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DOI
10.1007/s10798-024-09877-7

Publication date
2024

Document Version
Final published version

Published in
International Journal of Technology and Design Education

Citation (APA)
Zhu, C., Klapwijk, R., Silva-Ordaz, M., Spandaw, J., & de Vries, M. J. (2024). Investigating the role of spatial thinking in children's design ideation through an open-ended design-by-analogy challenge. *International Journal of Technology and Design Education*, *34*(5), 1733-1762. https://doi.org/10.1007/s10798-024-09877-7

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Investigating the role of spatial thinking in children's design ideation through an open-ended design-by-analogy challenge

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Accepted: 30 October 2023

Abstract

Spatial thinking is ubiquitous in design. Design education across all age groups encompasses a range of spatially challenging activities, such as forming and modifying mental representations of ideas, and visualizing the scenarios of design prototypes being used. While extensive research has examined the cognitive processes of spatial thinking and their relationships to science, technology, engineering, and mathematics learning, there remains a knowledge gap regarding the specific spatial thinking processes needed for open-ended problems, which may differ from those assessed in close-ended, analytical spatial tasks. To address this gap, we used educational design-based research to develop a nature-inspired, design-by-analogy project and investigate the spatial thinking processes of young, novice designers. 16 children from an international school in the Netherlands participated in this five-week design project. Multimodal evidence from classroom recordings and children's design works were triangulated to offer insight into the key spatial thinking processes involved in their creation of nature-inspired, analogy-based design prototypes. Our results revealed spatial thinking processes that might not align with those assessed in conventional spatial tests and may be unique to design or open-ended problem-solving. These processes include abstracting spatial features to infer form-function relationships, retrieving a range of relevant visual information from memory, developing multiple possible analogical matches based on spatial features and relationships, elaborating and iterating on the design concepts and representations to make creative and suitable solutions for the design challenge, as well as visualizing design prototypes in practical usage scenarios. By highlighting the nuanced differences between spatial thinking in open-ended, divergent thinking tasks and conventional spatial tasks that demand single correct solutions, our research contributes to a deeper understanding of how children utilize spatial thinking in design and open-ended problem-solving contexts. Furthermore, this case study offers practical implications for scaffolding children's analogical reasoning and nurturing their spatial thinking in design education.

Keywords Spatial thinking · Design education · Biomimicry · Analogical reasoning · Divergent thinking

Extended author information available on the last page of the article

Introduction

The ability to think spatially and deal with spatial information requires "searching the visual field, apprehending the forms, shapes, and positions of objects as visually perceived, forming mental representations of those forms, shapes, and positions, and manipulating such representations" in one's mind (Carroll, 1993, p. 304). These cognitive processes are often externalized through spatial representations like diagrams, sketches, and models (Gagnier et al., 2017; Novick et al., 1999; Stieff et al., 2005) as well as depictive or dynamic hand motions (Clement, 2008; Ehrlich & Levine, 2006; Pallasmaa, 2017). Together, these cognitive processes play an important role in the learning and practicing of science, technology, engineering, arts, and mathematics (STEAM) disciplines, including design (e.g. Buckley et al., 2018, 2022; Hegarty, 2014; Kell et al., 2013; Lin, 2016; Wai et al., 2009).

Over the past decades, a number of studies have confirmed that spatial thinking abilities can be trained and improved (e.g. Cheng & Mix, 2014; Hawes et al., 2017; Lowrie et al., 2017; Sorby, 2009; Uttal et al., 2013). Since spatial thinking is not used in a vacuum but often along with content knowledge (Atit et al., 2020; Hegarty et al., 2007; Ormand et al., 2014), it has been proposed that psychological and educational interventions should be designed to enhance not only individuals' spatial abilities but also their problem-solving performance in real-world learning tasks (e.g. Atit et al., 2020; National Research Council, 2006; Newcombe, 2017; Uttal & Cohen, 2012; Uttal et al., 2013; Zhu et al., 2023). To understand and support students' use of spatial thinking in authentic learning contexts, research has been dedicated to integrating spatial practices in day-to-day classrooms, such as in mathematics (Hawes et al., 2017), chemistry (Stieff et al., 2012), geology (Ormand et al., 2017) and engineering (Julià & Antolì, 2018; Sorby & Baartmans, 2000). However, there has been relatively limited exploration of developing spatial thinking through Design and Technology (D&T) education.

Engineers, scientists, and designers regularly engage in design practices that involve integrating interdisciplinary knowledge and skills to devise purposeful solutions to authentic problems (Klapwijk & Stables, 2023). Spatial thinking and the use of spatial representations are prevalent in design practices, especially when the designed products and processes have a material nature. As characterized by Schon and Wiggins (1992), "A designer sees, moves and sees again" (p. 135). Designers' exploration of the design problem space and solution space is visualized through their minds' eyes and often externalized through multimodal representations, including verbal elaborations, sketches, gestures, and the making of tangible or virtual prototypes (Kavakli & Gero, 2001, 2002; Schon & Wiggins, 1992). Attending to the visuo-spatial features in their design artifacts, such as the shapes, sizes, spatial relations, or spatial arrangements, may in turn lead to 'unexpected discoveries' about the design problems and possible creative solutions (Suwa et al., 2000). Unlike tasks commonly studied by cognitive scientists, design problems do not have a single correct answer (Cross, 1982) and the process of developing design solutions has, in essence, a divergent nature (Guilford, 1967). Moreover, designers often need to envision and create things that do not yet exist by visualizing the new products both in their minds and through materials. As a result, it is reasonable to speculate that the cognitive spatial processes used in design ideation may differ, to some extent, from those employed and assessed in widely-used spatial tasks with predetermined answers (e.g. Guay, 1977; Shepard & Metzler, 1971; Vandenberg & Kuse, 1978).

To generate creative solutions to open-ended design problems, designers employ various techniques to stimulate divergent thinking, such as re-representing or reframing problems (Zahner et al., 2010), examining pictorial examples (Purcell & Gero, 1996), and using design-by-analogy (Fu et al., 2015; Hey et al., 2008; Linsey et al., 2012; Qian & Gero, 1996). In the current study, we aim to understand how children utilize spatial thinking in an open-ended, design problem-solving situation that requires divergent thinking and analogical thinking. To investigate this, we developed a biomimicry design project, where children draw inspiration from various forms in nature, map form-function relationships observed in nature onto their own designs, and create spatially complex design-by-analogy prototypes. We expect that gaining insights into children's spatial thinking in this particular context will help identify spatial thinking processes that are unique to open-ended problem-solving.

Literature review

Developing spatial thinking in authentic learning contexts

Spatial ability has been a subject of extensive research in cognitive science, developmental psychology, and educational science (e.g. Gilligan et al., 2020; Hawes et al., 2017; Lowrie et al., 2019; Mix et al., 2021; Newcombe, 2017; Uttal et al., 2013). The association between individuals' spatial abilities and their academic performance has been investigated in disciplines such as science (Stieff et al., 2012), technology (Buckley et al., 2022), engineering (Hsi et al., 1997; Sorby, 2009), and mathematics (Hawes et al., 2015). There is a general consensus that higher spatial abilities are linked to better performance in these subjects as well as an increased likelihood of pursuing careers in these domains (Shea et al., 2001; Wai et al., 2009). Since spatial thinking skills develop from a young age and throughout childhood (e.g. 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 & Frick, 2010; Newcombe & Stieff, 2012).

Despite the considerable amount of lab-based research conducted to develop K-12 students' spatial thinking skills (e.g. Cheng & Mix, 2014; Gilligan et al., 2019; Xu & LeFevre, 2016), increasing effort has been made to situate spatial training in authentic learning contexts (e.g. Akayuure et al., 2016; Hawes et al., 2015, 2017; Lowrie et al., 2019; Taylor & Hutton, 2013; Zhu et al., 2023), which means situating learning in meaningful real-world situations (Herrington et al., 2014). By integrating spatial training or spatial activities into authentic learning contexts, findings from cognitive science research can be translated into educational practices. For example, Lowrie and colleagues (2019) developed a spatial thinking program for upper primary school children, where teachers provided instruction aimed at supporting children's spatial understanding of geometry knowledge. Following the three-week program, children showed improvements in spatial visualization, spatial orientation, and mathematics performance.

Most existing school-based spatial interventions, however, have primarily focused on mathematics education, which emphasizes using analytical thinking and convergent thinking to arrive at a single correct solution to a problem. In contrast, less attention has been given to design education, which places a strong emphasis on divergent thinking. The potential of engaging children in spatial thinking through design education warrants in-depth investigation. Yet before spatializing design education, it is essential to understand how children use spatial thinking when generating and implementing their design ideas, as the cognitive processes involved may differ from those used in solving math problems with predetermined solutions.

Spatial thinking in open-ended problem solving—with a focus on design

Our ability to bring our imaginings to life is a capacity that has shaped the world for centuries (Klapwijk & Stables, 2023). Since the eighties, the teaching of Design and Technology practices in primary and secondary education has gained popularity in countries such as the United Kingdom (Kimbell et al., 1996), the Netherlands (Raat & de Vries, 1986), and more recently under the term integrated STEAM or maker education in the United States, China, Singapore, and Australia (Blikstein, 2018; Cook & Bush, 2018; Zhan et al., 2022). Design problem-solving encompasses various processes such as problem identification and framing, user research, context mapping, identifying constraints and wishes, generating prototypes that represent design ideas in any medium (Houde & Hill, 1997), and testing and iterating on prototypes. Through iterative design processes, both professionals and novices can generate innovative and socially relevant solutions. For instance, professionals designed approaches to harvest solar energy that were inspired by leaves in nature (Benyus, 1997), while primary school children were able to design creative and functional ways to represent time without directly displaying it (Klapwijk & Stables, 2023).

While forming a mental representation of a tangible object in our daily life may sound simple, it demands various spatial thinking processes (Lane & Sorby, 2022), such as visualizing and memorizing the details. The development and realization of a design idea involve even more complex spatial thinking processes (Finke et al., 1992; Kavakli & Gero, 2001, 2002; Kosslyn, 1980; Purcell & Gero, 1998; Schon & Wiggins, 1992; Suwa & Tversky, 1997; Suwa et al., 1998; Williams et al., 2010), such as employing mental imagery and making use of spatial relations. A common creative thinking process consists of retrieving visual patterns from memories, mentally re-arranging, reassembling, synthesizing, and transforming what was known into something new, functional, and meaningful (Finke et al., 1992, p. 20–21), and visualizing the scenario when one explores the functions of the new design (p. 25). Furthermore, sketching and constructing three-dimensional prototypes allow designers to share their 'perception of the space' with users (Allen, 2010). It is important to note that not only trained designers but also lower secondary school students have demonstrated the use of spatial thinking when tackling open-ended engineering design tasks (Ramey & Uttal, 2017), including discussing spatial information, gesturing to represent static or dynamic spatial arrangements, and using analogical thinking to make sense of spatial properties and relations.

Research in design education, cognitive psychology, and neuroscience has endorsed the important role of spatial thinking in creative problem-solving (Aziz-Zadeh et al., 2013; Benedek et al., 2014; Chang, 2014; Finke et al., 1992; Kell et al., 2013; Muller, 1989; Suh & Cho, 2020). Conversely, a lack of necessary spatial skills may hinder the creation, comprehension, and manipulation of spatially complex designs (Sorby, 2009; Suh & Cho, 2020). Given its interdisciplinary and embodied nature, design as a learning process aligns well with the need to cultivate spatial thinking skills necessary for real-world problems. However, there has been a limited connection between cognitive research on spatial thinking and learning activities in engineering education (Ramey & Uttal, 2017) or in Design & Technology classrooms. As a result, design educators may lack the empirical understanding to identify and support spatial practices within design classrooms.

When faced with well-defined problems that have only one correct solution, such as determining the melting point of ice or selecting the rotated version of an image from multiple choices, one typically relies on convergent thinking. Design problems, however, are ill-defined, meaning that they are open-ended and can have many possible and innovative solutions (Cropley, 2006; Cross, 1982; Finke et al., 1992; Guilford, 1968; Purcell & Gero, 1996). While both divergent and convergent thinking are essential for developing novel and valid ideas (Cropley, 2006; Goldschmidt, 2016; Schut et al., 2020; Zhu et al., 2019), designers use divergent thinking extensively to explore many possible directions before ultimately converging on and evaluating one or several desired solutions (Finke et al., 1992; Goldschmidt, 2016; Guilford, 1968).

Research in neuroscience and cognitive psychology has also highlighted considerable differences between divergent and convergent thinking modes (Gabora, 2010). Divergent thinking requires a broad exploration space to generate a wide range of possible associations, while convergent thinking focuses on identifying and analyzing the cause-and-effect within a certain exploration space (Gabora, 2010). In mathematics education, which has traditionally emphasized using analytical thinking to derive the correct answer, some researchers have argued for the importance of cultivating creative and divergent mathematical thinking through open-ended problems (Becker & Shimada, 1997; Kwon et al., 2006). For instance, Kwon and colleagues (2006) conducted twenty learning sessions featuring open-ended mathematics problems with first-year middle school students. They found that traditional convergent mathematics problems offered students limited opportunities to explore and express different possible solutions. In contrast, open-ended problems allowed students to "try and find their own answers to the problems within their own scope and range of abilities" (p. 57), not only assessing their subject knowledge but also fostering their creativity and divergent thinking.

Existing research on spatial ability has predominantly focused on assessing or improving students' abilities to solve convergent, analytical spatial tasks, resulting in a gap in understanding how spatial thinking is utilized in open-ended tasks, which rely heavily on divergent thinking. Prior research suggests that designers may employ problem-solving approaches distinct from those in other disciplines, such as science (Cross, 1982). Lawson (1979) observed differing approaches between architectural design students and science students when facing a spatial problem. When tasked with devising an optimal spatial arrangement using three-dimensional blocks, science students often began by examining the rules underlying the problem to establish criteria for possible solutions. In contrast, architectural design students experimented with various solutions to identify the best fit and, in doing so, gained an understanding of the underlying rules. Given these findings, it is plausible that the spatial thinking processes involved in design may differ from those observed in other disciplines (e.g. science and mathematics) or those assessed in widely-used spatial tests, such as the mental rotation test (Vandenberg & Kuse, 1978) and the mental paper folding test (Shepard & Feng, 1972).

Potential relationships between spatial thinking and divergent thinking may be inferred from prior investigations into the relationship between fluid intelligence and divergent thinking by Nusbaum and Silvia (2011) and Beaty et al. (2014). Both studies included paper-folding tasks—which require participants to use spatial thinking to mentally visualize paper being transformed and altered—as one of the three measurements of fluid intelligence. Moreover, Nusbaum and Silvia's (2011) study incorporated a cube comparison task, where participants needed to use spatial visualization and spatial orientation to make decisions based on patterns shown on different cube faces. Results from both studies indicated that higher levels of fluid intelligence were associated with higher-quality divergent thinking responses. This correlation is particularly intriguing given that spatial ability was used as one of the proxies in assessing fluid intelligence. The link between spatial thinking and divergent thinking certainly merits further investigation.

To offer a fresh perspective beyond existing quantitative examinations, our case study seeks to understand the role of spatial thinking in design ideation—an open-ended problem-solving process that demands divergent thinking. Considering that numerous prior studies were conducted in lab-based or test-based settings, and that authentic problems appear to be better indicators of real-world creativity than standard divergent thinking measures that lack real-world relevance (Okuda et al, 1991), our investigation is situated in an authentic design learning context.

Thinking and designing with visual analogies

Designers make use of a variety of brainstorming techniques and reasoning tools, including analogy (Fu et al., 2015; Goel, 1997; Hey et al., 2008; Linsey et al., 2012; Moreno et al., 2015; Qian & Gero, 1996). Thinking analogically means using knowledge about one situation to inform a novel situation (Gick & Holyoak, 1983; Gentner, 1987; Sternberg, 1977)—in essence, transferring insights from the source to the target. This form of reasoning is central to the cognitive processes behind creative innovations (Chrysikou, 2014; Green et al., 2012) and is frequently employed by designers as a problem-solving and innovation strategy (Ball & Christensen, 2019; Beveridge & Parkins, 1987; Boden, 2001; Casakin & Goldschmidt, 1999; Daugherty & Mentzer, 2008; Gero, 1996; Goel, 1997; Goldschmidt, 1994, 1995). A classic example of design-by-analogy can be seen when engineers in Japan drew inspiration from the beak of the kingfisher bird to redesign the front of a bullet train, thereby enhancing its speed, reducing noise, and improving energy efficiency. Through analogical thinking, designers can transfer information from one domain to another to creatively explore solutions to open-ended problems (Finke et al., 1992). Visual analogies, in particular, have been found to stimulate the generation of novel solutions to design problems (Goldschmidt, 2001; Wilson et al., 2010) and are especially beneficial for novice designers (Casakin, 2004; Casakin & Goldschmidt, 1999).

A number of studies have revealed the important role spatial thinking plays in comprehending and working with visual analogies. "Higher-order visual-spatial thinking is inherently analogic," as Mathewson (1999) stated, and is "based on comparisons of mental representations" (p. 38). While some analogies can be reasoned through verbal representations, others rely heavily on comparing and making sense of visual mental representations (Beveridge & Parkins, 1987), which means mentally recreating the forms of actual objects or events, any spatial relations pertaining to them, and any dynamic processes happening to or in them (Clement, 2008; Finke, 1989; Kosslyn, 1980). These representations allow one to reason about spatial relations (Beveridge & Parkins, 1987; Huttenlocher, 1968), visualize problem context (Suwa et al., 2000), and generate hypotheses about extreme cases (Clement, 2008).

Through think-aloud interviews, Clement (1981, 1986, 1988, 2009) discovered that when participants generated analogies to solve technical problems, much of their thinking appeared to be spatial, such as visualizing how springs were stretched based on diagrams of coiling springs. For instance, one participant spontaneously came up with the analogy that "a spring is nothing but a rod wound up" and analyzed in his mind how rods might stretch similarly to springs under force (Clement, 1981, p. 3). During these thought processes, Clement (1988, 2008) observed that the participant mentally visualized the problem, compared mental models of a stretching spring to other objects that shared similar key features, imagined possible physical transformations, and determined whether the inferences drawn from one situation can be validly applied to another. Clement further noted that using analogies in problem-solving often entails the spatial reasoning process of "mentally performing imaginative spatial transformations such as deforming, cutting, and reassembling objects in novel ways" (2008, p. 1).

Recent research has shed light on how analogy can serve as a tool for supporting spatial understanding and thinking. Gentner and colleagues (2016) conducted a study at the Chicago Children's Museum with a group of 6-to-8-year-old children. They found that a brief training focusing on analogical spatial structures enabled the children to learn about an important spatial concept that diagonal structures provide stability. In another study, Yuan and colleagues (2017) examined the spatial reasoning and analogical reasoning performance of 3-year-olds. The children were tasked with finding hidden items in 3D rooms based on 2D maps. Through four experiments, the researchers found that children showed a better understanding of the maps and performed more successful spatial searches when there were consistent relational alignments between the source situation and the target situation.

The studies discussed above demonstrated how spatial thinking is utilized to mentally represent, compare, analyze, and draw inferences from analogical examples. However, it is worth noting that most of the tasks used in these studies are primarily analytical and have predetermined solutions. As a result, there is a need for additional research to understand how individuals spontaneously generate or identify connections through analogies in open-ended tasks (Weinberger et al., 2016) and how this process taps into their spatial thinking.

Design ideation through and with analogy

Generating novel design ideas through analogical thinking has nuanced differences from how analogies are used in common problem-solving (Qian & Gero, 1996). In cognitive science and psychology, analogical thinking is often assessed by selecting the correct answer from a range of given solutions (e.g. Simms & Richland, 2019; Yuan et al., 2017) and is, in a way, close-ended. Designers, on the other hand, appear to go through some distinct cognitive processes when using analogies for design ideation.

In authentic problem-solving contexts, designers typically do not identify or choose from ready-made analogies as would be seen in controlled experiments (Goldschmidt, 2001). Instead, designers usually need to first imagine various possible configurations of the target design before proceeding with mapping between the source and target. The analogy becomes clear in hindsight once a design-by-analogy product is created. However, during the design ideation process, or whenever one is searching for a problem solution mentally, the source and target may not be immediately obvious. Goldschmidt (2001) theorized that the mapping between source and target in design is bidirectional and dynamic, and the details in such structural mapping continue to iterate until finalization (Fig. 1). Generally, it seems that designers have ample space to explore mapping possibilities before arriving at one solution, such as identifying transferable and designable elements of the source, establishing various levels of mappings, and experimenting with different degrees of adaptation and transformation.

According to Qian and Gero's (1996) model of *analogical problem solving and exploring processes* in design, designers encode and retrieve functions and features of existing designs as retrieval cues for potential analogical mapping and carryover. Designers then

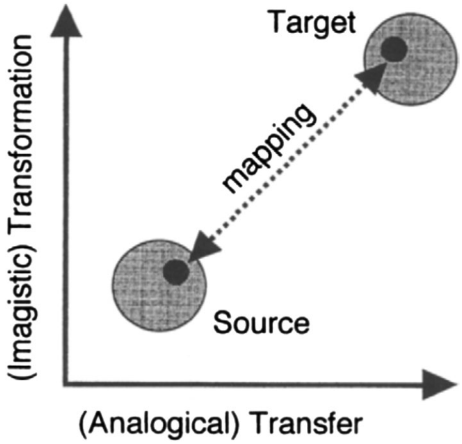


Fig. 1 Diagram of dynamic imagistic/analogical search processes in creative problem solving (Goldschmidt, 2001, p. 208)

make necessary adaptations or transformations to develop new designs based on the source design. Since design-by-analogy transfers only a certain number of features from the source to the target, designers need careful abstraction (Gentner & Medina, 1998; Qian & Gero, 1996) to determine which features to be transformed into the new design, disregarding features irrelevant to the analogy. Overall, the exploration of potential analogical mappings and the steps taken to narrow down the final design choice reflects how designers utilize a combination of divergent and convergent thinking processes to draw inferences and transfer insights between domains.

In summary, we have reviewed how spatial thinking plays a role in design ideation as well as in thinking with visual analogies. However, existing research primarily focuses on developing individuals' spatial abilities through convergent, analytical tasks. This leaves a gap in understanding how spatial thinking is used in open-ended problems that require divergent thinking and originate from authentic learning experiences. Furthermore, it appears that the use of analogy, both as a spatial reasoning tool and a design ideation tool, would benefit from further investigation into its usage in authentic and open-ended design problems. To address these gaps, this case study aims to unpack spatial thinking's role in the design ideation process. Specifically, we seek to understand (1) the spatial thinking processes involved in a design-by-analogy ideation process and, (2) more broadly, how spatial thinking used in open-ended design tasks differs from that used in tasks with predetermined solutions.

Current study

Biomimicry as a type of design by analogy

Biomimicry, a form of design-by-analogy, draws inspiration from nature's strategies to devise artificial creations and solutions. It is increasingly recognized as a valuable STEM topic for primary and secondary classrooms (Gencer et al., 2020; NGSS Lead States, 2013). Similar to other analogy-based design processes, biomimicry often begins by examining intricate patterns or structures in organisms in nature. By relating these observed forms to their potential functions, one can then map inferences from nature's form-function relationships onto human designs, resulting in biomimicry designs. This mapping process requires a far transfer of knowledge between nature's strategies and possible human designs, two markedly distinct contexts (Kolodner et al., 2003). To understand the spatial features of organisms in nature, such as their shapes and sizes (Rustaman & Rahmat, 2017), or the three-dimensional structures and processes in biology (Milner-Bolotin & Nashon, 2012), one needs spatial thinking. Engaging students in exploring nature's features for inspiration not only brings their attention to specific features of organisms that they might have overlooked before but also challenges their abilities to draw inferences from and make creative use of nature's form-function relationships.

The design project

We developed this design project following most of the biomimicry design processes listed in the Biomimicry DesignLens, a design guide made by Biomimicry 3.8 (2015). The first and third authors tailored the design project to be suitable for this age group and class structure, resulting in eight 45-min sessions. The design challenge involved asking children to create wind- or water-resistant biomimicry designs for camping. Given that the wind or water resistance functions are often performed by perceptible external features of organisms, we anticipate that children would use spatial thinking to observe, visualize, and abstract useful inferences from the visual-spatial forms seen in nature. Subsequently, they would apply these inferences to develop designs that incorporate salient visual-spatial features inspired by nature.

To support children's understanding of the complex concept of biomimicry and stimulate analogical, divergent, and spatial thinking related to the design challenge, we incorporated a series of scaffolds. Gick and Holyoak (1980) highlighted the importance of explicitly instructing students to reason analogically, as they might not automatically recognize how relevant information can serve as analogous solutions to problems. Other research also endorsed the educational strategy of providing students with ample opportunities to think relationally and visualize analogies across different domains (Stevens et al., 2021, 2022; Vendetti et al., 2015). Therefore, we developed six activities to scaffold children's analogical thinking and ideation. Each activity explicitly requires children to think analogically (Table 1). We expect that these activities will help children articulate their intermediate thoughts, gain a better understanding of the core elements of biomimicry designs, establish connections between organisms in nature and the human applications inspired by them, as well as successfully draw inspiration from nature for their own designs.

Methods

Design-based research

We adopted the design-based research approach to translate knowledge from research into educational applications. Design-based research systematically and iteratively tests innovative learning designs, draws from multiple evidence sources in educational contexts to present a holistic view of how learning occurs, and aims to develop actionable and generalizable knowledge regarding educational practices (Bakker, 2018; Design-Based Research Collective, 2003). To ensure the effectiveness and relevance of our design project, we collaborated closely with a Design & Technology teacher to co-create learning materials used in the project and integrate the project into one module within the International

Table 1 Structure of the biomimicry design project

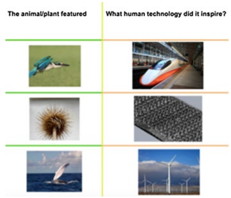
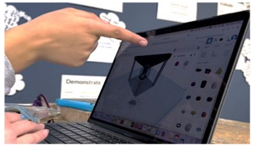
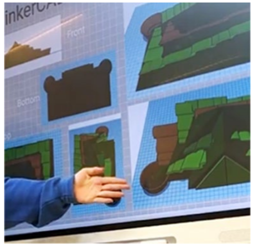
Session	Learning objectives	Activities that explicitly requires analogical thinking	Examples of children's work or progress
1	Understanding and examining the design problem; recognizing nature as a source of inspiration for human design	Learning about biomimicry design examples that have been inspired by visible visual-spatial features in nature: burdock burrs inspiring the design of Velcro, Kingfisher's beak inspiring the design of the front of the Shinkansen train, and Humpback Whales' flippers inspiring the redesign of wind turbines	
2	Exploring outdoors and brainstorming for preliminary design ideas	Engaging in a nature walk to observe and note down findings from nature using the "I notice, I wonder, It reminds me of, It inspires me to" worksheet	
3	Investigating organisms in nature for design inspirations; linking biological strategies to design strategies	Analyzing a biomimicry design example in detail to identify the organism, trait, function, biological strategy, and how these elements inspire a design strategy for human design applications	
4	Generating ideas and identifying the best ideas that reflect biomimicry and fit the design challenge	Sketching four different ideas and thinking divergently about different possible mappings from a chosen source	

Table 1 (continued)

Session	Learning objectives	Activities that explicitly requires analogical thinking	Examples of children's work or progress
5	Creating detailed sketches and annotations for the selected design ideas; giving feedback on each other's designs	Elaborating on selected design ideas using a design plan worksheet, describing the name, trait, function, and biological strategy of the inspiration source, as well as the feature, function, and design strategy of the design	
6 and 7	Creating and iterating on 3D prototypes of the design ideas using TinkerCAD		
8	Presenting design artifacts in class	Elaborating on design artifacts using a design presentation worksheet, detailing the trait, function, and biological strategy of the source of inspiration, the feature and function of the design, the design strategy, and how the source from nature inspired the design	

Baccalaureate (IB) design course. The learning objectives in this biomimicry design project aligned with IB learning goals, such as learning about forms and functions. Throughout the project, we continuously refined the activity structures based on feedback from the class and the teacher, with the goal of determining how best to support children's design processes.

Participants

Sixteen children aged 11 to 12 (10 boys, 6 girls) from the first year of secondary school at an international school in the Netherlands consented to participate in this design project. They were joined by their Design & Technology teacher who delivered all the design sessions. All participants gave researchers permission to use classroom recordings and design works as research data. Most of these children had one year of experience in design from their previous school year, which means they were familiar with the design process and certain design techniques, such as sketching and providing design feedback for peers. Children worked in duos for this design project, as is typical in design activities. In addition, since many of these children had prior exposure to TinkerCAD—a computer-aided design platform where children can combine, resize, and rotate 3D shapes to digitally represent their designs—they were encouraged to build their design prototypes on TinkerCAD.

Data collection and analysis

Data were collected from eight design sessions by the principal researcher and two other researchers. A total of 6 hours and 51 minutes of video and audio data were recorded, with a focus on design activities related to ideation. Classroom notes were taken during the sessions to provide additional context to the recorded data. Children's design worksheets, 2D and 3D design artifacts, and self-reflection forms were photographed.

Our analysis centered on children's spatial thinking processes in design, specifically on idea generation, elaboration, and development. We conducted an exploratory, data-driven thematic analysis (Boyatzis, 1998), using the qualitative analysis software MAXQDA to analyze classroom videos, audio, notes, children's design worksheets, and their 2D & 3D design artifacts. After transcribing the video and audio data, the principal researcher divided the transcriptions into segments. Each segment focused on children's discussion on a specific topic before transitioning to the next. Data from other modalities were incorporated into the segments to complement children's verbal communications, including children's design worksheets with written explanations and sketches, their 2D & 3D design artifacts, and any gestures observed in videos. This multimodal approach aimed to provide a holistic representation of the design processes and children's design choices (Van Mechelen, 2016). It is noteworthy that while children's spatial thinking can be externally represented through sketches, gestures, or verbal and written communications, a large portion of spatial thinking occurs internally within children's minds. Therefore, our analysis addressed data at both semantic (explicit) and latent (interpretative) levels (Boyatzis, 1998; Braun & Clarke, 2006).

The analysis process involved three iterative rounds of coding and discussion between four researchers. The principal researcher identified a range of initial codes related to the design processes as well as to spatial, analogical, and divergent thinking processes. These initial codes were then discussed with three other researchers to identify codes and segments relevant to the research questions. In the second round of coding, the principal researcher reviewed all data segments to refine the code definitions and reduce overlap between codes, resulting in a set of intermediate codes. All four researchers used these intermediate codes to independently code and interpret randomly selected data segments. By comparing the coding results and interpretations, the principal researcher shortlisted five themes that underpinned children's spatial thinking during the design-by-analogy ideation process and further refined the definition of these themes.

Results

All pairs of children created design prototypes that demonstrated a proper understanding of designing through biomimicry. That is, instead of merely replicating forms from nature, all children created prototypes based on the form-function relationships observed in nature. In their self-reflections, a majority of the children perceived their achievements in several areas as medium to high. These included closely observing the characteristics of organisms in nature to uncover new knowledge, applying what they learned from the biological strategies in their designs, generating multiple different design ideas using inspirations from nature, and gaining a fresh perspective on design and technology after exploring biomimicry design examples.

Through the data-driven thematic analysis of children's design artifacts and their verbal and written communications, we identified five main themes that capture the meaningful spatial thinking processes underlying the generation and development of their ideas. Two of these themes describe spatial thinking processes specific to analogy-based idea generation, while the remaining three themes describe spatial thinking processes relevant to general design ideation processes. All children's names to be mentioned below are fictitious (Table 2).

Spatial thinking processes pertaining to design-by-analogy

Abstracting spatial features observed in the source to infer form-function relationships

Throughout this design project, children actively observed various forms in nature and abstracted the spatial form-function relationships from these sources of inspiration. After returning from their outdoor exploration in the second session, all the children sketched and annotated the inspirations they gathered from nature. Below is an example of a child's observation and reasoning of ivy leaves and long grasses (Fig. 2).

Out of the many characteristics of these plants, such as color and texture, Iris identified the spatial features that ivies grew "in layers," and the dense hedge of grasses was "long enough to catch wind." Based on these observations, she reasoned that these features might serve functions related to wind and water resistance. The descriptions of layers of growth and the wind-catching feature further suggest that she may have observed or visualized in her mind how wind dynamically interacts with these plant hedges. These keen observations paved the way for further exploration of how forms observed in nature can potentially serve wind- or water-resistant functions. In this particular example, Iris theorized that the long grass hedge could function as a protective barrier for a campsite. Although she may not have fully grasped the exact mechanisms behind the wind and water resistance of these plants, her sketches and descriptions revealed how she was thinking spatially about the

Table 2 Themes of spatial thinking in the biomimicry design project

Theme	Description	Example
Spatial thinking processes pertaining to design-by-analogy		
Abstracting spatial features observed in the source to infer form-function relationships	Observing the forms of the source inspiration and abstracting spatial form-function relationships seen in the source	A duo of children noticed that ivies grow in layers and inferred that this form of growth may serve the function of resisting wind.
Developing various possible analogical matches by spatial features and relationships	Exploring different possible analogical matches from a single source of inspiration, or identifying more than one type of form-function relationships that can be analogically applied to inspire design, leading to multiple transformations of mental representations	A duo of children generated four different design ideas—tent, camping bag, camping chair, and camping shoes—all inspired by the form-function relationships observed in the spiral-grained growth pattern of pine trees, which allows the tree to be bendable in wind and aids in water distribution.
General spatial thinking processes		
Retrieving relevant visual information from memory	Retrieving a range of visual information from memory that either resembles the desired forms or provides relevant functions	After choosing the pinecone as their source of inspiration, a duo of children brainstormed several possible analogical matches based on form or function. They reasoned that while the mechanism of pinecone's scales—closing in wet weather and opening in dry weather—might not be a suitable inspiration for an umbrella design, it could inspire the design of a house or car that needs to be closed in wet conditions.
Elaborating and iterating on design concepts and representations	Elaborating on and externalizing mental representations of ideas through sketches and annotations, and continuously iterating on these visual representations of ideas	A duo of children noticed that the foldings on hornbeam leaves allow the leaves to be flexible in winds and rigid during photosynthesis. Drawing from this observation, they reasoned that a solar panel, serving the same light energy collection function as leaves do, could also be designed with foldings on its surface.

Table 2 (continued)

Theme	Description	Example
Visualizing the functionality of design prototypes in practical usage scenarios	Visualizing how the design prototypes would be used to evaluate their functionality, consider the user's perspective, and think of possible improvements	A duo of children visualized how falling water would interact with the flat-surfaced tarp they designed as well as the trajectory of water streams. They then iterated on the form of their design by elevating the top of the tarp to a pyramid shape and visualized again to consider the functionality of their improvement.

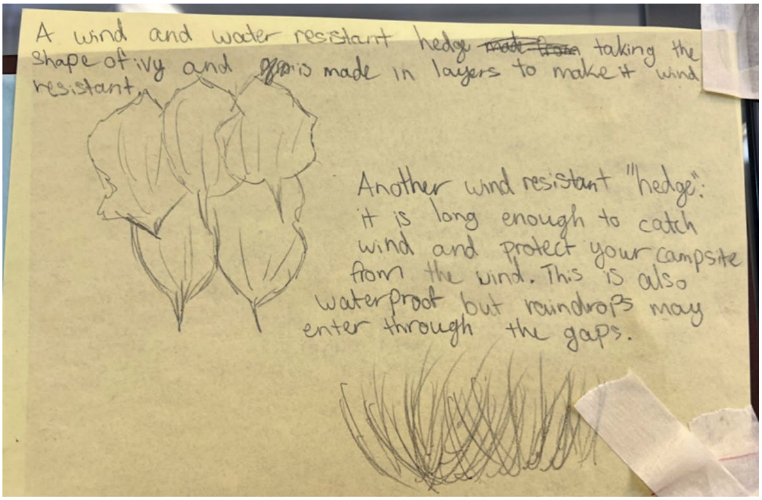
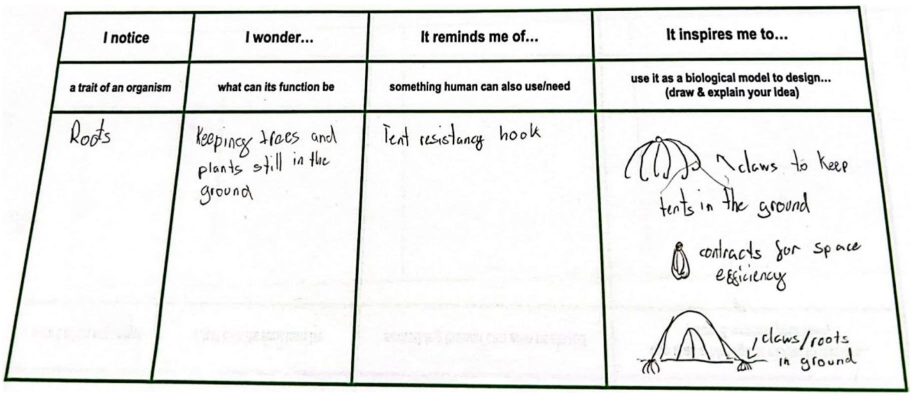


Fig. 2 Iris' observation of ivy leaves and long grasses

shapes and structures in nature, as well as using these abstracted form-function relationships from nature in potential design applications.

Jean and Beth directed their attention to the shape of roots. They recognized how the shape of roots helps stabilize plants in the ground against wind and reasoned that it serves the function of "keeping trees and plants still in the ground" (Fig. 3). Guided by the prompts in the worksheet, they associated the form-function relationship of tree roots with that of a hook, which is commonly used for stabilization, such as in tents. Interestingly, their sketch of the designed tent hook resembled the form of plant roots. They used sketches and annotations to visually elaborate on how the design would be used, detailing the steps of the hook being inserted into the ground to keep the tent stable, as well as the hook's ability to contract for space efficiency when not in use. These children's analogical exploration of forms and functions and their abstraction of form-function relationships



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. 3 Jean and Beth's observation and idea inspired by roots

indicated that they thought spatially about the form, position, and usage of the source (tree roots) and the target (tent hooks).

It is noteworthy that all children in the design project sketched or described new insights they learned about the features of organisms in nature. These examples highlight that developing design-by-analogy ideas typically requires understanding the visual-spatial features of the source, which, in this case, are organisms in nature. Close observations of the forms of these sources of inspiration and meaningful abstractions of spatial form-function relationships laid the groundwork for exploring potential analogical mappings and design ideas.

Developing various possible analogical matches by spatial features and relationships

After familiarizing themselves with the design problem and seeking inspiration from nature, the children embarked on a search for potential design solutions by exploring various possible analogical matches based on spatial features and relations. As an example, a duo of children generated four different design ideas inspired by the spiral-grained trunk of the Whitebark Pine (Fig. 4).

It is important to note that, while Jo and Sanne's inspiration stemmed from the spiral-grained tree trunk, their design ideas did not solely replicate its rigid shape. Having learned that the spiral form on the tree trunk allows for more bending and better distribution of pressure when faced with strong wind, they explored various ways to embody similar form-function relationships in their designs. They envisioned non-rigid spatial transformations of the spiral pattern and applied them to diverse contexts, such as the surface of a pyramid-shaped tent, part of a camping bag, and the soles of shoes. By adapting these biological strategies into design strategies, they reasoned that a tent with an uneven, spiral-grained surface might enhance wind resistance, and a chair with spiral-grained legs could offer more stability in camping scenarios.

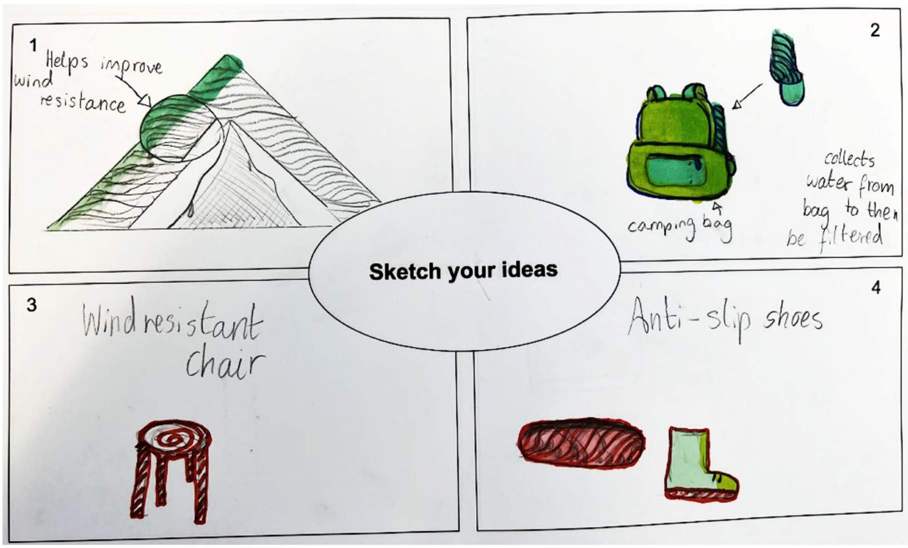


Fig. 4 Four different design ideas inspired by the spiral-grained trunk of Whitebark pine by Jo and Sanne

Interestingly, ideas 2 and 4 (see Fig. 4) were derived from two additional form-function relationships they identified. Jo and Sanne learned that the spiral-grained tree trunk facilitates the distribution of water across the trunk and its branches. Drawing on this observation, they developed idea 2, which incorporated a spiral-grained water-collecting and filtering device into a camping bag design. As for idea 4, these children speculated that the spiral pattern may enhance traction, even though the information about spiral-grained pine trees did not explicitly mention grip. Based on this hypothesis, they developed idea 4, where the spiral pattern was utilized to improve the shoe's grip.

This example highlights these children's ability to make use of more than one type of form-function relationship, exploring diverse ways to integrate spatial features into their own designs. By engaging in an open-ended search for various solutions, these children were able to visualize numerous spatial transformations in their minds.

General spatial thinking processes

The two themes discussed above reflect spatial thinking related to the design-by-analogy process. We will proceed to discuss three themes that were important to this specific design challenge but also appear to be applicable to many other design ideation processes.

Retrieving relevant visual information from memory

After being introduced to the design challenge, the children retrieved relevant information from their memory that was visually related to the desired form or matched the description of relevant functions. The example below shows a pair of children contemplating design ideas inspired by the pine cone, which has scales that open in dry weather and close in wet weather.

Hugh: look it cannot be an umbrella, because when it's cold and wet it's gonna close

Ellen: a house, okay never mind, oh a car, like a folding car, it opens when it's warm and closes when it's cold and rainy… like a convertible car…

From their conversation, we can infer that these children had a basic mental representation of pine cone's biological strategies in their minds. They retrieved various visual information from their memory, such as umbrellas, houses, and cars, to see if the design strategies of these items aligned with pine cone's biological strategies. During their discussion, Hugh quickly noticed that umbrellas open and close in a way opposite to the scales of pine cones. While the idea of a house seemed feasible, Ellen appeared to be more enthusiastic about the idea of a car. He reiterated the mechanism of how the car would open and close, possibly to confirm the compatibility of the two mechanisms.

Through this process of considering how the pine cone's biological strategies could be applied to their designs, Hugh and Ellen compared their mental representations of the form-function relationships observed in the source (pine cone) with potential targets (umbrella, house, car). They engaged in mental imagery to explore possible design ideas, likely visualizing the opening and closing mechanisms, imagining possible motions, and envisioning scenarios where these spatial changes would occur. Based on this comparison and reasoning, they quickly concluded that the umbrella was not a suitable fit. Given the open-ended nature of this design prompt, they further explored the house and the car ideas, as both offered potential for valid analogical mappings.

By tapping into their stored visual knowledge, these children drew from existing patterns and forms to inspire their design solutions. While close-ended spatial tests may also require retrieving relevant visual information from memory, the process of thinking divergently about many possible solutions encouraged the children to conduct a broader search in their memory for relevant visual information.

Elaborating and iterating on design concepts and representations

As the children explored different design options and ultimately decided to further develop one idea, they adapted inferences drawn from the form-function relationships observed in nature to their designs and engaged in a deeper level of reasoning within their design-by-analogy process. Below is a design plan worksheet from a duo of children who designed a foldable solar panel inspired by hornbeam leaves (Fig. 5).

Sean and Andi demonstrated a clear understanding of the form-function relationships in their source of inspiration. They recognized that the foldings on hornbeam leaves provide flexibility in wind and rigidity during photosynthesis. This understanding encompassed the spatial features of the source, the function denoted by the folding structure, and a basic mental representation of wind dynamically interacting with the leaves. As these children elaborated on the biological strategies and design strategies, they explicitly mentioned that just as the foldings on hornbeam leaves make the leaves flexible in winds and rigid during photosynthesis, their solar panel design, which serves a similar function to leaves in collecting light energy, can also benefit from having foldings on its surface. They further reasoned that these foldings offered additional benefits to the solar panel, allowing for a foldable and compact design that is easily portable for camping. Their elaboration on the design plan indicates that Sean and Andi were not only thinking spatially about the form of their design but also tailoring their design concept to the context of this design challenge.

Another example of elaboration and development of the design concept can be seen in the progression in sketching (Fig. 6). Jo and Sanne's sketches evolved from an initial concept to a more detailed visual representation. They not only added three-dimensionality to their sketch but also incorporated additional features to the tent, such as a clear entrance, attached strings, and buckets for water collection. Their understanding of the spiral patterns on the tree trunk, which aid in water and nutrient distribution, influenced the development of their design idea. Both Figs. 5 and 6 highlight how these children not only externalized

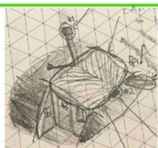
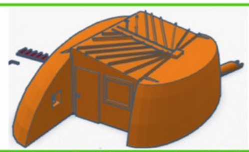
An organism in nature that inspires you	Hornbeam leaves 		
Trait (characteristics of this organism)	The foldings on the leaves		
Function of (a part of) this organism	Foldable leaves help balance out flexibility and rigidity, make leaves flexible in winds and rigid during photosynthetic cycle	**What makes this idea stand out from others?**	Our design is flexible in wind and deflect wind, it is compact, foldable and can be carried to camping. It also stand stiff when used as solar panel to collect solar energy.
Biological strategy of this organism	Hormbeam leaves' folds make it flexible in and resistance to high wind	**What's the design strategy of your design?**	Our folded, leaf-looking solar panel uses hornbeam leaf's strategy of deflecting wind by being flexible in wind and efficiently collects solar energy
Hornbeam leaves **could be a biological model for the design of** EcoSun			

Fig. 5 Design plan for the foldable solar panel inspired by hornbeam leaves, created by Sean and Andi

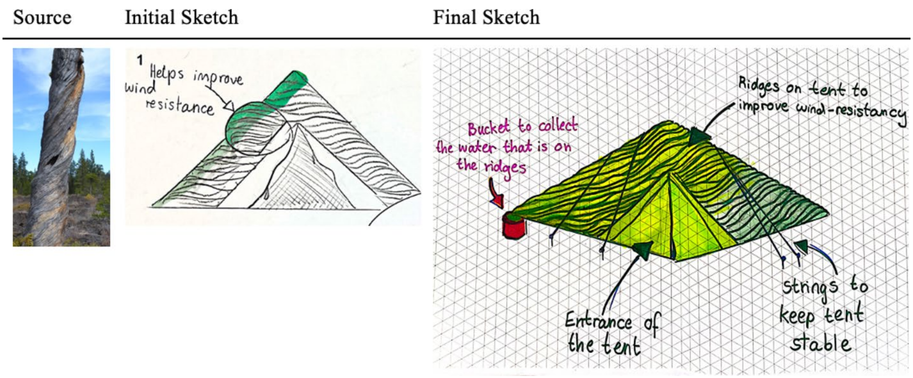


Fig. 6 Development of ideas seen from Jo and Sanne's design sketches

the mental representations via sketches but further expanded on their design ideas with increasingly detailed visualizations.

Visualizing the functionality of design prototypes in practical usage scenarios

According to Finke et al. (1992), the creative thinking process includes envisioning scenarios in which the functionalities of a new design are explored. In our data, we also observed children visualizing their design prototypes in use, evaluating functionality, considering the user's perspective, and thinking of possible improvements. Below, we present a sketch, a TinkerCAD model (Fig. 7), and a conversation segment from a duo of children who designed a camping tarp inspired by the spiral-grained trunk of Whitebark pine. They based their design on the observations that the spiral-grained tree trunk offers wind resistance and facilitates water distribution.

On TinkerCAD, Ivy was resizing the pyramid-shaped top so it became larger and its four angles reached the four corners of the box

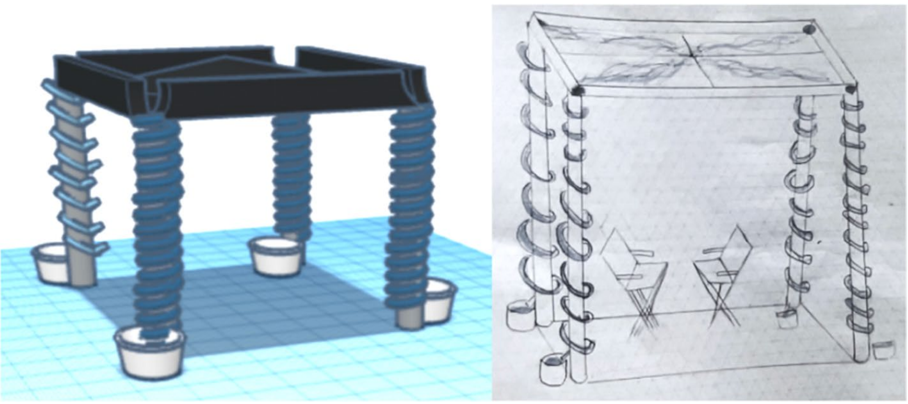


Fig. 7 Sketch and TinkerCAD artifacts from Beth and Ivy, showcasing their camping tarp design inspired by the spiral-grained trunk of Whitebark pine

Beth: does it make sense?… No you know what it doesn't work? because all the water will go over there, over there, and over there, and over there, and not to the corners

As they spoke, Beth pointed at the screen to gesture how the falling rainwater would go to the four sides of the pyramid, horizontally rotating the shape on the top

Beth: now it's perfect you see (dragging the design to check from the side and the top) so the water always goes into that direction, that direction, that direction and that direction…

From their conversation, it is clear that as Beth and Ivy progressed from the sketch on the left to the TinkerCAD design on the right (Fig. 7), they modified the camping tarp's top design into an elevated pyramid shape. These verbal, virtual, and bodily representations show that Beth was actively visualizing the scenario where the design would be used. She visualized how rainfall would interact with the top of the tarp, as well as the trajectory of water flow, concluding that an elevated pyramid-shaped top would address the issue of water overflow. This practice of validation through visualization not only engaged children's spatial thinking but also helped them identify potential areas of improvement in their sketch and TinkerCAD model. Subsequently, it prompted them to iterate on the form of their design to ensure its functionality and cater to users' needs.

Discussion and conclusion

This case study aims to bring together knowledge from the field of spatial ability research, creative cognition, and analogical reasoning. Through a triangulation of evidence from our data, we observed that design education offers unique and largely untapped opportunities to foster spatial thinking development even from an early age, given the social-material nature of design. Children's development of ideas through design-by-analogy demonstrated their frequent use of spatial thinking. They closely examined the spatial features of organisms in nature, abstracted the implications of these spatial forms for specific functions, and visualized—both in their mind and through sketches or modeling—how these form-function relationships could be transformed and applied to a variety of design ideas. Furthermore, the detailed visualizations of ideas created by these children (Figs. 2, 3, 4, 5, 6 and 7) resonate with Clement's (2008, 2009) proposition that imagistic mental simulations and imagistic spatial transformation are crucial for generating analogies to solve problems creatively. Meanwhile, we also noticed that the types, processes, and goals of spatial thinking seen in open-ended design ideation have nuanced differences from those in close-ended spatial tasks.

The first theme, *abstracting spatial features observed in the source to infer form-function relationships,* lays the foundation for analogical mappings. A close examination and abstraction of the key visual-spatial features or processes from biological examples is essential for understanding biological strategies and adapting them into design strategies (Stevens et al., 2021, 2022). Meanwhile, this theme also aligns with previous findings suggesting that design-by-analogy transfers only a certain number of features from the source to the target, requiring careful abstraction from designers (Gentner & Medina, 1998; Qian & Gero, 1996). To solve spatial tasks, observing and abstracting visual-spatial features is important, as one may derive the correct answer to a spatial problem by visualizing the transformation of a key feature (Barratt, 1953). However, in design-by-analogy, children observe and abstract spatial features with the unique goal of discerning their functional roles in nature, and subsequently transforming such form-function relationships into meaningful new designs. This is akin to what Finke et al.

(1992) described as mentally re-arranging and transforming what was known into something new. Hence, it appears that the objective of observations and abstractions in solving open-ended design tasks is distinct from that in conventional, close-ended spatial tasks.

In contrast to the use of spatial thinking in close-ended spatial tests, the themes, *retrieving relevant visual information from memory* and *developing various possible analogical matches by spatial features and relationships*, suggest that the search for possible solutions in open-ended tasks likely requires children to recall and browse through a wide array of relevant visual information. During this process, children might need to form, retain, and manipulate multiple mental representations—which act as 'temporary spatial displays' (Kosslyn et al., 1979)—before deciding on and finalizing the desired idea. By contrast, conventional spatial tasks typically present a selection of given choices. As Maresch (2014) reviewed and summarized, individuals can employ various strategies to tackle a spatial task, including using a falsifying strategy to rule out impossible answers or prioritizing the verification process once a potentially correct answer is identified, thereby dedicating less attention to other options. While these strategies may be effective for multiple-choice questions, they might not be applicable to open-ended prompts. Therefore, we argue that existing spatial training and tasks might not sufficiently prepare children for the visually and spatially demanding processes in design ideation. Such ideation often necessitates a broad exploration of visuals in different directions (Gabora, 2010) and is essential for creativity and innovation.

To share products of creative visualization with others, designers need to "mentally create, manipulate and communicate solutions effectively" (Isham, 1997, p. 2). Similarly, as these children developed their ideas, they continued to enrich the elaborations of their selected ideas by refining details, evaluating suitability, and brainstorming possibilities for improvements and iterations. The themes, *elaborating and iterating on the design concept and representations* and *visualizing the functionality of design prototypes in practical usage scenarios*, engage both divergent and convergent thinking. Prior research (Cropley, 2006; Goldschmidt, 2016; Schut et al., 2020; et al., 2019) indicated that convergent thinking plays an important role in the design process for generating viable ideas. Yet, we observed an interesting distinction between the convergent thinking applied in design ideation and that in conventional spatial tasks. In spatial tasks, convergent thinking is frequently used to determine a single correct answer, typically without the need to refine or improve on the answer. In design, children converge on their design concepts and visualize the functionality with the goal of identifying areas of improvement. This often leads to thinking spatially about possible improvements in their designs' forms (e.g. Figures 6 and 7). Once again, existing spatial training and tests may not adequately reflect how children employ spatial thinking to assess their design ideas or how they actively consider potential improvements to the visual-spatial features of their ideation products.

While spatial thinking is often trained with the goal of enabling participants to perform all transformations mentally, we must not overlook the important role embodied experiences play in spatial thinking (Frick et al., 2009; Link et al., 2013). In this design project, some design ideas stemmed from children's embodied interactions with organisms in nature. This leads us to wonder how these embodied interactions might have supported children's spatial thinking, as well as their analogical and divergent thinking. As Pallasmaa (2017) described, "In the arduous processes of designing, the hand often takes the lead in probing for a vision, or a vague inkling, which it eventually turns into a sketch, materializing thus the idea" (p. 104). Therefore, instead of treating bodily motions and cognitive capacities as distinct agencies, further investigation is needed, perhaps through a multimodal approach, to understand how embodied experiences in design may support children's spatial thinking processes.

In summary, this case study delved into the spatial thinking processes involved in a design-by-analogy ideation process and identified differences between spatial thinking observed in open-ended design ideation and that typically assessed or trained in existing spatial ability research. The potential differences discussed above warrant attention from future researchers especially when assessing spatial ability or developing spatial training, given that many real-life problems are open-ended, requiring a combination of divergent and convergent thinking. Presently, our understanding of spatial thinking largely derives from psychometric test results. By depicting these themes of spatial thinking observed in design ideation—themes not previously discussed in traditional spatial ability research—we suggest the potential need for a more comprehensive definition of spatial thinking. This might be especially relevant for the field of design or other fields that rely heavily on divergent thinking. Admittedly, our proposed themes might not be exhaustive, as our investigation focused primarily on design ideation. Future research is needed to uncover other spatial thinking processes seen in design iteration or design feedback phases.

Lastly, although the concept of biomimicry design was new to the children who participated in this design project, our case study suggests that children of this age can develop biomimicry designs when appropriate scaffolding is provided throughout the project. One type of scaffold came from the materials developed for this project. For instance, the worksheets we designed emphasized the form-function relationship and the analogical mapping between biological strategies and design strategies (e.g. Figures 3 and 5). Another type of scaffolding involved utilizing teacher's support to enhance children's learning throughout the design process. In this specific design challenge, the teacher's language and questions directed children's focus on the visual-spatial forms, such as spirals, folds, and layers of scales, and how these forms imply water- or wind-resistant functions. Such guidance ensured that the children focused on the key form-function relationships without being distracted by other characteristics of the organisms that were less pertinent to the design challenge. The teacher's support also stimulated valuable realizations and conversations among the children. For instance, to help a pair of children understand that biomimicry does not mean directly using organisms in nature (e.g. using pine cones as weather-tellers) but rather applying what can be learned from pine cone scales' weather-responsive mechanism to create a new design, the teacher reminded them of a prior design-by-analogy example they had learned about, in which the human femur bone and the Eiffel Tower may share a similar efficient structure but are made of distinct materials in different sizes. Subsequent discussions between these children reflected a clearer understanding of biomimicry. Practices like these align with the recommended strategies to support analogical learning (Vendetti et al., 2015). It is necessary to note that our analysis focused on the progress and artifacts produced by pairs of children rather than individual efforts. Thus, future research is needed to investigate how to scaffold individual child's spatial thinking, divergent thinking, and analogical thinking within a design project.

Acknowledgements We would like to thank all the children who participated in this study for their valuable contributions. We thank Eveline Holla and Rohit Mishra for their contribution to data collection. And we thank Laura Stevens for inspirations in the biomimicry activity design. Informed participation consent was obtained from the parents. Ethical clearance was obtained from the Human Research Ethics Committee, TU Delft.

Funding 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.

Declarations

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

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