



Delft University of Technology

**Biomimicry design thinking education
a base-line exercise in preconceptions of biological analogies**

Stevens, Laura; Kopnina, Helen; Mulder, Karel; De Vries, Marc

DOI

[10.1007/s10798-020-09574-1](https://doi.org/10.1007/s10798-020-09574-1)

Publication date

2020

Document Version

Final published version

Published in

International Journal of Technology and Design Education

Citation (APA)

Stevens, L., Kopnina, H., Mulder, K., & De Vries, M. (2020). Biomimicry design thinking education: a base-line exercise in preconceptions of biological analogies. *International Journal of Technology and Design Education*, 31(4), 797-814. <https://doi.org/10.1007/s10798-020-09574-1>

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.



Biomimicry design thinking education: a base-line exercise in preconceptions of biological analogies

Laura Stevens^{1,2} · Helen Kopnina¹ · Karel Mulder^{1,2} · Marc De Vries²

Accepted: 28 February 2020

© The Author(s) 2020

Abstract

Preliminary empirical research conducted by the leading author has shown that design students using biological analogies, or models across different contexts, often misinterpreted these, intentionally or unintentionally, during design. By copying shape or form without integrating the main function of the mimicked biological model, students failed to consider the process or system directing that function when attempting to solve the design need. This article considers the first step in the development of an applicable educational model using distant analogies from nature, by means of biomimicry thinking methodology. The analysis examines results from a base-line exercise taken by students in the Minor Design with Nature during the Spring semester of Industrial Design Engineering at The Hague University of Applied Sciences in 2019, verifying that students without biomimicry training use this hollow approach automatically. This research confirms the gap between where students are at the beginning of the semester and where they need to be as expert sustainable designers when they graduate. These findings provide a starting point for future interventions in biomimicry workshops to improve systematic design thinking through structural and scientifically based iterations of analogical reasoning.

Keywords Biomimicry · Analogical reasoning · Distant analogies · Design thinking · Sustainable design education

Introduction

This base-line study was initiated after preliminary research showed that students struggled to design truly sustainable solutions even after incorporating what they perceived as sustainable living structures from nature such as by mimicking the shape of honeycomb. In this example of a housing design, repeated horizontal hexagons were implemented without mentioning the exceptional use of this shape to contain liquids in combination with the minimal use of materials. By integrating biological form analogies such as this without considering the structural function of these within a system, they were unable to confirm nor could they evaluate

✉ Laura Stevens
laura.l.stevens@gmail.com

¹ The Hague University of Applied Sciences, The Hague, The Netherlands

² Delft University of Technology, Delft, The Netherlands

the sustainability of their designs on this aspect alone (Stevens et al. 2019). Biomimicry, as introduced by Janine Benyus (1997) in her book *Biomimicry—Innovation Inspired by Nature*, is based on integrating such biological functions plus the form, process and/or system, into engineering designs, making that jump between the contexts of nature to design. Because sustainability is a growing concern within education (THUAS 2020; United Nations 2020), this research examines the use of biomimicry as a sustainable design methodology while looking closer to understand how these types of analogies are used by novice designers when prompted to think back to nature for inspiration. Do their solutions remain superficial or do they show signs of a more holistic and more sustainable approach when including more elements from the original natural system, such as the way materials are made and how efficient energy is used in the biological world. Initially, we examine how analogical thinking fits within biomimicry education, and examine different types of analogies, describing how each are characterized. By initiating, examining and analysing the results of a student base-line exercise at The Hague University of Applied Sciences (THUAS), missing aspects of form, function, system or overarching natural patterns are pinpointed in a quick design exercise to finally determine which elements need improvement within future biomimicry design workshops. Throughout this article, we focus on students who are new to biomimicry, and are not yet inhibited by ‘facts’.

Earlier research on sustainability in design education conducted by Kennedy and Buikema, described a Biomimicry 3.8 transportation challenge during a minor *Integrating Biology and Design for Sustainable Innovation*. According to Kennedy et al. (2015), biomimicry addresses the mentioned issue concerning the design by following function and by translating biological mechanisms into engineering concepts. Kennedy describes one biomimicry exercise as the “art of cultivating this perceptive eye ... to think creatively about how to make a connection between what they [designers] saw and what application it could have” (2015, p. 90). This cultivated perceptive eye forms the [analogical] link between designers and the natural world and enables the starting point for new and humble designs (Baumeister 2014).

Motive

Experiencing the inspiring and dynamic field of biomimicry first hand via international workshops and Masters semesters at Arizona State University (ASU), led the leading author/researcher to attempt it in her own classroom. Virtually no research could be found at the time on the effectivity of education in this design methodology, but student enthusiasm and insights gained during preliminary workshops proved that there was something important to be discovered. Furthermore, the desire grew to find out what the key factors were that could help students design more sustainably and what the issues were that kept them from doing so. Biomimicry practitioners unable to fully understand an accurate “conceptual leap between biology and design” is sited as a key obstacle by biomimicry practitioner Rovalo and McCardle (2019, p. 1).

Goal

This article aims to look at examples of this conceptual leap made by students and to describe a starting point that novice designers use when trying out biomimicry for the first time, measuring what types or levels of analogical thinking they begin with compared to where they need to be when becoming expert practitioners. By understanding a designs’

proximity to sustainability issues, we also make generalisations about the level of insights or relationship to global sustainability issues to indicate participants 'on-hand knowledge' to design for a sustainable future.

Framework

This research combines the theories within biomimicry education, Design Based Learning (DBL) and analogical thinking specifying how these are connected. Life's Principles is an essential communication source necessary while practicing or considering biomimicry (Biomimicry38 2015) and is therefore added to the researched literature.

Biomimicry education

Biomimicry is a relatively new field that looks to nature for solutions to find inspiration based upon 3.8 billion years' worth of research and design we call Life. It aims to teach us how to integrate the deep patterns and principles found in nature and apply these inclusively, not separately, reconnecting humans with nature. "Bi-O-MIM-IC-RY [From the Greek bios, life, and mimesis, imitation]" (Benyus 1997). From most simple to most intricate, Biomimicry is the process of mimicking forms, processes, and systems from nature to advise the design of solutions to current human challenges. The Biomimicry Institute and Biomimicry 3.8 have advanced the education methodology on how to learn from nature and how to apply these learnings in our designs. Developed over the past 20 years with Dayna Baumeister from Biomimicry 3.8, the accumulated knowledge has become a Master of Science in Biomimicry at Arizona State University (ASU). ASU's program brings "biologists, designers, engineers and business majors together" (Baumeister, 2002) using modular building blocks of semesters all relating back to Biomimicry [Design] Thinking (explained later). Urmann (2016, p. 5) wrote how biomimicry education was compelling, integrated in current fields, interdisciplinary and connecting students to the real world outside the classroom. She stated that biomimicry was "a unique and powerful way to think and learn about sustainability" (Urmann 2016). Although it is well known within the field that analogies or metaphors from nature are used to help inspire designers, there are few research articles to be found on the use of analogies within the biomimicry education field.

Design based learning (DBL)

Design based learning or DBL is outlined here to define how this research obeys this method from the starting point in this base-line case study and which will be continued throughout the following semester. Stevens et al. (2019) cites Kolodner "Students identify what to learn, engage in investigative activities on what they've identified, apply this to achieve their design goal following up with reflection on the design process - all essential for analogical reasoning" (Kolodner 2003). Kolodner continued to describe this transfer of knowledge, as "a kind of analogical leap between two usually-separate contexts". DBL Assignments use relevant scientific knowledge and skills, and are practical and reflected upon so students may internalize in a way that allows for a variety of learning styles. Kolodner (2003) sums up the three main processes needed in DBL: "(1) recalling (identifying) something relevant from memory, (2) deciding on its applicability, and (3) applying what has been recalled". The link between biomimicry and analogical transfer within

design based learning is found when these three processes meet using relevant models from nature during recall. The base-line exercise in this article is the first phase in this current research where students look to nature, recall from memory, determine what is relevant, and apply this to a design idea.

Analogue reasoning

Accessing useful elements from familiar or prior knowledge to design new solutions is called analogue reasoning. Vendetti et al. (2015) describe analogue reasoning as “the ability to notice and draw similarities across contexts”. Genetner and Smith (2012) described analogies as “mental models” that could improve reasoning in new domains such as how designers might use them when solving problems (Wu and Weng 2013).

“Vosniadou (1988), specifies the importance of general analogies to ‘scientific discovery and creativity’, Dahl and Moreau (2002) describe the importance of far (also called distant) analogies, but maintain these are difficult to reproduce into measurable engineering” (Stevens et al. 2019). Holyoak and Thagard (1995) describe this process “as a way to capture remote associations” (distant analogies) which is “critical to problem solving” (Yang et al. 2015) as is necessary in design challenges. Vattam et al. (2010) describes how creativity enhances biologically inspired design through analogies. Vincent and Mann (2002) and Vincent et al. (2006) focus on the search for “biological analogies and follow principle extraction”. “Casakin and Goldschmidt (1999) established that the use of visual analogies improved the quality of novice designers work significantly. Consequently, students who are ‘novice designers’ have been known to ‘put more effort on the functionality of design’ (Yang et al. 2015), making this participant group ideal to work with during comparison of the functional aspect of the design need on one hand, to the functional strategy found in Nature” (Stevens et al. 2019) on the other hand. Yang et al. (2015) describes the research on analogue reasoning as involving “pictures, words, and sentence cues”. These cues are part of this analysis to understand which of these are perceived by participating design students. Yang states that novice designers have fewer inhibitions and could react to the challenge in a more out-of-the-box manner.

Analogue reasoning in biomimicry design thinking

Biomimicry 3.8 and ASU (2016) state stated in their curriculum that biomimicry design practitioners and experts must have the following elements in their design solution to be considered biomimicry: (1) the solution must accurately emulate the chosen biological strategy or mechanism, (2) it must have a sustainability win, (3) it must mimic form, process, ecosystem (or one of Life’s Principles—Fig. 2) with ecosystem being the highest level of biomimicry, (4) it must be an inter-disciplinary effort, and (5) the solution must show a gratitude and respect for the organism it was derived from (ASU 2016). Within the biomimicry methodology, analogue reasoning is widely used. From simply following the form or behavioural process of a Kingfishers’ beak for example, to implement a decrease of the sound impact from the Shinkansen high-speed train going through a tunnel (AskNatureorg 2019), to improving waste-to-resource cooperation between industrial facilities following an ecosystem as a model. Systems thinking, or

as Vendetti et al. (2015) explains, the “shared relational structure between domains”, is “critical for success in education”. Benyus wrote how *Nature as model* promotes learning from the best adapted models that inspire innovative solutions to human challenges (technological, design, social) for long-term survival.

Design Thinking and Biomimicry [Design] Thinking (BT) are quite similar and can be merged when practicing biomimicry. Kennedy et al. (2015) compares Design Thinking and Biomimicry Thinking through the phases of ‘defining the problem, exploration, creation and evaluation’. Biomimicry adds nature throughout each of these phases to explain how specific aspects improve the sustainability of the product (Baumeister, 2014). The biomimicry ‘Challenge to Biology’ process and is visualized below in the Design Lens created by Biomimicry 3.8 (Fig. 1).

The BT phases are as follows:

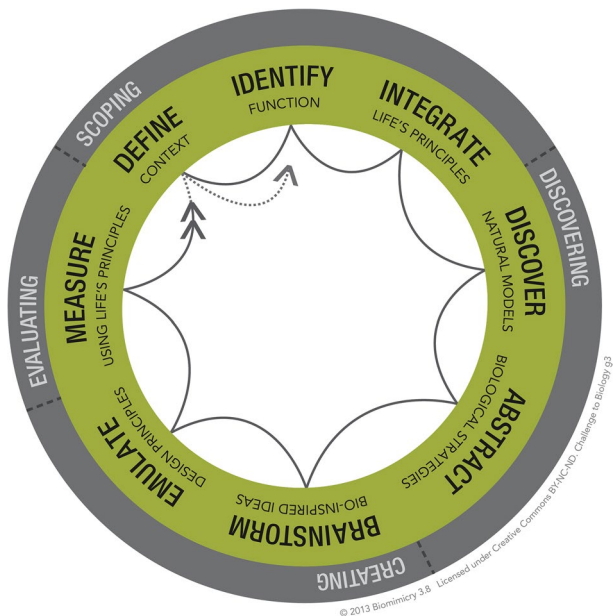
1. Scoping

- (a) Define context
- (b) Identify Function (starting point of determining design function need)*
- (c) Integrate Life’s Principles (cues from nature—described in next section)

2. Discovering

- (a) Discover Natural Models (form, process or system analogies matching design function analogy)*
- (b) Abstract Biological Strategies (abstractions of form, process or systems)

Fig. 1 Design lens challenge to biology (Biomimicry 3.8 2013). Permission granted by Biomimicry 3.8 under creative commons



3. Creating

- (a) Brainstorm by generating bio-inspired ideas (starting with abstracted translations from nature to design)*
- (b) Emulate: Design iterations of diverging and converging phases and prototype concepts

4. Evaluating

- (a) Measure using Life's Principles (overarching patterns in nature depicting form, process or system—Fig. 2)

*The base-line exercise described in the case study in section uses only 3 of the 8 sub-phases: (1) identify function, (2) discover natural models and (3) brainstorm bio-inspired ideas. This is an introduction, and a mere slice of the biomimicry design methodology. Later research stages include the entire cycle.

Life's principles as word and sentence cues analogies

Life's Principles (LP's) are the overarching patterns that all Life follows (Biomimicry38 2015). These are an integral part of the Biomimicry [Design] Thinking methodology and



Fig. 2 Design lens Biomimicry 3.8 life's principles (Biomimicry 3.8 2013). Permission granted by Biomimicry 3.8 under creative commons

are used intensively in all phases and are clustered into a series of six main categories. Biomimicry 3.8 developed these into clusters using words and sentence cues to label each of these patterns. Life's Principles (Fig. 2) are taught using both visual and textual analogies connecting phenomena from nature to understandable and usable design principles. For example, each LP has multiple corresponding organisms chosen from nature called 'champions'. Naming (and visualizing) a biological champion enables those who use the LP's to internalize their meaning. For example, the LP called 'Use readily available materials and energy' has the Dung Beetle as one of its champions (Fig. 3). Designers can visualize this and relate to this process while choosing materials.

Main research question

What would be necessary to raise the 'bar' to a higher level of biomimicry design thinking education to achieve a more sustainable result in students' solutions?

The phases for practicing biomimicry are pre-determined, but there is a gap between what novice designers know and what they are expected to know and use as expert designers at graduation. To discover exactly what the gap is, it was necessary to determine which level of analogical reasoning, and thus also which level of biomimicry emulation, was automatically used by students choosing to participate in a design semester geared towards sustainability.



Fig. 3 Design lens example LP champion card

Sub-questions are:

- What types of analogies are used by novice designers automatically?
- What sustainability aspects are implied by students at the start of the course?
- What needs to be developed to resolve found issues?

Method

Case study

This case study exercise is the accumulated result of first hand primary research in the form of an assignment. A base-line assignment was given to 20 primarily Industrial Design Engineering (IDE) students at The Hague University of Applied Sciences (THUAS) at the start of the minor Design with Nature in the Spring Semester of 2019. The research is qualitative in nature and is chosen because of the ability to gain a holistic view of the starting visual and textual level of analogical reasoning used by individual design students. Gathering examples from the students allows generalizations to be made from the multiple sources of evidence by focussing on specific issues (Noor 2008). Participants in this case were selected simply by enrolment in the course and were the students who were about to embark on their own biomimicry journey. Each had chosen the class and were aware of the ongoing research being conducted by the leading researcher. Requesting them to respond visually as well as in text on their design ideas as well as answering extra questions allowed a larger scope of possible patterns of what students already knew or had understood about biomimicry and using analogies (consciously or not).

The 15-min exercise (Fig. 4) involved sketching and responses to basic questions on biomimicry. This exercise required merely personal and individual recall from earlier knowledge and was of no consequence to their grade. On one hand, the base-line exercise was prepared to give insights into novice designers' use of pictures, words and sentence cues to describe their idea according to Yang. On the other hand, insights were also recorded by categorizing the use of form, process, system or to possible sustainability wins (Baumeister 2014) in a content analysis sheet using a coding scheme. This research design was chosen to mark these categories to define the current student level of biomimicry stimulated analogical thinking to determine which steps must follow to increase this level to the next.

Base-line case study procedure

At the start of the introductory biomimicry lesson, students were given the base-line exercise worksheet to establish the way they demonstrate using biological analogies in design at that point in time and to discover which factors might characterize their perceptions. The exercise required students to individually visualize and to write answers to four questions regarding this theme and was completed by all participating students of the minor. Participating students were asked to think of an organism that does something fascinating and to make/draw a mind-map in the first box concerning those aspects. Next, they were asked to draw a quick design idea that mimicked that organisms' qualities and answer the posed questions. Working quickly in a quite engaged manner, students appeared eager to respond. A few students were concerned that this was a 'test' because they did not know answers, but immediately continued their


Design with Nature	Student Name & number _____	
Student mini-baseline-Assignment (nul-meting)	_____	
What do you know about Biomimicry?		
<ul style="list-style-type: none">Choose an organism that does something cool and visualize and describe as clearly as possible how this design would mimic this quality. Brainstorm in the top window and sketch of idea(s) and label parts and mechanisms of the design in the lower window. (10 minutes)		
<div style="border: 1px solid black; height: 180px; width: 100%;"></div>		Organism brainstorm: What is special about the _____?
<div style="border: 1px solid black; height: 180px; width: 100%;"></div>		Quick Product Idea
<p>After that – signal from instructor (5 minutes):</p> <ul style="list-style-type: none">Take an initial survey to find out where they are now before the course.<ul style="list-style-type: none">What is your main motivation for taking this class?<ul style="list-style-type: none">To Reconnect with Nature, love for natureEthical reasons, to do good, because of design ethics to design good productsto design, create, emulate by learning how Nature does this already.other _____Give an example of Biomimicry that you know already:<ul style="list-style-type: none">_____Don't know.Name one Life's Principle that could be used as a design brief requirement _____		

Fig. 4 Empty base-line exercise

brainstorm mind-map and design idea after hearing it was just to see where they were now and that there were no consequences whatsoever of the outcome. The influence of the instructor during the base-line exercise was minimal as most of the students did not have prior experience with her. Participants were fully aware of their participation in the

ongoing research and consented to offering their work data as well as insights during the base-line exercise described in this article. Every attempt has been made to respect the students' privacy.

Data collection

The base-line exercise was developed to collect first design ideas from students and then to categorize these according to Yang's depth of depiction and the five characteristics of biomimicry categorization (Baumeister 2014), with an extra check on sustainability awareness. In the collection sheet, each idea was given a name fitting the organism it was derived from together with the product idea use. To set a base-line moment, it was essential to determine if novice design students did indeed think out of the box, but also to record in what manner they communicated their ideas. Scoring of these characteristics is to (1) understand of what level of visual communication their analogical thinking reaches before the semester begins and, (2) what biomimicry course characteristics need more support in learning. For example, could students quickly depict an idea, what it was used for and how this might work? Did they generally use the easiest level of biomimicry thinking using form analogies or is there evidence of mimicking ecosystems? In addition, all participating students had chosen for this semester, but it was unknown if they automatically thought of sustainable solutions.

A coding scheme (Table 1) was made to clarify how the answers were to be interpreted based on possible visual and textual answers given based on the visual and textual cues of Yang and the biomimicry cues of Baumeister. All 20 base-line exercise sheets were collected in the content analysis sheet (Table 2) to 'score' the data on students' initial knowledge and reasoning. Examples of each explanation helped to determine which category the idea should fall into.

- Initially, a quick overview could be made to interpret if students automatically used pictures (P), words (W) and/or sentences (S) to communicate their idea, determining a base-line moment in time. The quick product ideas were marked to ascertain which type of practice was characteristic of the students, according to Yang's earlier descriptions.

The remainder of the scoring are biomimicry characteristics to determine if a design idea had potential to become a biomimicry product idea fitting all five criteria.

- Each idea was examined to determine if key features of the biological strategy or mechanism were emulated giving higher points to those which resembled the organism more directly and no points to ideas without any mimicked strategy or mechanism depicted (+0 to +3 pts).
- The next looks to the United Nations Sustainable Development Goals (SDG's). A product must have a sustainability win (Baumeister 2014) to be considered biomimicry as it would do little good design to save energy for example, only to have the product made by children in a sweat shop. To measure independent from biomimicry, ideas were analysed on the level of sustainability by using United Nations Sustainable Development Goals (SDG's). If a design idea portrays an aim for one of these goals, it was scored (+1) as an idea geared towards sustainability. If not, the idea scored negative (−3 pts). This is to determine if a student automatically thinks of a design idea that addresses a global need. For example, a device aiming to filter plastic from the ocean considers the importance of Goal 14: Life below water (United Nations 2019).

Table 1 Coding scheme—Yang et al. (2015) plus biomimicry characteristics from Biomimicry 3.8


Categories	Explanations	Examples
<i>Coding scheme for study 1—score each design as follows</i>		
Yang	Pictures	A visual of a design idea is present—score a ‘P’
	Words	Single words describing the design are present—score a ‘W’
	Sentence cues	Short (incomplete) sentences are used to describe the design—score an ‘S’
B3.8	The source organism strategy/mechanism:	Strategy and mechanism are represented in the design idea—score 3 pts
		Strategy or mechanism is suggested in the design idea but no clear representation of how it works – 2 pts
		Strategy or mechanism resembles the organism vaguely, but not clear how it matches – 1 pt
		is not present in the design idea – 0 pts
B3.8	Sustainability win	The design idea expresses an aim for an SDG (United Nations 2019)—score 1 pt
		The idea expresses no aim to solve a SDG—score ‘–3’
B3.8	Form	Design idea form is mimicked and is characterized by having “the physical structure” like the organism it was inspired by—score 1 pt
	Process	Design idea mimics a chemical, physical, or behavior of an organism or behavior of an organism—score 2 pts
	Ecosystem	Design idea mimics multiple functions and relationships—score 3 pts
	Life’s principle	Design idea mimics or directly uses the terms used in the 26 Life’s Principles (see LP checklist)—score 1 pt if at least 1 is visible
		 <p>‘Collapse’ or ‘opening’ Series of connected words communicate</p> <p>Distal—Velcro, using form, function, behavior as a system and ‘replaces strategies that work’ Honeycomb uses minimal materials and containing fluids as direct storage Honeycomb wine rack</p> <p>No real connection organism-idea Idea on removing plastic (14—life under water)</p> <p>Honeycomb container with minimal material and filled with liquids Signals leave traces (like pheromones) Ants</p> <p>City logistics communicate and collaborate between stakeholders and shared networks and/or multiple use programs (like a coral reef) Uses readily available materials and recycles all materials (i.e. like hermit crab)</p>

Table 2 Content analysis sheet

Coding sheet base line assignment - Research 2019.07

students	Organism and function	The design idea...										*
		Used Pictures, words or sentence cues (P, W, S)	Clearly follows biological strategy or mechanism 3pts	Strongly suggests biological strategy or mechanism 2pts	resembles vaguely the biological strategy or mechanism 1pt	Does not resemble the biological strategy or mechanism 0pts	Is there a sustainability win for a SDG? Y, N, M 1pt for Yes/Maybe (-3 for 'no')	form 1 point	process 2 point	ecosystem 3 point	demonstrate at least 1 Life's Principle 1 pt	Total score
student 1	frog grip (shoe sole)	P/W		2			-3	1	2		1	3
student 2	snail move up (lift)	P			1		-3		2			1
student 3	bird wings open/close	P/W/S			1		-3	1	2		1	2
student 4	silverfish decomposing	P/S			1		1		2		1	5
student 5	penguin warming (sleigh)	P		2			-3	1	2		1	3
student 6	crab multi support (chair legs)	P		2			-3	1	2		1	3
student 7	pufferfish size change coat	P/W/S		2			-3	1	2		1	3
student 8	goat skull protection helmet	P/W/S		2			1	1			1	5
student 9	lobster exoskeleton dive suit	P/W		2			1	1			1	5
student 10	anteater crumb collector	P/W/S		2			-3	1	2		1	3
student 11	lobster scizzors nutcracker	P/W		2			-3	1	2		1	3
student 12	Chameleon paint color	S		2				1	2		1	6
student 13	oyster cement, bed, case layers	P/W/S		2			-3	1	2		1	3
student 14	snake moving vehicle	P/W/S		2			1	1	2		1	7
student 15	Chicken eyes on gun	P/S				0	-3		2		1	0
student 16	epaulette shark to amph vehicle	P/W/S		2			1	1	2		1	7
student 17	armadillo lamp shade	P/W/S		2			-3	1	2		1	3
student 18	bee pollen dust collector	P/W/S			1		-3	1			1	0
student 19	shrimp air filter	P/W			1		-3	1	2		1	2
student 20	shark swimsuit and flippers	P/W/S		2			-3	1			1	1

circle design ideas that have multiple ideas

* LP: replicate strategies that work

- Mimicking form, process or ecosystem demonstrates biomimicry emulation from most basic to the highest level. If the student used forms and shapes derived from the physical structure of the mimicked organism, then that was categorized as a form analogy (+1 pt). If the design mimicked a physical action or behaviour of the organism, it was categorized as a Process analogy (+2 pts). If the design idea mimicked multiple functions and relationships, it was categorized as a system analogy (+3 pts). A point was scored for each idea that used a form, process, system or Life's Principle (+1 pt).

A list of LP's and SDG's were attached to the scoring sheet along with a step by step explanation of how to score on the content analysis sheet. Not measured: 'Is solution an outcome of interdisciplinary effort?' as this was an individual exercise and 'Does the solution show gratitude and respect?' as it was considered as such through the 'choice of a favorite organism'. Both are also essential characteristics of biomimicry (Baumeister 2014).

An example of the base-line exercise and scoring of student 17 and 9 can be found in Fig. 5. The idea on the left is depicted in P/W/S, strongly mimicking the strategy of rolling up for protection like the armadillo, but has no relationship to any SDG. The idea mimics both form and process (or behaviour), and demonstrates the LP, 'Replicate strategies that work'. This results in a score of 3, branding it as insufficient to be called 'biomimicry'. The idea on the right also strongly mimics the strategy and form with its structural properties but not behavior, demonstrating the same LP, but scores higher with a 5 as it demonstrates a possible solution to global sustainability goals 'Life below water', number 14 of the SDG's.

• Choose organism that does something cool and visualize and describe as clearly as possible how this design would mimic this quality. Brainstorm in the top window and sketch of idea(s) and label parts and mechanisms of the design in the lower window. (10 minutes)

amradator.

Organism brainstorm:
What is special about the _____?

Quick Product Idea

After that - signal from instructor (5 minutes):

- Take an initial survey to find out where they are now before the course.
 - What is your main motivation for taking this class?
 - To Reconnect with Nature, love for nature
 - Ethical reasons, to do good, because of design ethics to design good products
 - to design, create, emulate by learning how Nature does this already.
 - other _____
- Give an example of Biomimicry that you know already:
 - recon, thinkampon? plane?*
 - Don't know.
- Name one Life's Principle that could be used as a design brief requirement _____

• Choose organism that does something cool and visualize and describe as clearly as possible how this design would mimic this quality. Brainstorm in the top window and sketch of idea(s) and label parts and mechanisms of the design in the lower window. (10 minutes)

Organism brainstorm:
What is special about the *lobster*?

Quick Product Idea

Diving armoring suit.

- Can withstand pressures
- Hard outer shell

After that - signal from instructor (5 minutes):

- Take an initial survey to find out where they are now before the course.
 - What is your main motivation for taking this class?
 - To Reconnect with Nature, love for nature
 - Ethical reasons, to do good, because of design ethics to design good products
 - to design, create, emulate by learning how Nature does this already.
 - other _____
- Give an example of Biomimicry that you know already:
 - also shaped like a beetle or a caterpillar. The design is based on the aesthetic function of their body.*
 - Don't know.
- Name one Life's Principle that could be used as a design brief requirement *not sustainability in a design alternative*

Fig. 5 Scanned base-line exercise examples

Each design idea was collected and scored separately in the content analysis sheet (Table 2). Ideas reaching all possible biomimicry characteristics were highlighted orange and those with multiple design ideas were highlighted green. Each sheet also counted for the number of Life's Principles (LP's) named to gauge the knowledge of these before the course began. Only one student had heard of one LP. While searching for sustainability terms within the designs, none were found.

Analysis

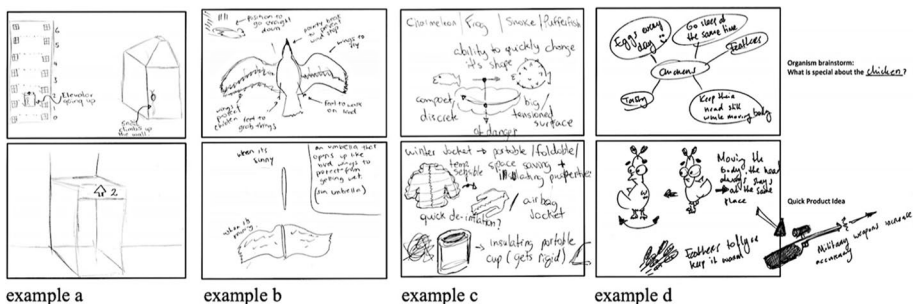
After internal scoring (by research team) and external scoring (independent scoring from outside of research team) of the design ideas in a content analysis sheet in Table 2, these were clustered to highlight findings (Table 3) while searching for patterns. As could be expected, with 90% of the students studying design engineering, all except 1 student depicted their ideas with at least a drawing. Most used words and half used longer sentences to depict and describe the design idea. Most of the students could at least suggest the strategy or mechanism mimicked by their chosen organism, but had no description of how this might work (key problem 1). This revealed that students were quickly able to give an impression of correct mimicking, which with further research (and time) could potentially be greatly improved. Both forms and processes were mimicked by the majority, but systems were not (key problem 2). This revealed that even though most students used the basic level of emulating the organisms form and behavior, still none attempted mimicking complete systems. Furthermore, students also had virtually no knowledge of the overarching patterns (Life's Principles) used in biomimicry that give recommendations towards sustainability, nor did they use terms implying sustainability in their texts (key problem 3).

Table 3 Findings table

Clusters from content analysis sheet	# students	%
Use of pictures	19 students	95
Use of words	14 students	70
Use of sentences	10 students	50
Use of sustainability terms in drawings	0 students	0
Strategy or mechanism in design strongly suggests the organism derived from	14 students	70
Strategy of mechanism resembled vaguely	5 students	25
Strategy of mechanism did not resemble	1 student	5
Sustainability win found?	6 students	30
Mimicked form	16 students	80
Mimicked process	16 students	80
Mimicked systems	0 students	0
Demonstrated LP	20 students	100
Named a life's principle correctly	1 student	5
Potential biomimicry product idea (score ≥ 4 potential and score ≥ 6 highly potential)	6 students	30
Sheets demonstrating multiple ideas	3 students	15

For the biomimetic quality of the ideas, a score of ≥ 4 was considered possible and a score ≥ 6 as highly potential biomimicry idea when a sustainability win was conceivable.

Below are examples of the highlighted clusters (Fig. 6). In examples 'a' and 'b', the students took inspiration from biological organism to integrate in design, but completely missed how to accurately incorporate the strategy or mechanism. Example 'b' shows that the function of 'open and close' of the bird wings is used quite differently than as in an umbrella in the design idea, demonstrating a similar function but clearly inaccurate mimicking of the mechanism. Example 'c' used accurate strategies derived from the functions chosen, but still did not expand on how this worked. This example also show both multi-functionality and diverged multiple ideas. Example 'd' was also unique, but in a negative manner. The participant had a design idea for the military. This idea was a military gun sight-mechanism. Since lethal weapons are not considered biomimicry, this bionic idea (as opposed to biomimicry which includes ethos and a reconnection to nature) could not be

**Fig. 6** Scanned base-line exercise comparisons

accepted as a potential idea following biomimicry. The mechanism appeared to mimic that of the chicken eyes following a target, but this is a metaphoric interpretation.

External discrepancies to be noted: It was discovered that while it is logical that design students use a picture to depict their solution, most, but not all, did so. The request to brainstorm on what their organism does in the top box, may have influenced some students to not add words and sentence cues to the design idea box. The internal and external scoring resulted in a difference of two final design ideas scoring externally as being 'potentially geared towards SDG's' by the external assessor. This and other slight discrepancies did not change the essential outcome of three key problems found, nor the results of the analysis. The percentage of potential ideas would in that case have risen from 30 to 40% allowing for a higher development of ideas reaching towards a sustainable goal in a future phase. Note: At this moment in time, the difference between the results of the base-line assignment and the results of a similar end exercise is not yet considered.

Discussion

Types of analogies used automatically by novice designers

This research has established a base-line position for novice design students ready to learn through Biomimicry Thinking methods. The types of analogies mainly used by novice design students when prompted to emulate biological functions into a design idea, are form and process analogies. This correlates with the research from Yang who stated that novice designers had been known to 'put more effort on the functionality of design' (Yang et al. 2015). However, there was little to no indication on how the functions were being carried out and few students expanded into multi-functionality and multiple ideas. The lack of the use of the highest level (Baumeister 2014) using system analogies, is considered a gap which needs filling. Vendetti et al. (2015) explains how more guidance during the process of comparison in an exercise led to a higher consideration of the relationships in the analogy. While the findings agree with this theory, there is a gap in research explanations of how and where to systematically prompt students on analogies. These systematic prompts fit within the framework of Design Based Learning (Kolodner 2003) and Biomimicry Design Thinking, but need specification in future research phases. Identification of the design need and a connection with possible organisms solving this need during application of the mechanism, must be backed up by science. Students need to learn how the mechanism works and how to relate these in the design as skilled visual communicators.

Sustainability inherent to novice designers

The base-line exercise showed that although some students had sustainability implications in their design, most did not. For students who have chosen to enroll in a minor clearly geared towards sustainability, lack of clear, automatic solutions for solving global issues is a point of concern. Life's Principles were not yet taught, however these offer designers a multitude of ways to improve any design when used as design brief requirements at the beginning and as evaluation measurement points choosing design ideas while developing and rating these on sustainability aspects.

Issues still to be resolved

Correct emulation of biological strategies and mechanisms into a design idea needs improvement. This base-line exercise was a 15-min moment in time where extended time for scientific research can solve understanding, if not application of such properties. The inclusion of systems and how a design fits within its operating conditions like the biological models do, has not yet been explored. And, the major issue of students not directly aiming for products and services to sustain future generations is a huge concern, and verified by this research.

Conclusions

This research aimed to determine what would be necessary to raise the ‘bar’ to a higher level of biomimicry design thinking education to achieve a more sustainable result in students’ solutions. To establish a starting point and plan next steps to increase the level of analogical reasoning, this needed verification within our own test group. It was surprising to acknowledge that the participating students were in fact at the level of using function, form *and* process analogies automatically. However, designs remain hollow and not measurably sustainable if these are not considered within the system. Education in using analogies in biomimicry must systematically gain input on student insights towards their design process and require students to reflect on a regular basis to catch and frame effective learning moments for the students. The assignment time limit may have been influential to the extent of student input however, the collected insights gained at this point help to verify that systems analogies and a more exact translation of the biological strategy and mechanism need to be specifically introduced into the program. Bearing in mind experts need to use holistic and systematic analogies with multiple functions and relationships, we have verified the need to discover where we can intervene to determine how the use of systems analogies can be integrated within the curriculum and understood within the design solution. Regarding a conscious sustainability factor, a biomimicry course requires a specific design solution quest more directed at certain Sustainable Development Goals. Considering the multi-disciplined nature of biomimicry, we must consider how to encourage other fields to join the minor and to designate its place within sustainable design education. Learning the ‘sentence cues’ of Life’s Principles and adding them to your design throughout each phase may prove to be essential to adding both new ethical elements as well as to helping the design fit within nature as a sustainable system.

In conclusion, one must agree with Vendetti et al., whose conclusions explain how the analogy comparisons can be enhanced by the students through providing structural support on how to view, internalize and integrate the new knowledge from nature, useful for design. The suggestions are to iteratively provide students with exercises comparing new learnings with previously learned ones, by connecting the “source and target analogies simultaneously”, providing cues moving between these to “highlight similarities and differences” and by “using relational language” (Vendetti et al. 2015), or in this case by having students simply name what kind of analogy they were successful with during a workshop. These points will be integrated into the following semesters and will be recorded in the next research phases.

Implications

Expert design practitioners are expected to be able to design holistic solutions with multiple relationships within a system. Structural cues inserted into instruction may help students recognize and improve their understanding and interpretation of the mechanisms wherein they occur, improving both the application of the found mechanisms as well as incorporating systems into their design process. Within the course, weekly surveys and end-of-course interviews should give insights to changing motives and changing student decisions on design ethics and record how this reconnection to nature influences their design. New design challenges must be geared towards solving global issues. Finally, the providing of cue's, asking students which level of analogical thinking they have achieved that day, inherently raises the bar internally as part of their design thinking process. The potential of researching biomimicry education and the involvement of students doing their own research within the classroom, is an exciting step that looks to learn from and to appreciate natures' tested solutions.

Acknowledgements This study was funded by The Hague University of Applied Sciences and supported by Delft University of Technology in the Netherlands. Open Access: This article is for educational purposes and is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), CC BY, which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Asknatureorg. (2019). AskNatureorg. Retrieved March 6, 2020, from <https://asknature.org/idea/shinkansen-train/#.Xm125JP0mWY>.
- ASU. (2016). *Excerpt from Arizona State University course [video] lessons or syllabus*.
- Baumeister, D. (2002). *Effects of Pinus flexilis on the dynamics and structure of plant communities on the northern Rocky Mountain front and Training biologists for emerging niches in non-traditional jobs*. Graduate student theses, Dissertations, & Professional Papers 9432.
- Baumeister, D. (2014). *Biomimicry resource handbook*. Missoula: Biomimicry 3.8.
- Benyus, J. M. (1997). *Biomimicry—Innovation inspired by nature*. New York City: HarperCollins.
- Biomimicry 3.8. (2013, 2014 & 2015). *Creative commons permission to reproduce*. Missoula: Biomimicry 3.8.
- Casakin, H., & Goldschmidt, G. (1999). Expertise and the use of visual analogy: Implications for design education. *Design Studies*, 20(2), 153e175. [https://doi.org/10.1016/s0142-694x\(98\)00032-5](https://doi.org/10.1016/s0142-694x(98)00032-5).
- Dahl, D. W., & Moreau, P. (2002). The influence and value of analogical thinking during new product ideation. *Journal of Marketing Research*, 34(1), 47–60. <https://doi.org/10.1509/jmkr.39.1.47.18930>.

- Genetner, D., & Smith, L. (2012). Analogical reasoning. In V. S. Ramachandran (Ed.), *Encyclopedia of human behavior* (2nd ed., pp. 130–136). Oxford, UK: Elsevier.
- Holyoak, K. J., & Thagard, P. (1995). *Mental leaps: Analogy in creative thought*. Cambridge: MIT Press.
- Kennedy, B., Buikema, A., & Nagel, J. K. S. (2015). Integrating biology, design, and engineering for sustainable innovation. In *5th IEEE integrated STEM conference*.
- Kolodner, J. L. (2003). Promoting transfer through case-based reasoning: Rituals and practices in learning by design classrooms. *Cognitive Science Quarterly*, 3(2), 183–232.
- Noor, K. B. M. (2008). Case study: A strategic research methodology. *American Journal of Applied Sciences*, 5(11), 1602–1604.
- Rovalo, E., & McCardle, J. (2019). Performance based abstraction of biomimicry design principles using prototyping. *Designs*, 2019(3), 38. <https://doi.org/10.3390/designs3030038>.
- Stevens, L., De Vries, M., Bos, M., & Kopnina, H. (2019). Biomimicry design education essentials. *Proceedings of the Design Society: International Conference on Engineering Design*, 1(1), 459–468. <https://doi.org/10.1017/dsi.2019.49>.
- THUAS (The Hague University of Applied Sciences). (2020). *De Haagse Hogeschool Nieuws*. Retrieved 16 January, 2020, from <https://www.dehaagsehogeschool.nl/over-de-haagse/de-haagse-actueel/nieuws/2019/04/05/sustainable-development-goals-als-kapstok-voor-wereldburgerschap>.
- United Nations. (2019). *United Nations sustainable development*. Retrieved 17 July, 2019, from <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>.
- United Nations. (2020). *UN environment programme*. Retrieved 22 January, 2020, from <https://www.unenvironment.org/about-un-environment/policies-and-strategies/un-environment-strategy-environmental-education-and>.
- Urmann, L. (2016). *Integrating biomimicry into higher education: Designing and developing a biomimicry minor at the University of California*. Santa Cruz: Thesis University of California.
- Vattam, S., Wiltgen, B., Helms, M., & Goel, A. K. (2010). DANE: Fostering creativity in and through biologically inspired design. In *Design creativity 2010* (pp. 115–122). London: Springer. https://doi.org/10.1007/978-0-85729-224-7_16.
- Vendetti, M., Matlen, B., Richland, L., & Bunge, S. (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>.
- Vincent, J. F., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A. K. (2006). Biomimetics: Its practice and theory. *Journal of the Royal Society, Interface*, 3(9), 471–482. <https://doi.org/10.1098/rsif.2006.0127>.
- Vincent, J. F. V., & Mann, D. L. (2002). Systematic technology transfer from biology to engineering. *Philosophical Transactions of the Royal Society of London, Series A*, 360(1791), 159–173. <https://doi.org/10.1098/rsta.2001.0923>.
- Vosniadou, S. (1988). *Analogical reasoning as a mechanism in knowledge acquisition*. Illinois: University of Illinois.
- Wu, Y. W., & Weng, K. H. (2013). Using an analogical thinking model as an instructional tool to improve student cognitive ability in architecture design learning process. *International Journal of Technology and Design Education*, 23, 1017. <https://doi.org/10.1007/s10798-012-9219-3>.
- Yang, C., Chai, C., Cen, F., Ruan, W., & Li, H. (2015). Behavioral analysis of analogical reasoning in design: Differences among designers with different expertise levels. *Design Studies*. <https://doi.org/10.1016/j.destud.2014.07.001>.