Delft University of Technology

Scaffolding Pupils’ Spatial Thinking through Design
A Biomimicry Project for the Primary Classroom

Zhu, Caiwei; Klapwijk, R.M.

Publication date
2022

Document Version
Final published version

Published in
PATT 39 On the Edge Proceedings

Citation (APA)
Zhu, C., & Klapwijk, R. M. (2022). Scaffolding Pupils’ Spatial Thinking through Design: A Biomimicry Project for the Primary Classroom. In D. Gill, J. Tuff, T. Kennedy, S. Jamil, & S. Pendergast (Eds.), *PATT 39 On the Edge Proceedings: Designing A Better World Through Technological Literacy for All* (pp. 142-154).

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

PATT 39

ON THE EDGE

TECHNOLOGY, INNOVATION & EDUCATION

PROCEEDINGS

DESIGNING A BETTER *WORLD* THROUGH TECHNOLOGICAL LITERACY *FOR ALL*

June 21 – 24, 2022
Memorial University,
St. John's, NL, Canada

Editors:
David Gill, Jim Tuff, Thomas Kennedy, Shawn Pendergast and **Sana Jamil**

MEMORIAL UNIVERSITY
MARINE INSTITUTE
PATT
100 years of excellence
FACULTY OF EDUCATION MEMORIAL UNIVERSITY
Newfoundland Labrador CANADA
Newfoundland & Labrador English School District
CONSEIL SCOLAIRE FRANCOPHONE PROVINCIAL

PATT 39

PATT on the Edge

Technology, Innovation and Education

St. John's, Newfoundland and Labrador, Canada

June 21st-24th, 2022

Edited by:

Dr. David Gill
Memorial University
Mr. Jim Tuff
Memorial University
Dr. Thomas Kennedy
Memorial University
Dr. Shawn Pendergast
Memorial University
Ms. Sana Jamil
Memorial University

Faculty of Education
Memorial University of Newfoundland

© 2022 The Authors

ISBN: 978-0-88901-505-0

Scaffolding Pupils' Spatial Thinking through Design: A Biomimicry Project for the Primary Classroom

Caiwei Zhu[1*], Remke M. Klapwijk[1]

[1]Delft University of Technology, Faculty of Applied Sciences, Science Education and Communication, Delft, Netherlands

[*]Correspondence: c.zhu-1@tudelft.nl

Abstract

Spatial thinking is embedded in science, technology, engineering, arts, and mathematics (STEAM) learning. Design and Technology education inherently encompasses a wide range of spatial activities, such as mentally transforming objects to form design ideas, visually representing design ideas, and creating 2D and 3D design artifacts. Among different design topics, biomimicry offers a unique avenue for pupils to recognize and analyze forms and functions in nature. It is expected that pupils exercise multiple types of spatial thinking when envisioning the analogical links between nature's strategies to design strategies. This case study is one of the first to highlight the opportunities to scaffold primary-school pupils' spatial thinking through a biomimicry design project. Embracing the methodology of educational design-based research, this project is designed along with teachers' input and authentic classroom feedback. Data are gathered from sixteen 11- to 12-year-olds at an international school in the Netherlands. Classroom videos and audios, pupils' self-documentation of the design process, 2D and 3D design artifacts, a baseline survey of spatial reasoning ability, formative assessment on design, and semi-structured interviews with pupils triangulate evidence for pupils' spatial thinking in this project. Our preliminary findings suggest that pupils actively used their spatial thinking when forming biomimicry design ideas and visually elaborating their designs. This study contributes to the growing theories of integrating spatial training in primary curriculums and offers empirically-grounded recommendations for the design of spatially engaging learning ecologies.

Key Words: Spatial thinking, Design education, Analogy, Biomimicry, Primary education

1. INTRODUCTION

Spatial thinking is fundamental to the learning of a wide range of STEAM (science, technology, engineering, arts, mathematics) disciplines, including Design and Technology (D&T) (e.g. Buckley et al., 2018, 2022; Hegarty, 2014; Kell et al., 2013). Applying spatial thinking appropriately can fuel creativity and facilitate problem-solving in D&T (Kell et al., 2013; Suh & Cho, 2020). However, a lack of necessary spatial thinking skills may lead to frustration in comprehending and creating designs (Sorby, 2009).

The process of forming a mental representation of a tangible object in our daily life, as Lane and Sorby (2021) explained, demands a variety of spatial thinking, such as imagining an altered version of an object. The process of designing is even more challenging as it requires not only formulating, manipulating, and communicating mental representations of ideas that are not yet present in reality but also the transformation of 2D sketches into 3D artifacts. We find D&T education to be a suitable vehicle to nurture a higher level of spatial thinking. However, little research has looked into how pupils use and develop their spatial thinking in design and technology classrooms.

One way to develop spatial thinking in the classroom is through the use of analogies (Newcombe, 2010, 2016, 2017). Analogy, as one of the essential expressions of creativity (Boden, 2001), means mapping the knowledge about one situation parallelly to prescribe for another situation. A specific approach to designing through analogies is biomimicry, where designers use knowledge from nature to inspire human designs. Since analogical comparison between highly different fields is especially helpful for stimulating innovative ideas (Chan et al., 2011), we believe that biomimicry, which combines the knowledge from design and biology, will provide a challenging yet exciting opportunity for pupils to practice spatial thinking.

In the biomimicry design project we developed, we provided 11-to-12-year-old pupils with ample opportunities to exercise their spatial thinking, including closely observing, visualizing, using mental transformation to relate forms with functions, sketching, modeling, and physically interacting with organisms in nature. To solve the design challenge of creating nature-inspired, wind- or water-resistant camping gears, pupils are expected to explicitly identify the analogies between nature's strategies against excessive wind or water and possible human design strategies. Through envisioning the spatial features of organisms in nature and identifying the analogical links between nature's design and human design, pupils will draw spatial insights from nature to inspire their designs.

The main goal of this case study is to uncover how a design project emphasizing analogies between nature and human designs can entail opportunities for pupils to exercise spatial thinking. Currently, only a few studies have zoomed in on the processes during which learners develop spatial thinking (e.g. Cohrssen et al., 2017). Therefore, our study aims to add to the knowledge base about how spatial thinking can be engaged and scaffolded in the classroom through design projects.

2. LITERATURE REVIEW

2.1. Spatial thinking in the classroom

Spatial thinking consists of the understanding of the properties of space, the utilization of representations, and the reasoning to make meaning and use of spatial information (National Research Council, 2006). Whether it is identifying the spatial features of organisms in nature, such as their shape and size (Ermayanti et al. 2017), or visualizing and creating representations of three-dimensional structures and processes in biology (Milner-Bolotin & Nashon, 2012), spatial thinking plays a critical role. While spatial thinking can be developed (e.g. Hawes et al., 2017; Sorby, 2009; Uttal et al., 2013), the challenge lies where multiple rather than a single spatial skill are usually required to solve complex spatial problems (Atit et al., 2020). Thus, there is a substantial need for pupils to learn and practice spatial thinking in the context of real-world problems (Uttal et al., 2013).

Integrating spatial training in the classroom and spatializing the existing curriculums have drawn increasing attention from researchers (Buckley et al., 2022; Newcombe, 2010, 2016, 2017; Newcombe et al., 2013). For example, Hawes et al. (2017) infused spatialized geometry instruction in classrooms and successfully translated the knowledge from research to create an educational impact. Therefore, to achieve a holistic design of spatial training, it is important to integrate spatial thinking with domain knowledge in mind (Atit et al., 2020).

2.2. Analogy as a way to integrate spatial thinking in the classroom: analogical links in Biomimicry

One way to integrate the training of spatial thinking and skills in classrooms is through analogies (Newcombe, 2010, 2016, 2017). Positioning analogous examples side by side allows pupils to recognize the common patterns in their features and relations (Gentner et al., 2003). Such processes are fundamental to spatial thinking (Mathewson, 1999) and have been used to facilitate the development of spatial thinking. For example, 6-to-8-year-olds can learn the spatial concept of stability through reasoning analogically about two similar spatial structures (Gentner et al., 2009). In Geosciences, Ormand et al. (2017) trained students' mental slicing skills, such as visualizing the slices of fossils, through an analogous Slicing Fruit activity.

Biomimicry, an example of design by analogy, plays an increasingly important role in both design processes and design education (e.g. Benyus, 1997; Stevens et al., 2021) and has been recognized as an important STEM topic to be taught in primary classrooms (NGSS Lead States, 2013). According to the U.S. National Research Council (2006), spatial thinking processes can be summarized as "extracting spatial structures, performing spatial transformations, and drawing functional inferences" (p. 47). In the case of biomimicry, pupils extract spatial features of organisms in nature, perform a spatial transformation with an analogy to a potential human design, and draw functional inferences from nature for their designs.

The role of biomimicry in developing pupils' spatial thinking has not been explored much. Wolf et al. (2022) made a promising attempt to use phenomena in nature to support young children's spatial development. However, their research uses the visual language system in nature to mainly support mathematics education rather than design education. Thus, no other previous research to our knowledge has explored the potential of using a biomimicry design project to engage primary pupils in spatial thinking.

A powerful use of analogy, which is especially valuable in design education, is mapping the knowledge about one situation to inform a similar but novel situation (Holyoak, 2012). We expect that by placing analogous biological examples and human design examples side by side, pupils will identify the commonalities between examples at both the form level (spatial features) and the function level (what those features do) and then transfer the knowledge gained from biological examples to inform their own biomimicry designs. We expect the design-by-analogy process would engage them in multiple types of spatial thinking, such as constructing and comparing visual or spatial representations (Smith & Gentner, 2012; Vendetti et al, 2015), identifying the shared spatial relations (Loewenstein & Gentner, 2001), visually and verbally elaborating the mental models (Goldschmidt, 1995), and the learning of spatial concepts (Gentner et al., 2009).

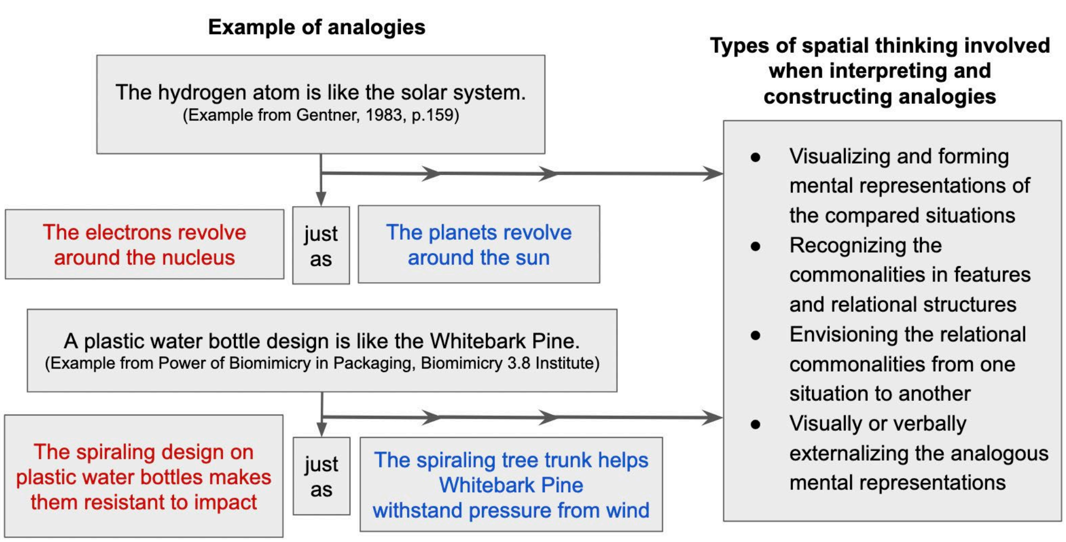


Figure 1. An example of an analogy from Gentner (1983) and a biomimicry example from Biomimicry 3.8 Institute that reflect analogical comparison and the potential spatial thinking required for analogical comparison

2.3 Developing spatial thinking through Design and Technology education

Using analogy to scaffold pupils' spatial thinking fits well with Design and Technology education since analogy has been studied extensively for problem-solving and innovation in these disciplines (e.g. Beveridge & Parkins, 1987; Casakin & Goldschmidt, 1999). Applying visual analogies, especially with a wide range of analogous examples given, boosts the generation of novel solutions to design problems (Goldschmidt, 2001; Wilson et al., 2010) and may be especially helpful for those who are new to design (Casakin, 2004). Given the emerging efforts to study spatial thinking in the field of Design and Technology (e.g. Bhaduri et al., 2019; Buckley et al., 2022), we believe that D&T education provides an ideal platform to study how spatial thinking training can be integrated into formal and informal D&T curriculums and consequently influence pupils' interest and performance in STEAM.

3. METHODOLOGY

We developed the biomimicry design project in this study and adopted a design-based research (DBR) approach to bridge the gap between the knowledge from research and the application in authentic education settings. DBR provides the empirical grounding to test innovative education designs with the goal of developing generalizable theories on educational practices and phenomena (Bakker, 2018).
Our project is conveniently designed into one module in the International Baccalaureate (IB) design course. Working collaboratively with the classroom teacher, we adapted the content in the design project to not only reflect the aim of our study but also what pupils have been practicing in their IB design modules, such as TinkerCAD, a 3D computer-aided design platform where pupils can use functions such as combining shapes, resizing, and rotating to digitally represent their designs. The core concepts in this biomimicry design project align with several IB key concepts, such as form, function, and seeing in perspectives. We refined the activity structures after each design session using feedback from the class and the teacher.

3.1. Participants, lesson structure, and data collection

16 pupils and one classroom teacher from an international school in the Netherlands have consented to participate in the study. In eight 45-min sessions, pupils were expected to solve the design challenge by sketching their nature-inspired, wind- or water-resistant camping gear designs in 2D and then creating 3D visualization of their designs on TinkerCAD (Figure 2). We selected this design topic since wind- or water-resistant function is often performed by organisms' external features, which requires pupils to use spatial thinking to observe and visualize. Analogical comparisons between nature and human design were practiced in every session, before and during the design process.

Session 1	Introduction: nature as a source of inspiration for human design
Session 2	Seeing the unseen: first biomimicry design ideas gained from outdoor exploration
Session 3	Analogical comparison: linking biological strategies to design strategies
Session 4	Idea generation: linking biological strategies to potential design strategies and sketch initial design ideas; identify best ideas that both reflect biomimicry and fit the design challenge
Session 5	Creating detailed sketches and annotations for the design ideas
Session 6	Creating 3D models of the design ideas on TinkerCAD
Session 7	Iterating on and finalizing the prototypes on TinkerCAD
Session 8	Presenting the design artifacts: sources of inspiration (biological examples), links between biological strategies to design strategies, features, and functions of the final designs

Figure 2. Session plan

Multiple strands of quantitative and qualitative data are collected to demonstrate pupils' spatial thinking in the design project. We used the Spatial Reasoning Instrument (Ramful et al., 2017) primarily to understand the baseline spatial reasoning ability of pupils in this class and as an additional reference to explain potential differences in their use of spatial thinking in design. This instrument surveys mental rotation, spatial visualization, and spatial orientation and is appropriate for our age group. Qualitative data consist of video and audio from each session, pupils' self-documentation of their design process on Google Jamboard, intermediate design artifacts (2D annotated sketches), final design artifacts (3D design on TinkerCAD), formative assessment of pupils' design, and semi-structured interviews with pupils.

4. RESULTS

In our data, we looked for moments where pupils actively exercised their spatial thinking, including but not limited to when they observe and analyze the spatial features of organisms in nature, analogically compare nature's strategies to human design strategies, and when they visualize and elaborate design ideas through spatially complex sketches and TinkerCAD designs. Three themes emerged about how this design project can scaffold pupils' spatial thinking.

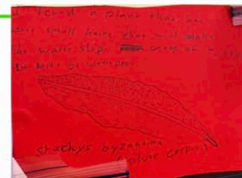
4.1. Designing with embodied experiences

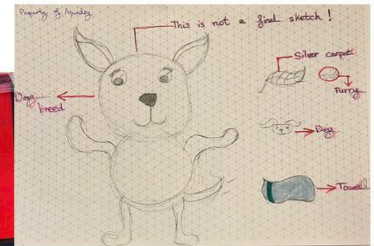
In the second session, pupils gathered specimens from nature and used sketches to explain their initial ideas towards a wind or water-resistant design inspired by nature. Through close observation and physical interaction with a plant called the silver carpet, two pupils noticed that "the small hairs (on its surface) will make the water slip," serving a water-resistant function while making the leaf feels soft in touch. Their understanding of the function of the small hairs on silver carpet indicates that they visualized, to some extent, the motion trajectory of water droplets on the leaf surface. They then aligned these characteristics with something humans can make use of: a silver-carpet-inspired, water-resistant teddy bear that feels soft and does not get wet easily (Figure 3). Being the first pair of pupils to come up with a design idea, they mentioned that what they observed and felt in nature helped them most in mapping out the nature-design connection and grasping the challenging idea of biomimicry.

While both pupils were at the lower end of the baseline spatial reasoning scores compared to their classmates, their thorough examination of the silver carpet leaves helped them recognize the shared physical features of the leaves and a teddy bear. They imagined and mentally transformed both the form and the function of tiny hairs on a plant as being used on a toy and used their spatial thinking to represent this idea visually. While these pupils' work only shows their initial ideas, we can infer from this case that embodied experience and analogies helped them think and design spatially.

Our sketch

Our inspiration from nature





An organism in nature that inspires you	Silver carpet leaves	**Design a possible human application**	
Trait (<u>characteristics</u> of this organism)	Very small hairs on its surface		
<u>Function</u> of (a part of) this organism	The small hairs on it makes it water resistant and feels fluffy	**What makes this idea stand out from others?**	The silver carpet inspired Aquadog is fluffy and help kids who feel homesick when camping, and because it is water resistant it can be taken anywhere
<u>Biological strategy</u> of this organism	The tiny hair on silver carpet leaves makes water drop slip and make it water resistant	**What's the <u>design strategy</u> of your design?**	The Aquadog looks and feels like a toy teddy bear, but it has tiny hair that makes it resistant to water like how silver carpet is water resistant
Silver carpet **could be a biological model for the design of** Aquadog			

Figure 3. Two pupils' design of water-resistant teddy bear: Aquadog

4.2. Using analogies to clarify the design theme and spark novel ideas

In the fourth session, one pair of pupils used pine cones as their biological model but encountered difficulties. They first thought of directly using pine cones as weather-tellers, yet they received feedback from the teacher that a biomimicry design means burrowing the function served by pine cones' scales instead of using the entire organism to make a new design. To further clarify the concept of biomimicry, the teacher reminded them of one previous example they learned, in which the human femur bone and the Eiffel tower share a similar structure that maximizes stability but are made of distinct materials and are of different sizes. This example helped them realize that their design goal was to use pine cone's form and function as an inspiration for an analogous situation.

Eventually, they designed a pair of camping shoes with bottoms that close when raining to provide grip and prevent people from slipping in the rain (Figure 4). Their design reflects their visualization of the transforming process, where the bottoms of the shoes close when in contact with water just like the scales of pine cones. In this case, analogical examples served as anchor points for pupils to check their understanding of the shared spatial features between nature and human design and transfer knowledge from nature to inspire their design.

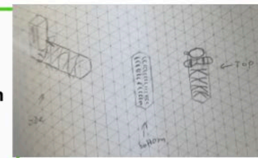
An organism in nature that inspires you	Pine cone 	**Design a possible human application**	 
Trait (<u>characteristics</u> of this organism)	They have scales that can open or close when weather change		
<u>Function</u> of (a part of) this organism	The scales close when it is wet outside and opens when it is dry	**What makes this idea stand out from others?**	It prevent people from slipping and it is inspired by pine cone
<u>Biological strategy</u> of this organism	The scales automatically close when it contact water and rain	**What's the <u>design strategy</u> of your design?**	When its scale bottom close because of rain, it provides grip to the shoes, so people don't slip on the ground in rain
Pine cone **could be a biological model for the design of** Non slip grip shoes			

Figure 4. Two pupils' design of non-slipping shoes suitable for walking in the rain

Another pair of pupils recalled that the idea of biomimicry was hard to grasp at first. Yet after being exposed to many design-by-analogy examples in the first four sessions, they were able to clearly distinguish what is or is not a biomimicry design. When given the hornbeam leaves as a source of inspiration, this pair of pupils not only correctly identified that the foldings on the leaf allow for its flexibility in the wind but also identified an additional trait, being that the foldings help the leaf stay rigid during photosynthesis. They associated photosynthesis in plants analogically with the solar energy gathering by humans, thereby deciding on designing a wind-resistant solar panel that mimics how hornbeam leaves cope with strong wind (Figure 5).

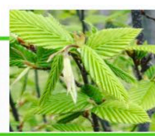
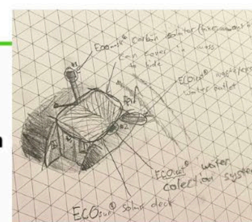
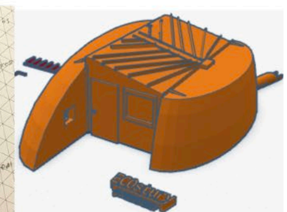
An organism in nature that inspires you	Hornbeam leaves 	**Design a possible human application**	 
Trait (<u>characteristics</u> of this organism)	The foldings on the leaves		
<u>Function</u> of (a part of) this organism	Foldable leaves help balance out flexibility and rigidity, make leaves flexible 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.
<u>Biological strategy</u> of this organism	Hormbeam leaves' folds make it flexible in and resistance to high wind	**What's the <u>design strategy</u> 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			

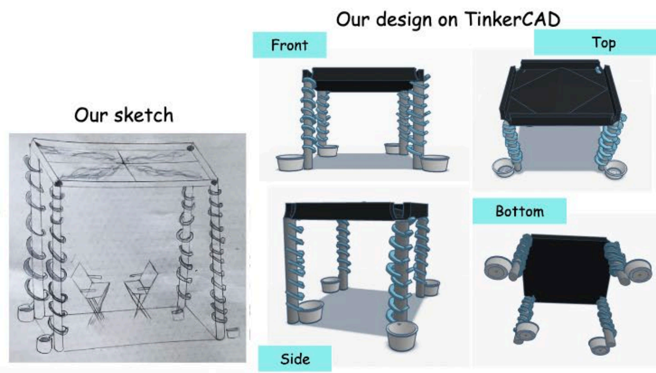
Figure 5. Two pupils' design of wind-resistant solar panel: EcoSun

4.3. Visualizing the design in the use

By the end of the fifth session, two pupils identified that a spiral-grained trunk allows the tree to better cope with the tension from wind and also help the distribution of nutrient. They used their spatial thinking to extract the spatial features of the tree trunk, comprehend the function served by the spiraling form, and envision how spirals can be transformed and applied in an analogous situation that requires wind resistance. They also learned about a spatial concept that, compared to a straight-grained structure, a spiral-grained structure deflects tension by allowing more bending.

Upon finalizing their camping tarp design on TinkerCAD (Figure 6), one of the pupils questioned if this design would really work. “Actually, it doesn’t work because all the water will get stuck at the four corners,” the other pupil responded in realization, pointing to the screen and explaining that their current design might not work mechanically as intended. They solved this problem on TinkerCAD by first elevating the surface of the tarp to make a pyramid structure and then using a sphere to cut out four corners for the water to fall.

We observed that three out of eight pairs of pupils actively visualized through their thinking and discussions about how well their designs will hold up to wind or water. By mentally testing their designs out, they not only need to imagine a spatially complex process where their designs are in use but also visualize the solution to any perceived obstacles when testing the functionality of their designs. Notably, the three pairs of pupils who actively visualized how their design would function in reality all scored on the higher end in the baseline spatial reasoning test compared to their classmates.



An organism in nature that inspires you	Spiral trees	Design a possible human application	
Trait (characteristics of this organism)	Spirals on its trunk		
Function of (a part of) this organism	1. Spiraling trunk provides wind resistancy 2. Water spirals down and get distributed on the trunk	What makes this idea stand out from others?	it stays in shape in strong wind and spirals can help collect rain water, so it does not flow all over the place
Biological strategy of this organism	The trunk spirals the wind away, it also makes the rain spiral down to its roots and nutrients up to its branhces	What's the design strategy of your design?	Rain water is collected on top of the tent and it flows down through spirals to the buckets, also spiral tent poles help the tent stand against wind
The spiral trees could be a biological model for the design of the Drytent			

Figure 6. Two pupils’ design of a wind-resistant and water-recycling camping tarp: Drytent

5. CONCLUSION AND DISCUSSION

In our preliminary analysis, 14 out of 16 pupils in this class successfully produced designs that reflect biomimicry and provide promising solutions to the design challenge. We identified two specific moments where pupils actively used multiple types of spatial thinking in this biomimicry project. First, when forming biomimicry design ideas, pupils used one or more of the following spatial thinking processes, including visualizing how organisms in nature react to excessive wind or water, identifying common features between biological examples and human designs, using mental transformation to relate forms with functions, drawing functional inferences from the spatial features of biological examples, and analogously applying mechanisms found in nature to develop design ideas for a different context, the campsite.

The second moment is seen when pupils visually elaborated their design thinking through detailed 2D sketches and 3D models in TinkerCAD. Pupils often need to visualize their designs from different perspectives, mentally rotate and resize the many components of a design, and measure the different components to create accurate representations of their ideas. It is worth highlighting that some pupils mentally tested out whether their design would work in real life, indicating that they may have used their spatial thinking to imagine a series of interactions happening between their designs and the surroundings. Thus, the active visualization of designs in real-world applications may be a helpful practice in design education that challenges pupils to create functional designs and exercise their spatial thinking. How to support all students to embark on a spatially challenging evaluative process remains a question.

We also observed that the interaction with physical objects in nature allows pupils to understand the functions served by the spatial features of organisms and aids their generation of novel design ideas, even among pupils with relatively lower spatial reasoning scores. Physical manipulatives from nature might have acted as a scaffold for pupils to understand nature's strategies and apply such knowledge in their designs. Our finding on using embodied experience to scaffold the process of spatial thinking in design projects aligns with what Stull et al. (2012) suggested about using physical models to help students envision and solve spatially-challenging chemistry problems.

This case study documents how and where in a design project do pupils practice spatial thinking and demonstrates the potential of a design-by-analogy project in scaffolding pupils' spatial thinking. As one of the first attempts in Design and Technology education to implement a biomimicry design project in the primary classroom, this study adds to the theories of integrating spatial thinking training in the classroom (e.g. Buckley et al., 2022; Newcombe, 2010, 2016) and practicing spatial thinking in the context of real-world problems (Uttal et al., 2013).

Additionally, this project invited pupils to draw knowledge from design, technology, and biology and the design of this project has been iterated based on inputs from teachers and researchers from different disciplines. It resonates with Bruce et al.'s (2017) proposal for taking a transdisciplinary approach to studying spatial thinking. We will explore the possibilities of developing concrete practices in Design and Technology projects to scaffold pupils' spatial thinking through future studies.

6. ACKNOWLEDGMENTS

We would like to thank the teachers and pupils for their participation. This research is part of the SellSTEM project (https://sellstem.eu/), funded by Marie Skłodowska-Curie Innovative Training Network (grant no. 956124).

7. REFERENCES

Atit, K., Uttal, D. H., & Stieff, M. (2020). Situating space: Using a discipline-focused lens to examine spatial thinking skills. *Cognitive Research: Principles and Implications*, 5(1), 1-16. https://doi.org/10.31234/osf.io/jyuvz

Bakker, A. (2018). *Design Research in Education: A Practical Guide for Early Career Researchers (1st ed.)*. Routledge.

Benyus, J. M. (1997). *Biomimicry: Innovation inspired by nature.* New York: Morrow.

Beveridge, M., & Parkins, E. (1987). Visual representation in analogical problem solving. Memory & Cognition, 15(3), 230-237. https://doi.org/10.3758/bf03197721

Bhaduri, S., Van Horne, K., & Sumner, T. (2019). Designing an informal learning curriculum to develop 3D modeling knowledge and improve spatial thinking skills. *In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, 1-8. https://doi.org/10.1145/3290607.3299039

Biomimicry 3.8 Institute. *Power of Biomimicry in Packaging* [Brochure]. https://b38.app.box.com/s/o1fpgxb39tkmlcqvq2okot2itvcbnes4

Boden, M. (2001). Creativity and knowledge. In A. Craft, B. Jeffrey, & M. Leibling (Eds.), *Creativity in education* (pp. 95-102). London: Continuum.

Bruce, C. D., Davis, B., Sinclair, N., McGarvey, L., Hallowell, D., Drefs, M., ... & Woolcott, G. (2017). Understanding gaps in research networks: using "spatial reasoning" as a window into the importance of networked educational research. *Educational Studies in Mathematics*, 95(2), 143-161. https://doi.org/10.1007/s10649-016-9743-2

Buckley, J., Seery, N., Canty, D., & Gumaelius, L. (2018). Visualization, inductive reasoning, and memory span as components of fluid intelligence: Implications for technology education. *International Journal of Educational Research*, 90, 64-77. https://doi.org/10.1016/j.ijer.2018.05.007

Buckley, J., Seery, N., Canty, D., & Gumaelius, L. (2022). The importance of spatial ability within technology education. *In Applications of Research in Technology Education* (pp. 165-182). Springer, Singapore. https://doi.org/10.1007/978-981-16-7885-1_11

Casakin, H. (2004). Visual analogy as a cognitive strategy in the design process. Expert versus novice performance. *Journal of Design Research*, 4(2), 197-217. https://doi.org/10.1504/jdr.2004.009846

Casakin, H., & Goldschmidt, G. (1999). Expertise and the use of visual analogy: implications for design education. *Design Studies*, 20(2), 153-175. https://doi.org/10.1016/s0142-694x(98)00032-5

Chan, J., Fu, K., Schunn, C., Cagan, J., Wood, K., & Kotovsky, K. (2011). On the benefits and pitfalls of analogies for innovative design: Ideation performance based on analogical distance, commonness, and modality of examples. *Journal of Mechanical Design*, 133, 081004. https://doi.org/10.1115/1.4004396

Cohrssen, C., de Quadros-Wander, B., Page, J., & Klarin, S. (2017). Between the big trees: A project-based approach to investigating shape and spatial thinking in a kindergarten program. *Australasian Journal of Early Childhood*, 42(1), 94-104. https://doi.org/10.23965/ajec.42.1.11

Ermayanti, Rustaman, N. Y., & Rahmat, A. (2017). Types of reasoning in framing based plant anatomy and it relation to spatial thinking. *In Journal of Physics: Conference Series*, 812 (1), 12-55. IOP Publishing. https://doi.org/10.1088/1742-6596/812/1/012055

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, 7(2), 155-170. https://doi.org/10.1016/b978-1-4832-1446-7.50026-1

Gentner, D., Levine, S., Dhillon, S., & Poltermann, A. (2009). Using structural alignment to facilitate learning of spatial concepts in an informal setting. *In Proceedings of the Second Analogy Conference*, 175-182. NBU Press Sofia, Bulgaria.

Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology*, 95(2), 393. https://doi.org/10.1037/0022-0663.95.2.393

Goldschmidt, G. (1995). Visual displays for design: Imagery, analogy and databases of visual images. *Visual databases in architecture*, 53-74. Avebury Press.

Goldschmidt, G. (2001). Visual analogy—a strategy for design reasoning and learning. *Design knowing and learning: Cognition in design education*, (pp. 199-219). Elsevier Science. https://doi.org/10.1016/b978-008043868-9/50009-7

Hawes, Z., Moss, J., Caswell, B., Naqvi, S., & MacKinnon, S. (2017). Enhancing children's spatial and numerical skills through a dynamic spatial approach to early geometry instruction: Effects of a 32-week intervention. *Cognition and Instruction*, 35(3), 236-264. https://doi.org/10.1080/07370008.2017.1323902

Hegarty, M. (2014). Spatial thinking in undergraduate science education. *Spatial Cognition & Computation*, 14(2), 142-167. https://doi.org/10.1080/13875868.2014.889696

Holyoak, K. J. (2012). Analogy and relational reasoning. In K. J. Holyoak & R. G. Morrison (Eds.), *The Oxford handbook of thinking and reasoning* (pp. 234-259). New York: Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199734689.013.0013

Kell, H. J., Lubinski, D., Benbow, C. P., & Steiger, J. H. (2013). Creativity and technical innovation: Spatial ability's unique role. *Psychological Science*, 24(9), 1831-1836. https://doi.org/10.1177/0956797613478615

Lane, D., & Sorby, S. (2021). Bridging the gap: blending spatial skills instruction into a technology teacher preparation programme. *International Journal of Technology and Design Education*, 1-21. https://doi.org/10.1007/s10798-021-09691-5

Loewenstein, J., & Gentner, D. (2001). Spatial mapping in preschoolers: Close comparisons facilitate far mappings. *Journal of Cognition and Development*, 2(2), 189-219. https://doi.org/10.1207/s15327647jcd0202_4

Mathewson, J. H. (1999). Visual-spatial thinking: An aspect of science overlooked by educators. *Science Education*, 83(1), 33-54. https://doi.org/10.1002/(SICI)1098-237X(199901)83:1<33::AID-SCE2>3.0.CO;2-Z

Milner-Bolotin, M., & Nashon, S. M. (2012). The essence of student visual–spatial literacy and higher order thinking skills in undergraduate biology. *Protoplasma*, 249(1), 25-30. https://doi.org/10.1007/s00709-011-0346-6

National Research Council. (2006). *Learning to Think Spatially.* Washington, DC: The National Academies Press. https://doi.org/10.17226/11019

Newcombe, N.S. (2017). Harnessing Spatial Thinking to Support Stem Learning, *OECD Education Working Papers,* No. 161, OECD Publishing, Paris. https://doi.org/10.1787/7d5dcae6-en

Newcombe, N. S. (2016). Thinking spatially in the science classroom. *Current Opinion in Behavioral Sciences*, 10, 1-6. https://doi.org/10.1016/j.cobeha.2016.04.010

Newcombe, N. S. (2010). Picture this: Increasing math and science learning by improving spatial thinking. *American Educator*, 34(2), 29.

Newcombe, N. S., Uttal, D. H., & Sauter, M. (2013). Spatial development. In P. D. Zelazo (Ed.), *The Oxford handbook of developmental psychology* (Vol. 1): Body and mind (pp. 564–590). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199958450.013.0020

NGSS Lead States. (2013). *Next Generation Science Standards: For States, By States.* Washington, DC: The National Academies Press. https://doi.org/10.17226/18290

Ormand, C. J., Shipley, T. F., Tikoff, B., Dutrow, B., Goodwin, L. B., Hickson, T., ... & Resnick, I. (2017). The Spatial Thinking Workbook: A research-validated spatial skills curriculum for geology majors. *Journal of Geoscience Education*, 65(4), 423-434. https://doi.org/10.5408/16-210.1

Ramful, A., Lowrie, T., & Logan, T. (2017). Measurement of spatial ability: Construction and validation of the spatial reasoning instrument for middle school students. *Journal of Psychoeducational Assessment*, 35(7), 709-727. https://doi.org/10.1177/0734282916659207

Smith, L. A., & Gentner, D. (2012). Using spatial analogy to facilitate graph learning. *In International Conference on Spatial Cognition* (pp. 196-209). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-32732-2_13

Sorby, S. A. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, 31(3), 459-480. https://doi.org/10.1080/09500690802595839

Stevens, L., Kopnina, H., Mulder, K., & de Vries, M. J. (2021). Analogies in Biomimicry. *In Design-Based Concept Learning in Science and Technology Education* (pp. 248-281). Brill Sense. https://doi.org/10.1163/9789004450004_012

Stull, A. T., Hegarty, M., Dixon, B., & Stieff, M. (2012). Representational translation with concrete models in organic chemistry. *Cognition and Instruction*, 30(4), 404-434. https://doi.org/10.1080/07370008.2012.719956

Suh, J., & Cho, J. Y. (2020). Linking spatial ability, spatial strategies, and spatial creativity: a step to clarify the fuzzy relationship between spatial ability and creativity. *Thinking Skills and Creativity*, 35, 100628. https://doi.org/10.1016/j.tsc.2020.100628

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: a meta-analysis of training studies. *Psychological Bulletin*, 139(2), 352. https://doi.org/10.1037/a0028446

Vendetti, M. S., Matlen, B. J., Richland, L. E., & Bunge, S. A. (2015). Analogical reasoning in the classroom: Insights from cognitive science. *Mind, Brain, and Education*, 9(2), 100-106. https://doi.org/10.1111/mbe.12080

Wilson, J. O., Rosen, D., Nelson, B. A., & Yen, J. (2010). The effects of biological examples in idea generation. *Design Studies*, 31(2), 169-186. https://doi.org/10.1016/j.destud.2009.10.003

Wolf, A., Parikh, V., & De Lisi, I. (2022). The pattern alphabet: Nature's patterns are the language of spatial reasoning and biomimicry. *In Biomimicry for Materials, Design and Habitats* (pp. 57-105). Elsevier. https://doi.org/10.1016/b978-0-12-821053-6.00010-2