me before to do a STEM lesson. I'd be like Oh my God what do I do, where do I start but now, I know that you can actually create it around something you're doing in your class and it is as basic as, the idea of Goldilocks and the three bears (name of story). So I think going forward we will….*
Ms Katherine:..have a bit more confidence
Ms Cassidy: We'd tweak our 'Aister' lessons to include more of the story stimulus and more design and make by giving the children a task to solve. So, it would be very easy to (implement), you know. Definitely, we'll be doing more of it.
Ms Grainne: *I think from my own personal experience, I would have always been afraid of STEM, and I think, you know, just doing the lesson proves that you don't need all these lovely fancy resources for a lesson to go well; we just need actually good ideas in our head, and I'll be more confident moving forward.*
Ms Aine: we also decided that it would be something we might try and do once a month, that's the choice, especially because Michelle works in my room for support for about an hour and a half every day. So we thought even once a month, now the children are used to that kind of setup in the classroom, that we're kind of not afraid of doing it more regularly now and just seeing what children come up with. And we also felt that the story was a lovely introduction for children as well, especially stories that they're familiar with.

Ms Katherine reflects on her increased confidence in design and making, attributing it to the lesson study experience. Her statement,"It gave me… like I wouldn't be the best teacher I feel in design and making myself, but that has given me a bit of confidence,"highlights the positive impact of the lesson study on self-efficacy of Ms Katherine. Ms Rose echoes this sentiment, expressing how the Lesson Study has changed her attitude towards teaching STEM lessons. She shares her previous apprehension, stating,"If someone said to me before to do a STEM lesson… I'd be like Oh my God what do I do, where do I start but now, I know that you can actually create it around something you're doing in your class."This shift in attitude demonstrates an enhancement in her knowledge, belief, and attitude towards incorporating STEM activities. Ms Cassidy further illustrates the teachers'increased confidence by discussing plans to integrate lesson study techniques into their regular curriculum, indicating a willingness to continue the process beyond the project's duration. Ms Aine also reflects on her personal growth, admitting her previous fear of teaching STEM but acknowledging the lesson study's role in changing her perspective. She emphasizes the importance of innovative ideas over fancy resources, stating,"just doing the lesson proves that you don't need all these lovely fancy resources for a lesson to go well; we just need actually good ideas in your head,"indicating an improvement in her confidence and attitude towards STEM instruction. Ms Aine discusses plans to incorporate spatial design activities from stories into their classroom routine more regularly, suggesting that they may implement them once a month. This decision is influenced by the positive experiences of the lesson study and the support available from Michelle (observer teacher), who works in her room for about an hour and a half every day. Ms Aine also highlights the value of using stories as a means of introducing spatial thinking activities to children, recognizing their familiarity with such narratives as a starting point. Anie's remarks underscore the potential for sustained integration of spatial thinking activities into the classroom environment. Overall, these reflections highlight the positive impact of lesson study on teachers'self-efficacy and attitudes towards design and technology education.

Discussion

Our aim was to study the outcomes of a Lesson Study approach and how it may deepen teachers'knowledge of their pupils, teaching practices, and its impact on teacher self-efficacy, specifically in relation to spatial reasoning during story-based design activities.

Firstly, the deepening of teachers'knowledge of their pupils was evident in each classroom. Across classrooms, teachers reassessed their assumptions about how different pupils engage with spatial tasks. In some cases, they were surprised by the depth of spatial thinking demonstrated by lower-ability pupils, while in others, they recognized that high-ability pupils faced challenges such as design fixation. Teachers also identified the role of spatial language and gestures in supporting pupils' design processes and became more aware of how classroom dynamics, grouping strategies, and instructional choices influenced engagement and learning outcomes. Teachers selected pupils based on their professional judgment, but using Lesson Study helped clarify how to identify spatial thinking in their classrooms. Making predictions, even incorrect ones, proved to be a valuable learning experience for participating teachers.

Secondly, changes in teaching practices and instructional strategies were evident in each classroom, though the extent varied. While change does not always equate to improvement, the key theme is that teachers are exploring effective ways to teach spatial concepts to their pupils. These changes were mostly the result of teachers' understanding of their pupils. Some teachers incorporated new strategies, such as scribing (episode 9) and all teachers used sketching, to support pupils' spatial reasoning, while others refined their approaches by adjusting group sizes, integrating role-play, or explicitly teaching spatial vocabulary. These instructional shifts were often shaped by teachers' reflections on their pupils' learning, underscoring the iterative nature of Lesson Study in refining spatial thinking instruction. For example, classroom 3 (episode 9) teachers added a new spatial thinking tool into teaching by using scribing, which could be a spatial thinking tool for young learners as sketching is a spatial tool described by Newcombe (2017). Additionally, tensions between sketching and 3D modeling in design-based learning, as discussed by English (2019) and Welch et al. (2000), highlight the need for structured scaffolding to support young learners in translating their ideas across different representational forms.

Lastly, teachers' confidence in supporting spatial reasoning appeared to increase, as evidenced by their willingness to implement new instructional strategies. While self-efficacy is inherently subjective, post-lesson discussions revealed that teachers felt more capable of recognizing and fostering spatial thinking in their classrooms. The iterative nature of Lesson Study, along with exposure to five spatial tools introduced during the workshop, likely contributed to this sense of empowerment. These tools—spatial language, gestures, manipulatives, story-based design tasks, and Lesson Study—served as a foundation for integrating spatial thinking into the curriculum. However, further research is needed to assess the long-term impact of these changes on instructional practices. The workshop and collaborative design of lesson provided teachers with the confidence to try out new ideas to support spatial thinking in their classrooms while integrating STEM thinking. This is particularly significant given that early childhood teachers often exhibit spatial anxiety (Gilligan-Lee et al., 2022; Rocha et al., 2022; Sokolowski et al., 2019), which can sometimes hinder the sustainability of spatial activities in the classroom when direct training of spatial skills (Sorby, 2009; Lane & Sorby, 2022) is used. By using story-driven design activities, teachers felt more confident, and the Lesson Study process offered essential community support for integrating new content and addressing the needs of spatial thinking in early childhood classrooms. Research suggests that educators who engage in professional development (PD) typically already possess high levels of self-efficacy, which motivates them to improve their practices and set high

personal teaching and learning goals (Chen et al., 2021). However, low levels of self-efficacy and a lack of confidence in engaging with early STEM education have been noted among early childhood educators (Bates et al., 2023; DeJarnette, 2018; Edwards & Loveridge, 2011). Additionally, uncertainty about how STEM is conceptualized (Moore et al., 2020) or defined can lead to more formal teaching methods, as opposed to the integrated play-based pedagogy typical of early childhood education. However, in this study, even teachers with initially low self-efficacy towards design tasks (check episode 11) participated actively and developed their efficacy in teaching STEM through the Lesson Study approach.

Compared to earlier professional developments (PDs) on spatial thinking integration in classrooms, such as those by Moss et al. (2015), Lowrie et al. (2017), and Bufasi et al. (2024b), one of the biggest barriers has been the time constraints for participating teachers in long professional development interventions. Our results suggest that the Lesson Study processes implemented in our study could motivate teachers to integrate spatial thinking into their classrooms while still adhering to their curriculum. The results also showcase the teachers'creativity in crafting assignments from storybooks, demonstrating their ability to incorporate design-based spatial activities. However, developing these design assignments does not definitively indicate whether teachers acquired new skills or already possessed them. The focus on spatial elements within storytelling appears to be a new emphasis. For instance, in episodes 9 and 3, teachers realized that students needed additional scaffolding to understand spatial design tasks. Previous research by Kharbanda and Khunyakari (2025) also highlighted that children's attention to design challenges within stories often required guidance from teachers/researchers. They noted instances in which children in early education fixated on visualizing specific details, such as the construction of a house in our study in episode 10, which could be addressed by a model of a house or the need for 3D model of a tree in episode 6 and 7, to aid pupils in prototyping their designs within the story context.

Implementing Lesson Study also posed logistical challenges (Bufasi et al., 2024a). Organizing cycles of lesson planning, observations, and post-lesson discussions required significant coordination between researchers, school administration, and teachers. Establishing a clear timeline for lesson study meetings helped mitigate scheduling conflicts, but finding common time for discussions remained a challenge. Additionally, workshops needed to be tailored to the classroom context through work-shadowing, emphasizing the essential role of a knowledgeable other. These challenges highlight the need for adaptable structures in Lesson Study implementation (Schipper et al., 2023), particularly when integrating new topic like spatial thinking into early childhood education.

Limitations

This study focused on post-lesson discussions among teachers, which provided valuable insights into teacher learning but did not capture direct teacher–pupil interactions. Future research could incorporate pupil interviews for a more comprehensive perspective. Teachers identified case pupils based on professional judgment rather than formal testing, which may have influenced pupil selection. Adaptations to the Lesson Study structure (Sect."Adapted lesson study structure for integrating spatial thinking in curriculum") were made to fit the context, potentially affecting teacher learning. Our focus on applying spatial thinking, rather than measuring pupils'capacity, shaped our approach. While we built on established Lesson Study research in mathematics, our open-ended approach in design-based learning allowed teachers flexibility in instructional changes.

Another limitation was the difficulty of arranging cross-school observations (public lessons) due to geographical constraints. To address this, we facilitated online sessions where teachers from both schools shared their experiences with colleagues and administrators. Future investigations are needed to delve into mechanisms of Lesson Study and role of researcher contributing to these outcomes, including the workshop's alignment with participants'personal knowledge and the effectiveness of five spatial tools and observations in enhancing teachers' perceived self-efficacy.

Conclusion

This study offers valuable insights into the under-researched domain of teacher professionalization, on identifying and guiding spatially challenging design tasks from storybooks for early childhood STEAM education. The Lesson Study structure and workshop equipped teachers with the skills and self-efficacy necessary to comprehend children's engagement in design processes, emphasizing spatial language and gestures. Our findings provide a foundation for future investigations to empower teachers in effectively supporting children with diverse spatial abilities. Future research could explore follow-up Lesson Study addressing emerging issues in scaffolding design tasks based on varying spatial abilities and assessing the impact of Lesson Studies on student learning.

Key points highlighting the potential of Lesson Study in integrating spatial thinking in early childhood classrooms using story-based design assignments include:

- Lesson Study dynamics enhance teacher awareness related to design and technology projects.
- The Lesson Study structure fosters creative task identification and challenges teacher perceptions.
- Design-based play, coupled with goal-directed storytelling, enables teachers to set better learning objectives for pupils.
- The cyclic nature of Lesson Study, complemented by observations and pupils' interviews, facilitates changes in teaching practices.
- Collaborative exploration of spatial design tasks during Lesson Study cycles positively influences teachers'approaches to spatialized design activities.
- Teachers'discussions, observations, and reflections play a pivotal role in establishing criteria for transitioning to spatially challenging design tasks, deepening knowledge of pupils, instructional strategies, and developing self-efficacy in this new teaching domain.
- The results under present conditions show the potential effectiveness of Lesson Study in this process suggests its significance as a professional development tool for spatialized design assignments in early childhood classrooms.
- Lesson Study's pupil-focused approach aids in creating effective formative assessments tailored to individual learning needs.
- Lesson Study in real classroom settings integrates logistical considerations such as structured classroom time and resource arrangement, often overlooked but crucial for effective teaching.

Implementing story-based design activities with Lesson Study in early childhood classrooms can enhance teachers'understanding of pupils'spatial abilities, leading to improved instructional strategies. Teachers gain insights into the importance of pupils'interests and backgrounds, and their confidence in teaching spatial thinking increases. This approach integrates spatial thinking into the curriculum effectively, providing authentic design scenarios for pupils to develop spatial reasoning. The collaborative nature of Lesson Study supports continuous professional growth, making teachers more adept at crafting design tasks and fostering a supportive community essential for implementing new strategies. A particularly interesting possibility is the synergistic interplay between storytelling, spatial reasoning, and literacy development. The idea of reversing the process—where a designed and constructed artifact becomes the stimulus for storytelling—could further strengthen this connection. For example, children could talk about the adventures of objects they design with their teachers and peers. Such an approach might provide new avenues for integrating spatial thinking with early literacy development.Our study lay a foundation for empowering teachers to effectively support children with diverse spatial abilities using design tasks in early childhood education.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10798-025-09986-x.

Acknowledgements We are grateful to Teresa McSorley, Director of the Monahan Education Center in Ireland, for her support throughout this research. We also thank Caiwei Zhu for data analysis contributions, Estefania Gamarra Burga for her editing comments and Preeti Gungun for assistance in transcription. Special thanks to the participating teachers, students, and school principals from both schools involved.

Author contributions All authors contributed to the study conception and design. Material preparation and data collection were performed by [Rohit Mishra]. Formal analysis and investigation: [Rohit Mishra] and [Remke M. Klapwijk]. The first draft of the manuscript was written by [Rohit Mishra] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

This research is part of SellSTEM-Spatially Enhanced Learning Linked to STEM-Marie Skłodowska-Curie Innovative Training Network to investigate the role of spatial ability in and for STEM learning. It has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 956124.

Ethical Standards Ethical clearance was obtained from the Human Research Ethics Committee, TU Delft, The Netherlands. Informed consents were obtained from all participants.

Conflict of interest We have no conflicts of interest including no relevant financial or non-financial interests to disclose.

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