Chapter 4
Spatial Reasoning in Explorative, Creative, and Playful Science and Design Learning

Remke Klapwijk and Caiwei Zhu

Abstract Spatial reasoning is often described as the capacity to understand, interpret, and manipulate visual and mental representations of objects in three-dimensional space and plays an important role in science and design activities. It serves as a cognitive cornerstone that underpins various aspects of learning, problem-solving, and creativity. In this chapter, we explore the nature of spatial reasoning and demonstrate how it can be nurtured through playful science, design, and making activities. First, we explain what spatial reasoning is and why it is important to pay explicit attention to fostering spatial reasoning skills development in curricula. Next, we describe four educational strategies: using models, diagrams, spatial language, and engaging in sketching and gesturing, all of which can potentially help students think more spatially in science and design lessons. We then focus on the relation between spatial reasoning and designing, illustrating that spatial reasoning is required at all stages of the design process, including empathizing, ideating, as well as in prototyping and testing. This is clarified through examples of playful design activities for preschoolers and primary school students. Spatial reasoning is often implicitly present in science and design education. However, when educators appropriately scaffold learning processes that require spatial reasoning, learners are more likely to develop their spatial reasoning skills.

4.1 Introduction

Spatial reasoning[1] is ubiquitous in everyday life. Finding our way in a shopping mall, estimating how much paper we need to wrap a present, making a jigsaw puzzle, and reading instructions to assemble flat-pack furniture are a few examples of how

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[1] In this chapter, we use the terms spatial reasoning and spatial thinking interchangeably.

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we engage with the world in spatial ways. In many professions, such as artists, scientists, designers, engineers, technicians, and mathematicians, strong spatial skills are needed. It is worthwhile to invest in the development of spatial reasoning skills in science, technology, engineering, and mathematics (STEM) education as these skills can be developed through learning and practising (Uttal et al., 2013a).

There are a variety of ways to support students' spatial reasoning skills development in science education (Newcombe, 2017). For instance, when teachers use models and gestures in the classroom, such as modeling the solar system and gesturing about how the Earth rotates, students can visualize and imagine the scientific processes in a more concrete and tangible way. Sensing exercises followed by probing questions, for example, encourage students to become better explorers of the world. Students might notice that the beak of a small tree finch is long and skinny with a bent beak that looks like a needle-nose plier, while the big tree finch has a strong, wide beak that resembles the beak of a parrot (Poelman, 2015). Probing questions, such as 'which of these birds eats insects and which uses its beak to crack nuts', can help students relate forms seen in nature to their functions.

Design and technology education also benefits from spatial scaffolding. In any design process, students first explore the situation to understand the design problems, then think divergently to generate multiple, varied solutions and select the most promising ones to develop further (Cross, 2006). Ultimately, they create solutions that are original and valuable to the students themselves (Craft, 2003). Throughout these processes, imagining solutions in one's mind and elaborating on them through sketches and rapid prototypes engage novice designers' spatial thinking skills (Zhu et al., 2024). If the design does not work as intended, children are still learning, especially when they are given room and support to improve their design ideas (Sonneveld et al., 2024).

In this chapter, we will explain how many of the science and design activities are spatial in nature and how educators can apply age-appropriate approaches to integrate spatial reasoning in science and design education, from preschool through the end of primary schools.

4.2 What is Spatial Reasoning?

Spatial reasoning involves understanding how objects, including ourselves, relate to one another and to the spatial environment (Gifford et al., 2022). It includes interpreting, creating, and manipulating visual-spatial representations both mentally and through various medium. Here are some examples of circumstances where we need spatial reasoning in our daily lives:

- When you are figuring out how to reach a certain store in a shopping mall, you are thinking about positions and paths.
- When you are designing a pop-up card, you may mentally visualize how the pop-up card will look after cutting the figures.

– When you see a graph of the cross-section of a tree trunk, you can use this to imagine how the inside of the tree looks.

When we talk about mathematics or language literacy, it is clear to most of us that there are many different elements involved. The same is true for spatial reasoning or spatial thinking, as it consists of many elements (Buckley et al., 2018). Cognitive scientists make a distinction between large-scale and small-scale spatial reasoning (Newcombe & Shipley, 2014; Uttal et al., 2013a). Large-scale abilities relate to orienting oneself in a larger space, such as way-finding, map reading, and creating mental maps of routes. Small-scale abilities involve thinking about transformations within objects or structures, like positioning Lego blocks to build a structure or determining how many students should sit on one end of a seesaw when a parent sits on the other end.

Spatial reasoning skills undergo considerable development during infancy and early childhood (Newcombe & Frick, 2010) and develop throughout the entire life (Uttal et al., 2013b). Playing with spatial toys has been part of education since Friedrich Fröbel (1782–1852) developed hands-on, playful educational materials featuring mechanical spatial elements, such as construction sets of wooden blocks (Liebschner, 2006). Meanwhile, the school and its surroundings can be considered as a spatial environment that students use to develop observation, sensory, tactile, and perspective-taking skills. In addition, physical play and exercises help children develop the ability to sense and perceive the movement and position of their bodies, developing spatial-motor skills (Maresch & Sorby, 2021).

Recently, Ramey and Uttal expanded the definition of spatial reasoning from focusing solely on forming and manipulating images in our minds to including both internal cognitive processes and external objects or spatial representations, such as prototypes, models and diagrams (2017, p. 278). This broader definition is especially helpful when we discuss science and design education, where students actively engage with the material world, do experiments, make sketches and prototypes, and continuously iterate between visualizing and refining their design ideas—both mentally and physically—through discussion, sketching, and prototyping. A recent meta-analysis found that the use of tangible, concrete materials during spatial training sessions appear to have a positive effect on students' math performance later on (Hawes et al., 2022). Therefore, design and science activities, which are often fundamentally material in nature, offer a promising route to develop spatial reasoning skills.

In line with the growing emphasis on how mind and body work together in developing knowledge, skills, and understanding (Barsalou, 2008), the Assessment of Performance Unit (APU) model of iterative design processes (Fig. 4.1) highlights the alternation between internal and external cognitive processes. Internal processes like speculating and reflecting, represented on the left side of the model, involve using the mind's eye to imagine solutions. External processes happening outside of the head, shown on the right, include peer discussions, gestures, and tangible representations such as sketches and prototypes (Ramey & Uttal, 2017; Van Mechelen, 2016). Through these iterative internal and external cognitive processes, hazy ideas about design or STEM problems become increasingly tangible.

Both science and design activities are multi-modal in practice: students use language, gestures, sketches, as well as tangible and digital materials, including two-dimensional and three-dimensional models, to explain their ideas to peers, teachers, and themselves. Much research on spatial skills training in STEM disciplines has focused on solving problems that have only one correct answer (Zhu & Klapwijk, 2024), such as determining how a certain structure appears after being rotated by 90 degrees in a multiple-choice question. In design and technology projects, however, students learn to develop new or original solutions through divergent and convergent thinking, while using spatial thinking in creative ways (e.g. Sonneveld et al., 2024; Zhu et al., 2024). Therefore, integrating spatial thinking in science and design classrooms provides teachers with opportunities to teach both analytical and creative

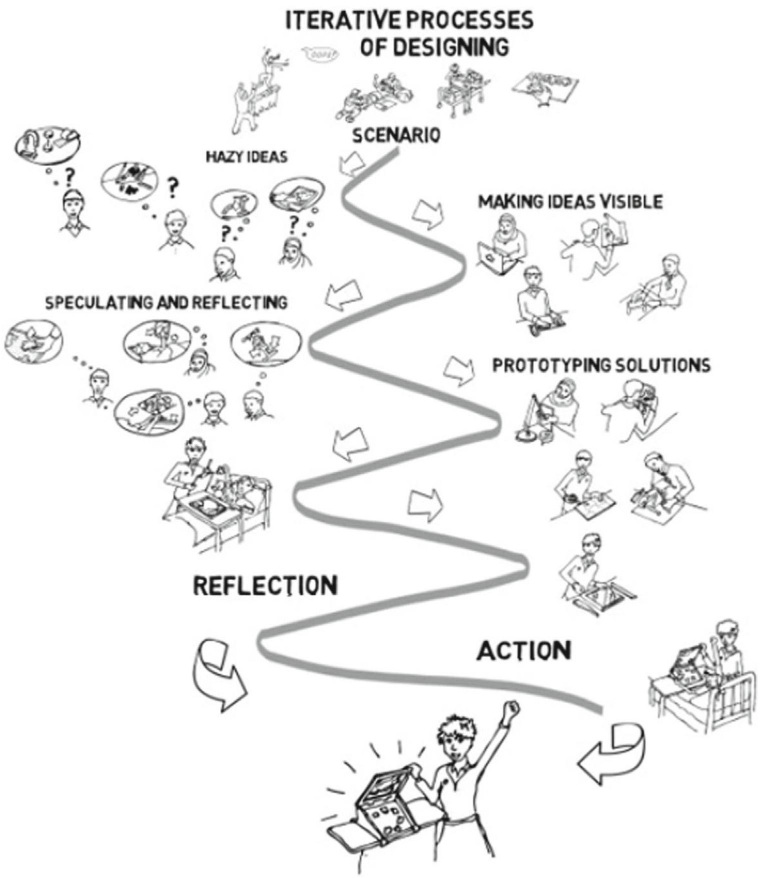


Fig. 4.1 The APU design and technology iterative model of designing (Klapwijk & Stables, 2023)

problem-solving, which will be elaborated on in the following sections on educational strategies and stories of practices.

4.3 Why Spatial Reasoning is Important in the Classroom

Spatial thinking plays an important role in scientific breakthroughs and technological advancement (Kell et al., 2013). The U.S. National Research Council described the process of spatial thinking as 'using the properties of space as a vehicle for structuring problems, for finding answers, and for expressing solutions' (2006, p. 3). Such a thinking process resembles what is needed to conduct scientific inquiry, as well as design and engineering problem-solving.

STEM learning and spatial reasoning skills development go hand in hand, with each positively influencing the other (Buckley et al., 2018; Wai et al., 2009; Zhu et al., 2023a). Prior research indicated that primary school students who have higher spatial ability tend to perform better in mathematics (Gilligan et al., 2019) and science (Hodgkiss et al., 2018). For students who are new to science subjects, such as geology, spatial ability is one of the important predictors of the learning outcome (Hambrick et al., 2012). Compared to students with higher spatial ability, those with lower spatial ability may face more challenges visualizing and comprehending spatially challenging concepts in STEM, potentially leading to poorer performance (Uttal & Cohen, 2012). Altogether, it appears that having a higher level of spatial ability is generally helpful for STEM learning, and spatial ability may even serve a role as important as the 'gatekeeper' in early STEM learning (Uttal & Cohen, 2012; Uttal et al., 2013b). In the long run, students with high spatial ability are more likely to pursue STEM subjects and careers (Wai et al., 2009) and perform better in engineering classes (Sorby, 2009).

For these reasons, it seems valuable to pay attention to spatial reasoning in science and design classrooms and to engage students in spatially challenging activities. Luckily, spatial ability can be developed through appropriate activities and opportunities (Uttal et al., 2013a) that can be integrated into pre-school and elementary classrooms as well as the STEM curriculum (Lowrie et al., 2018).

Some research has revealed gender differences in spatial reasoning skills, showing that boys outperform girls in certain tasks, such as mental rotation tasks (Neuburger et al., 2015). However, in a recent meta-analysis, Lauer et al. (2019) found no significant gender difference in mental-rotation skills among preschoolers, though a small male advantage emerged in students between the ages of six and eight. This suggests that, while these results do not exclude the possibility that biological influences may contribute to the gender gap, other factors such as gender roles and social norms (Bartlett & Camba, 2023), as well as test types and formats (Neuburger et al., 2015) likely play a role in gender differences in performance.

For a teacher, it is important to challenge all students with spatialized activities at the appropriate level and realize that certain girls will be top performers while some boys may struggle with spatial reasoning. Through our collection of stories of practice, we will highlight several good practices that exercise and cultivate spatial reasoning skills in science and design classrooms.

4.4 Four Educational Strategies to Involve Spatial Reasoning in Science and Design Classrooms

Educators, often unknowingly, provide learners with a variety of spatialized science and design activities while also utilizing a variety of spatial learning tools in science classrooms, including spatial language, diagrams, graphs, models, analogies, as well as action-based tools like gesturing and sketching (Newcombe, 2017). In this section, we explicate these tools so you can use them more frequently in your classrooms.

Strategy 1. Experimenting with manipulatives and models

Connecting learning with doing in science classrooms often stimulates students' interest and curiosity, keeps them motivated and engaged, and connects their knowledge with practices (National Research Council, 2012). By using tangible materials to experiment with, students can make abstract and symbolic models in science classrooms, such as models of sound waves or electrical circuits. These models act as tools "for thinking with, making predictions, and making sense of experiences" (National Research Council, 2012, p. 56). They further allow students to connect the observed with the unknown to test out their hypotheses through hands-on trials, formulate explanations, and grasp abstract science concepts. Sixth-graders who experimented with building different robotic models in an educational robotics project showed improvement in their spatial orientation task performance and exercised their mechanical reasoning skills (Julià & Antolì, 2018).

A simple yet fun example would be modeling sound waves with slinkies (e.g., see resources available on Exploratorium.edu (2024), 'Slinky in Hand: Physics & Waves Science Activity'). Through compressing, stretching, and creating waves with slinkies, students can learn about how sound travels and the different properties of sound waves. Meanwhile, to connect the movement of the slinky with the sound wave to understand abstract concepts such as antinodes of slope or frequency of oscillation, students also need spatial thinking to visualize the effects of different motions, and how such effects can relate to and be represented through 2D symbolic representations of sound waves in their textbooks.

Strategy 2. Using diagrams and graphs

Learning to understand, use, and create scientific diagrams is an important skill to be cultivated through the science curriculum in primary education, especially in the upper primary years. Diagrams are important scientific reasoning tools that contribute to science learning outcomes and engage students' spatial reasoning skills (Cromley et al., 2013). Whether it is learning about living things and their habitats, the solar system, or learning about physics topics such as sound, light, forces, and electricity, diagrams are not only visually exciting and challenging for students but can also inspire engaging classroom activities. For instance, the diagram (Fig. 4.2) below is a learning activity from the Oxford Primary Illustrated Science Dictionary Free Resources (2019) that probes students' understanding of the food web.

Having knowledge about the different organisms mentioned in this activity is perhaps not enough for students to successfully fill out the blanks. Students need to realize how information about predator–prey relations is visualized in the diagram. The arrows in the diagram point from one blank to another to indicate either unique or shared predator–prey relationships between these organisms. Filling out one blank with an organism's name would require students to think about how this blank is positioned

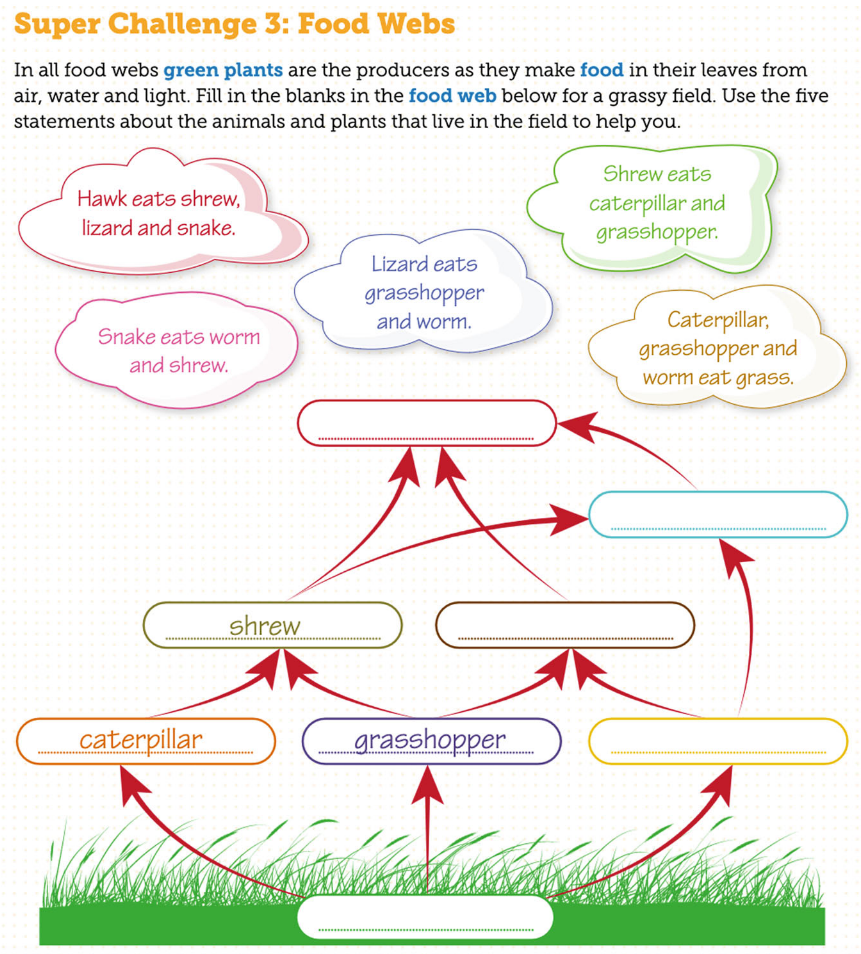


Fig. 4.2 Learning about and visualizing the food web through a diagram (Oxford Primary Illustrated Science Dictionary Free Resources, 2019)

regarding the entire diagram and regarding other blanks. Therefore, in this diagram learning process, students need to constantly think about how the relationships among the organisms can be visualized on this food web and the spatial relations among the blanks.

In science classes, educators can use drawings to formatively assess their students' understanding of scientific concepts. For example, at the start of a new subject or during the activities, students can create drawings of how they understand a scientific concept, such as how the heart and the circulatory system work, to see what students already know and if there are any pre- or misconceptions prevalent.

Ten to fifteen-year-old students were asked to draw a heart and to describe its parts and function in the human body (Fančovičová & Prokop, 2019). Students' drawings of the heart were in three shapes, some students drew it as Valentine heart, others drew it as a circle and other students drew the heart in its real shape (Fig. 4.3). Educators can evaluate these drawings by asking questions such as: Do students divide the heart and display specific parts of the heart? Are there signs of veins and arteries, like outlets from and to the heart? Do they schematically divide the heart into upper left and right atria and lower left and right ventricles? Do they realize that the heart is connected to the respiratory system? In practice, each pupil could individually draw a scientific process, then come together in small groups to share their drawings and collaboratively create the best drawing version.

In summary, diagrams seen in learning materials as well as making diagrams can potentially be good opportunities to examine and nurture students' understanding of scientific concepts while exercising students' spatial thinking. This also accounts for charts, graphs and other visuals that represent information or data in visual-spatial ways.

Fig. 4.3 The shapes of heart in students' drawings (*Source* Fig. 4.1 in Fančovičová & Prokop, 2019, p. 553)

Strategy 3. Using spatial language

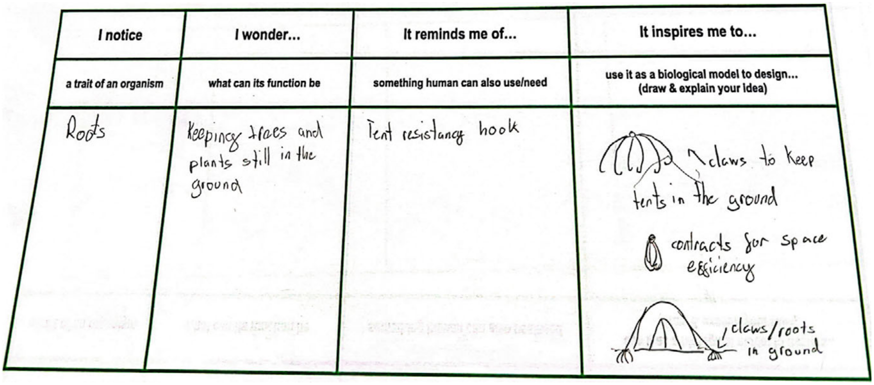
Educators incorporate spatial language and gestures in many of their teaching activities. For example, when teaching writing, a teacher might say and gesture, 'Around, up, down, and tick.' Spatial language serves as a cognitive tool that facilitates the representation and reasoning about spatial information (Gentner, 2016). Exposure to spatial language enhances students' understanding of spatial relations, shapes, forms and transformations. Newcombe (2017) wrote, '*language can highlight dimensions that might otherwise be less likely to be noticed and remembered. For instance, students find it easier to remember left–right relation when someone has drawn attention to the relationship using language, even when the language is not strictly relevant to the precise spatial arrangement, for example when one side is simply said to be prettier than the other (p. 25).'*

To cultivate a habit of using more precise spatial vocabulary in the classroom, teachers could consider what they want to communicate and aim to be specific about the shapes and spatial relations of objects. For example, you might say, 'Could you hand me the rectangular book?' or 'Look at the pretty red block that is above the blue one.' Using the following five categories of language will help teachers incorporate more spatial language to their talk in science or classes (Gamarra & Nguyen, 2024). As a result, educators will draw attention to the spatial aspects of objects and spatial relations between them.

- Description of shapes (e.g., square, circle, cube, prism, wobbly).
- Comparison (e.g., bigger, smaller).
- Spatial prepositions (e.g., between, on, in, under).
- Movement (e.g., "the electrons flow", "when one gear spins, the other will spin too").
- Location (e.g., "on the first page", "perpendicular to").

Strategy 4. Encouraging sketching and gesturing

Two additional action-based spatial reasoning tools are sketching and gesturing. We tend to think of these two as tools to communicate or represent thoughts and solutions. Yet besides this, they are also reasoning tools that offer visual and motor input into the thinking process, influencing and supporting learning (Newcombe, 2017). Figure 4.4 shows an example of two 11-year-olds' notes with sketches when recording their observations of nature and thinking about what they could design based on forms and functions seen in nature. From observing the shape and learning about the functions of tree roots, these students came up with a claw-like tent hook design that can help hold tents firmly in the ground like tree roots do for trees, while also being able to 'contract for space efficiency'. Sketching while thinking ensured that the students were actively observing, documenting, analyzing, interpreting, and organizing knowledge about the visual-spatial properties seen in nature, meanwhile sparking further inquiries.



I notice	I wonder...	It reminds me of...	It inspires me to...
a trait of an organism	what can its function be	something human can also use/need	use it as a biological model to design... (draw & explain your idea)
Roots	Keeping trees and plants still in the ground	Tent resistancy hook	claws to keep tents in the ground contracts for space efficiency claws/roots in ground

Fig. 4.4 Children's observations of nature in a biomimicry design project (*Source* Fig. 4.3 in Zhu et al., 2024)

Besides sketching, both cognitive and design researchers have emphasized the importance of gesturing in learning to think spatially and visualizing ideas. Novice students who were encouraged to gesture while thinking through geology problems, compared to those who were not allowed to gesture, showed improved performance in reasoning about 3D diagrams and spatial relationships (Atit et al., 2015). Meanwhile, gestures, along with conversations, drawings and models, constitute the language of design (Cross, 2006), and are often used by designers when discussing visual representations, such as models, sketches or drawings (Jornet & Roth, 2018). In design and science education, gestures can be used to explain processes (e.g., gesturing the opening and closing of a pine cone's scales) or to describe how an envisioned product will look like (e.g., gesturing that an additional piece of fabric with folds will be used to lengthen a skirt). Even students new to design have been observed using gestures to talk about their sketches and prototypes, explaining to peers and teachers what they envisioned in their designs (Zhu et al., 2024).

An additional benefit of sketching and gesturing is that they can help reduce the cognitive workload required to process complex spatial information. For instance, when sketching arrows to indicate the direction of gravity and static friction to solve a physics problem (Hubber et al., 2010) or gesturing to mimic the movement of tectonic plates in geology (Atit et al., 2014), students no longer need to constantly keep these pieces of information in their minds, and can direct their freed-up cognitive resources to solving problems and generating new lines of inquiry.

In summary, spatial reasoning can be supported and developed in science and design classrooms through:

1) Experimenting with manipulatives and models
2) Using diagrams and graphs
3) Using spatial language
4) Encouraging sketching and gesturing

Let us now look into a number of spatial design activities in which learners use spatial reasoning in a creative way.

4.5 Explorative, Creative, and Playful Design Activities

As outlined in the framework for K-12 science and engineering education developed by the U.S. National Research Council (2012), using design practices to seek solutions for real-life engineering and technology problems and to meet the needs of individuals and society can foster meaningful learning and practice of scientific knowledge. In design, several things are considered important (Klapwijk & Stables, 2023; Lawson & Dorst, 2009). First, the design process progresses through a sequence of phases: it typically begins with problem exploration, followed by the formulation of goals and design criteria, after which one or more solutions are constructed. Second, progression occurs in iterations: several steps are repeated as insights grow. For example, after developing an initial series of solutions, a new design criterion may be discovered, or it may become clear that the problem is not yet well understood, indicating that further investigations are needed. Through research we conducted as part of the SellSTEM (Spatially Enhanced Learning Linked to STEM) project (www.sellstem.eu), we noticed several benefits brought by integrating design activities into STEM classrooms.

4.5.1 Story-Based Design Assignments in Pre-School

In pre-school, play and storytelling are important means of learning. Sonneveld et al. (2024) developed a design task for pre-schoolers around a dog named Boris using a picture book. Children were asked to create a new home for Boris, because the father of the family was allergic to dogs. This project showed that spatial reasoning skills are needed at many stages of the design process, during problem exploration (Boris needs a roof and walls to protect him), while building design prototypes, and during prototype testing. Interestingly, this research revealed that the problems preschoolers encountered while designing and making were related to their play preference. Many of the preschoolers with a preference for role play constructed a building around Boris. They discovered in the testing stage that Boris could not leave the building anymore and was locked in. Often these preschoolers also noticed that the dog was sitting in the dark because they had not thought about adding a door or windows to their structure. Children who had a preference for construction play encountered another spatial problem that their dog was usually outside their built structure and could not enter.

There are many other storybooks available that contain spatial design problems. A recent study by Mishra and Klapwijk (2024) described how preschool educators developed design assignments from storybooks by identifying key characters in storybooks and the problems these characters encountered. Next, the teachers applied a lesson study approach in which one teacher gave a spatialized design lesson and another teacher observed and were interviewed post-lessons. Through observations and interviews, educators better understood the level of their students' creative spatial thinking and the types of scaffolding (including the four strategies described in Sect. 4.4) they could apply to support students' spatial skills development. This research showed that educators were often surprised by their students—those whom they thought would have low spatial ability performed well, while students expected to be high performers had difficulties in generating and elaborating spatial design ideas (Mishra & Klapwijk, 2024). Although we cannot generalize from this study, the results indicated that teachers are not always aware of the spatial ability of their students and that focused observation and reflection help them better understand their students.

4.5.2 Real-Life Design Assignments

It is also possible to use design problems related to the everyday experiences of learners. In preschool classes, drinking cups often topple over. Why not ask preschoolers to develop a solution using Knex, building blocks and crafting materials? We did this in a preschool in Rotterdam. We noticed that although the girls would not play with the available Lego during free play, they were very engaged in our design activity and came up with creative solutions. During understanding the problem, generating ideas, making the design, and testing, spatial reasoning was applied. Some students built a wall to prevent the cup from falling; however, none of the students in our study realized that a cup can fall in all directions. The teacher and researcher asked them what would happen if the cup would fall in another direction (see Fig. 4.5, Sonneveld et al., 2023). Even after the demonstration, none of the students made a cup holder that would surround the cup completely.

4.5.3 Biomedical Design Challenges

Biomedical design challenges are spatial in nature as the students have to think about, for example, how they can help people with rheumatism and other health issues who struggle with everyday tasks like peeling carrots. We will demonstrate how all design processes in biomedical design challenges—ranging from problem exploring, generating ideas, building, testing, and improving prototypes (3D representations)—involve spatial reasoning.

Exploring and formulating

A design process can start with a problem or a wish, thinking about the user and the purpose. In this case, bus driver John loves to cook food, but it is challenging for

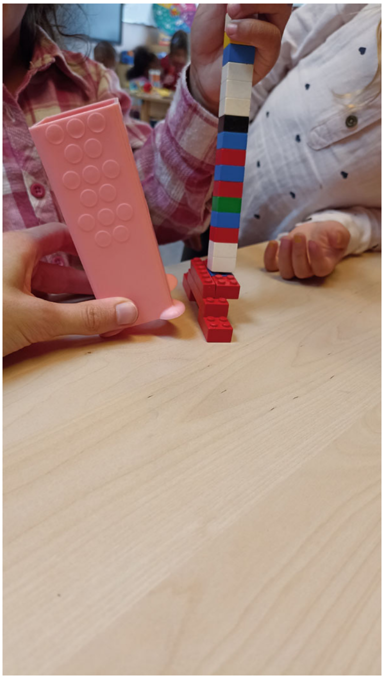


Fig. 4.5 Preschoolers thinking spatially to solve a design problem (Sonneveld et al., 2023)

him to do so with one arm. Through simulations followed by interviews, students experienced the problem. They needed to reason spatially to understand why peeling carrots and other tasks could be difficult when one has to do it with one arm only (Fig. 4.6).

Generating and selecting ideas

Creative people spend a lot of time in the early stages of a process. Therefore, a brainstorming session to think of as many solutions as possible is often organized. Figure 4.7 showcases numerous design ideas to enable a child who needs a wheelchair to play marbles, such as lowering the wheelchair or playing marbles at a table. These solutions were spatial in nature and used different spatial compositions to bring the marble and the flat space on which the marble will roll together. Additionally, a variety of spatial solutions were generated for moving the marble.

Elaborating and testing prototypes

Using sketches, a 3D prototype of a wheelchair that can be used to play marbles was built. During testing, the students tried to get a marble through the bent pipe. When the marble got stuck, the students thought that their design was not working. However, when the teacher asked the students if they were able to sit in the wheelchair, the students realized they had built a scale model of the wheelchair and used a small bead to test the piping system. In design, thinking in scale models is an important ability.

Fig. 4.6 Students simulating to empathize with the users

Providing students with scale models of people is one way educators can support scaling activities (Strand & Lutnæs, 2022).

In each design stage, spatial reasoning was engaged. Simulations, interviews with users, brainstorming sessions, sketching, prototyping, and testing all involve spatial reasoning. Educators can assess students' spatial reasoning through their discussions, representations, and gestures and notice where spatial reasoning is needed—like the teacher in our example who observed that the students did not scale correctly (Fig. 4.8).

4.5.4 Data Physicalization

In a world where data is ubiquitous, we encounter data every day in a variety of formats: numbers, tables, graphs, charts, and all kinds of 2D or 3D visualizations. Knowing how to read, understand, and interpret common data graphs such as bar graphs and pie charts are among the key learning goals in the primary science curriculum.

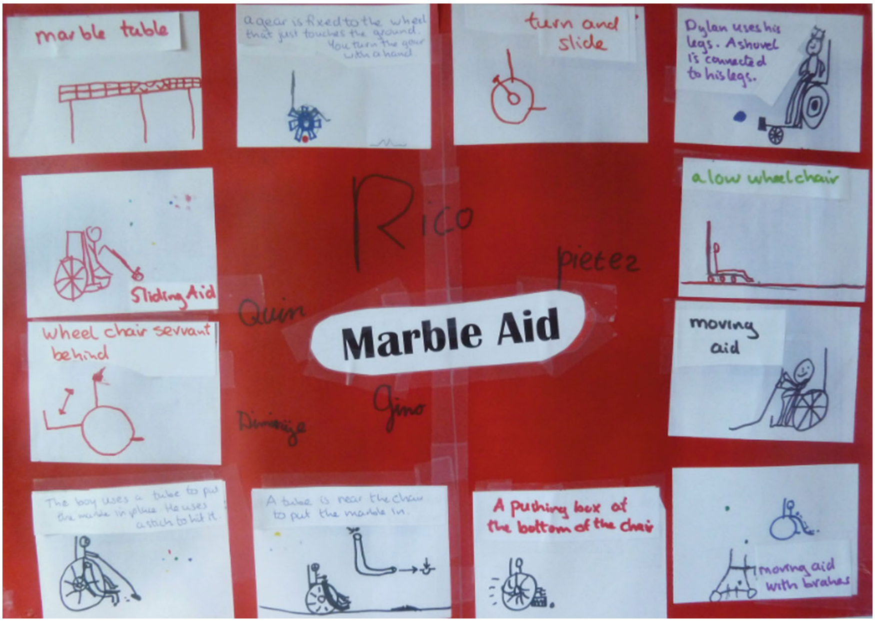


Fig. 4.7 Generating numerous solutions through brainstorming

Data physicalization means physical artifacts with geometrical or material properties that represent data (Jansen et al., 2015). By situating tangible materials in the 3D space, data physicalization models are not only innovative and engaging ways to communicate data obtained from a range of science subjects but also useful mediums to examine the patterns in and meaning of the data. Meanwhile, it engages spatial reasoning, as one would need to visualize non-tangible numbers as having tangible properties, such as length, depth, volume, and location, as well as to construct and communicate the visual-spatial relations between numerical values (Zhu et al., 2023b). Data physicalization appears to be an especially suitable classroom activity not only because of its engaging and versatile nature but also since analyzing and interpreting data as well as developing and using models are both listed as essential practices to be harnessed in K-12 science classrooms (National Research Council, 2012). Learning from and with data has the potential to immerse students in inquiries while the making of models enables students to test their hypotheses and make sense of learning through embodied experiences.

In our research project, we organized a data physicalization workshop with 11 and 12-year-olds (Zhu et al., 2023b). The workshop, featuring the Circular Economy theme to align with the ongoing module at the studied school, consisted of two 45-minute class sessions. The students were first introduced to data visualization and physicalization, read and selected data tables on waste production, and then spent around 40 minutes making their data physicalization model, followed by presenting their models in class for 15 min. They were encouraged to use a range of crafting

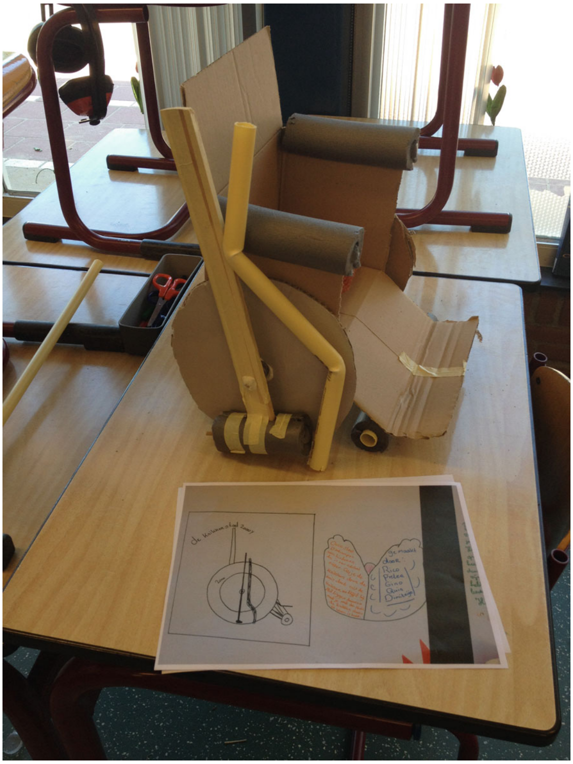


Fig. 4.8 From sketching to 3D prototyping

materials that are commonly seen in primary classrooms, including playdough, elastic bands, straws, pipe cleaners, paper cups and plates, yarn, beads, and balloons. This allowed students to not only playfully explore the different material properties but also to mold, shape, tie, stuff, or stack to arrange the materials in creative and meaningful ways. Below is an example showing how two students were actively exploring and experimenting when making their data physicalization model (Fig. 4.9). The conversation between these students proceeded as follows:

> Lia: I have an idea, so for compost and food we can fill it up until halfway or something (putting the pom poms in the cup to explain the idea) say this is the recycling thing. And fill it up that much. Like, really little, for 5%. Then, say, for this one (compost), we fill it almost halfway.
>
> Ada: So then, Um, How Much We Fill the Plastic?
>
> Lia: We Have to Fill Exactly the Same as the Paper.
>
> Ada: What if, to Make, Say, the Plastic Higher, We Can Put This on Top Here, and then We Put the Lid… and then We Can Fill
>
> That. It's Full of Plastic. So Wait, but is This 14% About?
>
> Lia: This One Has to Be Filled Slightly more…and the Plastic It Has to Be Filled Exactly the Same.
>
> Ada: That Looks Kind of the Same.

Lia: Yeah, that's Fine, that's Fine. Although, This Has to Be More Than This… the Tin is 5%…

Ada: So, This is 10% Compared to 5%. that's About Half.

Lia: Yeah, I think. Look, I had this fun experiment. Let us dump them all into one and see if that makes exactly a full cup. A full hundred percent. I do not think it will because I think it's a bit too much. That makes about a full 100%.

Ada: It's a Bit Over, Right?

Lia: Okay, I'm Taking Out One of Each just to Make It Slightly Smaller.

These two students chose to represent data tables of the percentages (by weight) of five different types of waste produced at their school in 2020. They explored the available materials and formed the idea of filling five paper cups with different amounts of different materials to symbolize the different types of waste produced at school. During the making, they frequently used language that demonstrated mathematical and spatial reasoning and continued to gauge, compare, and experiment with the amounts they added into each cup to reach a more accurate representation of the exact percentages of the data values and the ratio differences among those numbers. Through trial and error, they tested their understanding of numerical data

Fig. 4.9 Two students experimenting with materials to improve their data physicalization model (Zhu et al., 2023b)

values using objects that have visual-spatial properties, such as height, volume, and position.

Moreover, these students initiated an especially interesting experiment. They decided to dump all the materials they added to the five cups into one cup, to examine if these materials would fill up one paper cup that indicates 100%. This was a clever way of testing the hypothesis they had in mind as well as their mental model—that the estimated amounts of materials used to fill the five cups should be rather accurate and should be able to be combined together to represent a whole entity. Using tangible materials, they could visually compare their predictions about the physical embodiment of numerical numbers, analyze how accurate they were when mapping percentages onto volumes, and practice using mathematical reasoning.

After making data physicalization models, a majority of the students reported that they could comfortably interpret the meaning of numerical data, confidently communicate the meaning behind the numbers using their data physicalization models, and gained a better understanding of the different possible ways of representing data.

4.6 Discussions, Recommendations, and Opportunities for Practice

Most of the research on the development of spatial reasoning skills of primary school students has focused on analytical activities in the domain of mathematics education under the label of direct spatial training. In this chapter, we have demonstrated that science and design education are inherently spatial in nature and can be effectively used to develop spatial reasoning skills. These activities evoke spatial thinking in a rich and engaging context, allowing students to apply spatial reasoning skills during analytical and creative problem-solving activities in science and design. Compared to direct spatial training, integrating spatial thinking in science and design activities is a more authentic way to learn to think spatially and is more related to actual STEM practices.

We conjecture that the relation between science, design, and spatial reasoning is reciprocal. Science and design education contribute to the development of spatial reasoning skills, while the development of spatial skills will also contribute to the students' science and design capabilities. When educators pay explicit attention to the spatial aspects of science and design learning, we expect that students will develop their understanding of these subjects more effectively.

Although science and design are spatial in nature, educators can support the development of spatial reasoning skills in various ways. First, using age-appropriate science and design projects centered around real-life problem-solving will provide students with an authentic context to practice applying spatial skills to solve problems that have more than one correct answer. Moreover, appropriate use of models and manipulatives, spatial language, diagrams and graphs, as well as gestures and sketches will help educators to draw students' attention to the spatial aspects of the science and design activities they are engaged in, see Fig. 4.10 for an overview of the key strategies.

More research on the development of spatial reasoning through science and design is needed. Although there is substantial evidence that tools like spatial language, gestures, 2D- and 3D-representations are supportive, research on these tools in the context of primary science and design education is scarce. In addition, as these tools reflect the spatial reasoning processes of students, the ways in which students externalize their thoughts through language, gestures, or models may be used to formatively and summatively assess students' spatial understanding, benefiting future educational practices. Although (formative) assessment of spatial reasoning in science and design classrooms is not yet well-developed, educators can follow the spatial reasoning processes of their students by observing their interactions with the materials and their group discussions. Using prompts that help students evaluate the spatial dimensions of their work is recommended.

Lastly, spatializing the curriculum is not a difficult endeavor that requires extensive resources, as demonstrated by the data physicalization, biomedical, story-based, and real-life design projects. Resources for these projects are freely available on the Delft University of Technology website (https://www.tudelft.nl/en/wetenschapsknooppunt/your-turn).

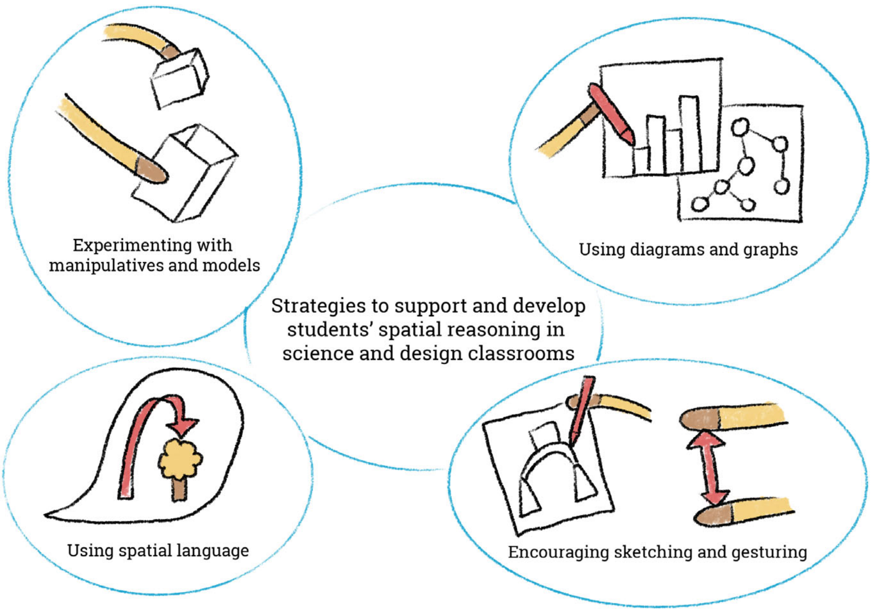


Fig. 4.10 Strategies to support spatial reasoning in science and design classrooms

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