Biologically Inspired Design in Introductory High School Engineering Design Courses: Student Expectations, Fixation and the Importance of Prior (Fundamental Research)

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Abstract

This study explores students' engagement in and perception of biologically inspired design (BID) as a result of their participation in a seven-week BID engineering curriculum. The participants included high school students (*n*=52) enrolled in an engineering course. Students were purposively selected for this mixed methods study due to their willingness to participate. The qualitative findings revealed that students' engagement in BID ideation resulted in a fixation on initial solution ideas, exploring a few potential solutions to create design concepts, and tending toward existing, well-understood solutions. In comparison, the quantitative findings showed modest shifts in students' views regarding the value of BID from pre- to post. The survey data revealed that slightly more students agreed after the course that using concepts from biology is useful for developing engineering solutions. In contrast, students who believed biology was a good source for engineering ideas showed a larger increase. While many students initially agreed that biological inspiration was easy and exciting, fewer believed so after their engagement in the curriculum.

Introduction

Engineers are often confronted by complex challenges that require disciplinary knowledge and the ability to work across cross-disciplinary environments [1]. Over the years, there has been greater emphasis being placed on engineers to understand the "social, economic and environmental impacts of engineered solutions" [1, p. 2] to foster their ability to think about the "whole system at different levels of fidelity and in different time scales" [1, p. 2]. Consequently, placing greater emphasis on undergraduate engineering education to train future engineers to solve multidisciplinary problems and collaborate across boundaries has become a necessary competency [2], [3]. Hence, biologically inspired design has emerged as a unique approach for engineering teaching to achieve this goal in higher education.

Bio-inspired design (BID) encourages inspiration from natural systems to develop solutions for engineering problems, leveraging biological analogies to support design ideation. Teaching BID in higher education has several documented benefits [4], [5], [6]. BID integration can result in complex and unique engineering solutions to complex problems [6] and be engaging for students [7]. Further, it can reduce fixation [8], which can be challenging for novice engineering students [9]. Prior studies have also suggested that integrating BID and associated scaffolds into the engineering design process (EDP) in the engineering classroom increases creativity and prepares students for interdisciplinary problem-solving [10], [11], [12]. Furthermore, whereas women are underrepresented in engineering, they are represented in equal or greater numbers in biology and biomedical engineering, suggesting BID may help shift this imbalance. Considering the positive outcome observed in higher education, there is an advantage in introducing pre-college students to multidisciplinary BID learning through integrative BID design curricula [13], [14].

This study is part of a larger grant funded by the NSF entitled *BIRDEE*, in which we developed a BID-integrated curriculum for the 'Foundation of Engineering' course for first-year high school students. The curriculum aligns with the state's engineering standards and infuses BID engineering projects and practices into the traditional engineering pathway in high schools. More information about the BID curriculum is described below in the methods sections [12], [13, [14].

Background & Literature

Ideation

Design is a fundamental element of engineering as it can increase student learning, foster 21st-century skills, and drive innovation [15], [16]. Asunda and Hill [17] define design as "the process of devising something. It is a creative, iterative, and often open-ended process of conceiving and developing components, systems, and processes" (p. 26). The ability of students to develop innovative design solutions to complex problems is also promoted by ABET [18] to cultivate design skills. In the engineering design process (EDP), ideation and idea generation are crucial for successful innovation [19]. Thus, in the ideation phase of the engineering design process, learners are encouraged to generate multiple diverse concepts [20]. These diverse ideas aid in broadening perspectives, stimulating novel solutions, and supporting deeper consideration of the real problem [21]. Ideation practices, such as brainstorming, can encourage "limiting early evaluation and documenting any new idea, even if it seems impractical, as a "wild" idea could be transformed into a successful solution and inspire other ideas" [22, p. 2], [23].

Ideation in engineering education is often taught in the context of a traditional engineering design process (See Table 1) [15]. The ideation step, as taught using the traditional EDP process, involves four steps: (1) idea search, (2) concept mechanism understanding, (3) design concept selection, and (4) design integration. These ideation steps are not specific to BID but rather can be generalized to ideation processes in which design ideas are collected, understood, evaluated, and integrated into a conceptual design, regardless of whether they came from analogical or traditional design sources. However, similarities can be seen between this ideation process and the design-by-analogy process steps by Linsey et al. [24].

- ***Idea search*** is the act of identifying potential solutions to the current problem, usually by function-matching existing manufactured solutions to the problem. Depending on the complexity of the solution, potential solutions may be holistic solutions to the problem or solutions to subsystems or subfunctions that must be integrated later.
- ***Design concept mechanism understanding*** analyzes the potential solutions to understand how the structures achieve this function; that is, what is the stepwise or scientific explanation for how this function is executed by the solution being investigated.
- ***Design concept selection*** analyzes each potential solution to determine which best fits the design problem and typically selects among the top potential solutions.
- ***Design integration*** combines the selected potential solutions to develop a design concept for the design problem. Different potential solutions may constrain, enable, or combine with other potential solutions such that multiple distinct design concepts are possible.

In our curriculum, the BID ideate stage includes four steps: (1) biological search, (2) biological mechanism understanding, (3) biological concept selection, and (4) biological design integration (See Figure 1). These are described below.

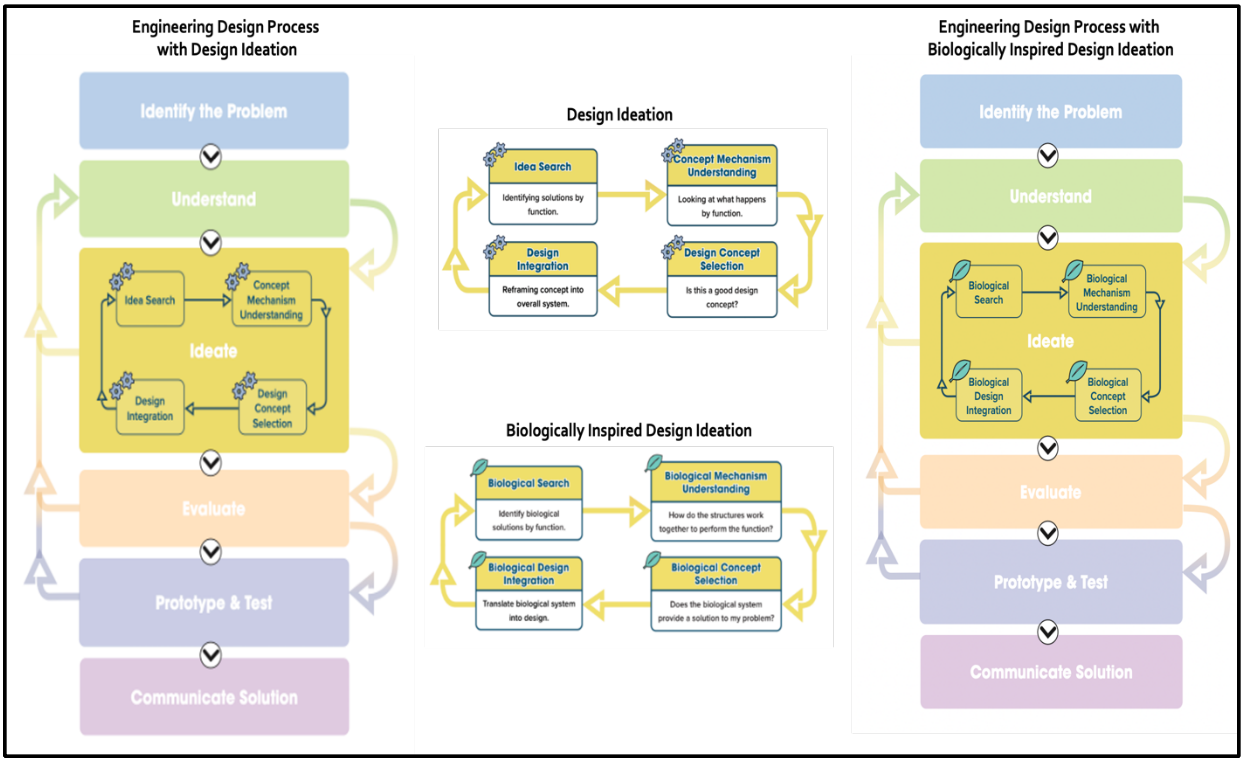


Figure 1: EDP with ideation (left), design ideation (top center), BID ideation (bottom center), and EDP with BID ideation (right) [12].

- ***Biological search*** - The act of finding as many biological analogies (function matching) as possible that could support the problem or some aspect of it.
- ***Biological mechanism understanding*** – The act of analyzing the biology (structure-function-mechanism) in detail to understand how it achieves this function.
- ***Biological concept selection*** – Analyzing the biological analogies to determine which analogies best fit the design problem and selecting the top source (or sources) of inspiration.
- ***Biology design integration*** - Apply the mechanism learned from biology to the conceptual design solution, also called transfer.

These steps specific to BID are simplified based on the various BID models discussed in the literature [2]. The decision to simply BID was three-fold. First, in pre-college education, engineering teachers have limited knowledge regarding biological principles, which could impact BID implementation in engineering [12]. Therefore, to limit the scope of what students and teachers must learn about biology for this introductory curriculum, we removed the need for teachers to learn about the biology domain more broadly. Second, ideation in pre-college engineering is often taught in the context of a traditional engineering design process (EDP) [15]. Subsequently, the BID processes are embedded within the ideate stage of the traditional EDP to minimize the cost of the more nuanced aspects of BID [2], [25] and enable seamless integration of BID processes within the traditional EDP. Third, to reduce cognitive dissonance as a result of learning multiple new ideas/processes simultaneously in engineering [26]. As suggested by constructivist theories of knowledge, new knowledge is constructed from existing knowledge [27]. If new knowledge lacks connections with existing, then student motivation will be lower, and effective learning is less likely to occur [28], [29]. Based on these premises, in this introductory curriculum, students are first introduced to the traditional EDP, including the ideate stage, followed by BID ideate processes within the traditional ideate stage to help students acquire the knowledge necessary to apply BID to their design solutions. Thus, this research is necessary to explore students' BID ideation and their perception of BID as a result of their engagement in the BID-integrated EDP.

Research Purpose & Questions

This study explored students' engagement in and perception of biologically inspired design (BID) during participation in a seven-week BID engineering curriculum. The research questions addressed in this work are*: 1) How do high school students engage in ideation during a bio-inspired engineering design challenge? 2) What impact does engaging in BID have on students' perception of its value for engineering design?*

Methods

Research Design

A mixed method convergent parallel design (QUAL→quant) was employed to address the research questions. A mixed method design is advantageous when the research seeks to address questions such as 'how' and 'what' holistically within a specific context or situation [30]. Thus, in this study, mixed methods convergent parallel design allowed for a deeper understanding of students' engagement in and perception of BID during participation in a 7-week BID engineering curriculum. The qualitative and quantitative methods were implemented during the same phase of the research process, but the analysis of the two components was conducted independently [30].

Participants & Setting

The participants of this study were ninth-grade engineering students (n=52). The students were purposively selected due to their willingness to participate in the research study and completed both student assent and parental consent. Students were divided into teams, and each team encompassed three to four students ($n^{of\ teams}$ = 18). The teams were diverse in regard to gender and race (See Table 1 for student demographic).

The study was conducted at a STEM-focused public high school in the southeastern metropolitan school district of the United States. The school's student body was diverse. The teacher was a second-year teacher who taught one section of the introductory Foundations of Engineering course, which was divided into three block sections, with each block approximately 90 minutes in length.

Table 1. Students' demographics.

Category	Subcategory	Frequency (*n*)	Percent (%)
Gender	Male	25	48%
	Female	27	52%
Race	White	14	27%
	African American/Black	8	15%
	Asian	23	44%
	Hispanic	1	2%
	Native American	1	2%
	Multiracial	3	6%
	Other	2	4%

Context: BID-focused engineering curriculum

Students participated in a seven-week BID-focused engineering curriculum in which they were introduced to the EDP and BID through design-based activities and design challenges [14]. The design challenges were situated in a socially relevant context in which design solutions were iteratively developed over multiple weeks. As students engaged in problem-solving through the EDP, they integrated BID into the EDP by leveraging analogical design tools (i.e., structure, function, mechanism breakdown) that aided with facilitating a transfer of biological strategies to design challenges [12], [14]. These tools scaffolded the key engineering design skills of problem understanding and design ideation (See Figure 1 above).

In the introductory curriculum, students engaged in two design problems. In the first design challenge, students learned about the lotus effect and modeled the water-repellent properties of lotus leaves using a product called NeverWet. Students investigated the NeverWet product in light of the problem of how best to keep shoes clean, as this product can be applied directly to surfaces and creates a repellent and protective coating. In this introductory challenge, students are first introduced to the EDP and the BID concept, and each step of the EDP is modeled through the design challenge to solve the problem of dirty shoes [12], [14].

In the formal design challenge, students are requested by a client (EatEZ) via a client memo to design a better food delivery system (lunch boxes) for senior citizens. As students engage in the design challenge, they learn biological concepts of thermoregulation. Students are presented with various examples of animals that have evolved complex and effective methods for regulating their body temperature (polar bear fur, whale blubber, etc.). Students apply their understanding of nature and thermoregulation as they decide what design would be best for their design solutions [12], [14].

Data Sources

The data sources for this study included final engineering design logs (EDPL), final presentations, and an engineering survey (pre-post). The EDPL is an electronic version of an engineering notebook designed for students to document their engagement in the EDP [31].

At the culmination of the curriculum implementation, student teams presented their lunchbox design solutions for their final presentation (FP). The presentations were seven minutes in length and required students to identify the problem, describe the different thermal regulation systems in nature (i.e., polar bear, whale blubber, penguins, etc.) they explored for their design solution, which system(s) were incorporated into their design and how they were incorporated. Additionally, students presented their design iterations, including models/images, along with results and modifications for each design, leading to their final design solution. The presentations were audio-recorded and transcribed for data analysis.

Finally, students completed an engineering survey (pre-post), which comprised 5-point Likert-scale items (ranging from 1-strongly disagree to agree 5-strongly). Students were asked to respond to items covering their intent to persist in engineering, the value of biologically inspired design, general engineering self-efficacy, and environmental values. The researchers developed the items based on the expectancy-value theory (EVT) because EVT postulates that students' motivation in learning relies on their beliefs in academic success and the values they perceive relative to the task they are learning [32]. The items showed good reliability based on Cronbach's alpha (> 0.75). For this study, we only examined students' perceived value of biologically inspired design (pre-post) to determine if students' views about the use of biology in the context of engineering changed after their experience (see Table 2 for the items).

Table 2. Value of biologically inspired design survey items.

Items	Construct
1. Using concepts from biology is useful for developing engineering solutions.	Value of Biologically Inspired Design
2. It is easy to find inspiration for engineering designs in the natural world.	
3. When working on engineering design problems, nature is a good source of ideas.	
4. Biology-inspired designs are an important part of engineering	
5. Using biology-inspired designs to solve engineering problems is exciting.	

Data Analysis

For this study, a mixed methods approach was employed for analysis [30]. First, we applied qualitative content analysis [33], [34] to analyze the students' final presentations and EDPL. Qualitative content analysis is a systematic way of analyzing documents, which may include transcribed communication, pictures, symbols, and written text to describe the meaning of the material [33], [34]. Further, it can be used on material for which context is important and that requires some interpretation [34]. This method was chosen to allow us to holistically examine how students engaged in the *ideation stage* of the EDP. The coding process commences with the first two researchers, who individually open-coded the data, which included a combination of inductive and deductive coding, which was used to code students' final presentations and the EDPL. The deductive codes leveraged previously documented practices in idea generation to contextualize the findings [19]. Coding discussions were had between the two researchers to discuss code names and meanings before finalizing the codes. The researchers then went through the process of establishing inter-rater reliability. Inter-rater reliability consisted of an iterative process where segments from final presentations and EDPL were selected randomly and independently analyzed by both researchers. The coding results were then compared, and the process was repeated until 90% or higher reliability was achieved. The coding of the data was further discussed during multiple two-hour sessions as a research group where four researchers participated in coding and refining code definitions of the data. If definitions were modified, re-coding of the data ensued. Whenever coding and definitions changed, consensus was sought among all of the researchers before proceeding with the change. Trustworthiness was established through multiple coders and data sources [35].

Three major themes emerged from the data to identify high school students' engagement in ideation during a bio-inspired engineering design challenge. These themes include *fixating on initial solution ideas, generating a few ideas, and tending toward existing, well-understood solutions* (See Table 3 below for themes and their definition). For participant anonymity and clarity, the following identifiers are used: Final Presentations-Team (FPT#) and Engineering Design Process Logs-Team (EDPL-T#).

Table 3. Three major themes and their definition.

Themes	Description
Fixation on an initial idea	Attachment to a single design concept, with only incremental change to that initial concept
Generating a few ideas	Students evaluating less than three design concepts.
Tending toward existing, well-understood solutions	Students find and use potential solutions from existing, similar products to generate solutions.

Afterward, descriptive statistics (i.e., frequency, percentages) were used to capture changes in students' perceptions of the BID in engineering. Specifically, we examined the *value of a biologically inspired design scale* (pre-post) to determine if students' views towards the value of BID for engineering design changed due to their engagement in a 7-week BID-focused curriculum. Any student who did not complete either pre- or post-survey was removed during analysis. Additionally, for data analysis purposes, the agreement options (strongly agree & agree) were merged to represent 'pre-agreement' or 'post-agreement.' Meanwhile, disagreement options (strongly disagree & disagree) were merged to represent 'pre-disagreement' or 'post-disagreement' [36], [37].

Results

The qualitative findings revealed that students' engagement in BID ideation resulted in a fixation on initial solution ideas, exploring a few potential solutions, creating a few design concepts, and tending toward existing, well-understood solutions. The frequency table (Table 4) highlights the number of teams that engaged in each of the themes out of the total number of teams (n^{teams} = 18) presented in column 3. It is important to note that while some teams' data aligned with multiple themes, in this table, we only opted to categorize it under the theme that was most prevalent across their data.

Table 4. Summary of team engagement in each theme.

Themes	Description	Engagement in each Theme (n=18)
Fixation on an initial idea	Attachment to a single design concept, with only incremental change to that initial concept	9 teams
Generating a few ideas	Students evaluating less than three design concepts.	5 teams
Tending toward existing, well-understood solutions	Students find and use potential solutions from existing, similar products to generate solutions.	4 teams

Fixated on initial solution ideas

The theme fixated on initial solution ideas highlights students being attached to a single idea or similar idea that carried over into their final design. Many teams conceptualized one idea for their lunchbox design but presented it as multiple ideas (i.e., varied angles and features). For instance, Team #3 claimed they conceptualized multiple ideas, which they indicated met all of the design requirements and were inspired by a "penguin" (EDPL-Team #3). However, it was a single idea presented from different angles as three different design concepts (Figure 2).

(a) (b) (c)

Figure 2. Lunchbox design: (a) concept A top, (b) concept B side, and (c) concept C inside.

Team #1 was also fixated on a single design, which they tested multiple times against the design requirements (See Figure 3). During each test, slight modifications were made, such as adding more insulation. Nonetheless, their idea was biologically inspired by the warmth of the Arctic hare. The team stated in their EDP Logs that they selected the arctic hare because the arctic hare's small ears reduce how much of its skin is in contact with air. They further claimed,

> *They stay warm in cold weather. The Arctic hare's fur keeps its temperature at a higher level. It has long, transparent, hollow hair that scatters sunlight to provide camouflage while allowing skin pigment to absorb warmth* (EDPL-Team #1).

(a) (b) (c)

Figure 3. Lunchbox design: (a) inside of the box, (b) more insulation, and (c) outside handle.

Similarly, Team #11 tested one idea with minor modifications to address the design requirement. Figure 4. illustrates the team's design as presented in the EDP log. Concept A is a possible lunchbox model that can work to keep the food warm and safe. Concept B is the inside of the lunchbox model covered with aluminum for thermoregulation. Concept C is another example of concept B, but it is just with added insulation and separated into two sections. This team stated in the EDP logs that their design solution was inspired by a whale, which "Gave us the idea of structure and rigidity inside and outside the box" (Team #11).

(a) (b) (c)

Figure 4. Lunch box design: (a) lunchbox model, (b) inside the model box thermoregulation, and (c) inside the model box thermoregulation two.

Students' final presentations (FP) also confirmed their' fixation, as many claimed that they conceptualized a single idea that they slightly modified to meet the requirement. Teams #11 and 5 stated while presenting their final lunchbox prototype,

> *In our first prototype, we used aluminum foil as our main insulator. [Then], in our second, we used bubble wrap. So, [in] our final prototype, we ended up adding more layers of insulation. We switched the closure of the blocks from Velcro to thumbtacks and a rubber band* (FP-Team #11).
>
> *Here is our prototype, which is much more realistic and durable. We used a wood frame to secure the food inside, and we have our insulators with the Styrofoam bubble wrap in nylon. These layers should contain heat or cold to make it the right temperature so the seniors can have the right temperature for the food* (FP-Team #5).

Interestingly, while teams were fixated on a single idea, they also explored a single biological system (i.e., whale or polar bear). Although, they were presented with many examples and were allotted the opportunity to explore others. Further, students were most concerned about one design requirement, which in this case was sustaining temperature, and they addressed it by adding additional insulation, often using the concept of "layered insulation" as their biological inspiration.

Generating few ideas

The theme of generating a few ideas refers to students considering less than three ideas, which is what was required of them. While many teams conceptualized a single idea, some teams generated more than one idea and even prototyped and tested those ideas before finalizing. For instance, Team #9 conceptualized three ideas, though one was a modification of the first idea. In concept A, the lunch box was divided into two compartments (e.g., hot vs. cold), with a removable insulation pouch, included a side pocket for a label, and "had double layers of aluminum to insulate hot meals." Concept B included six compartments, with "a pocket for an ice pack in the top left compartment and "a hot pack in the top right compartment." The box also included a handle. Finally, concept C was a slight modification of concept A with extra insulation on the inside as well as outside, along with a magnetic closure. The team then went further and prototyped and tested each of these ideas against the design requirements (Figure 5), ultimately finalizing concept C as their design solution.

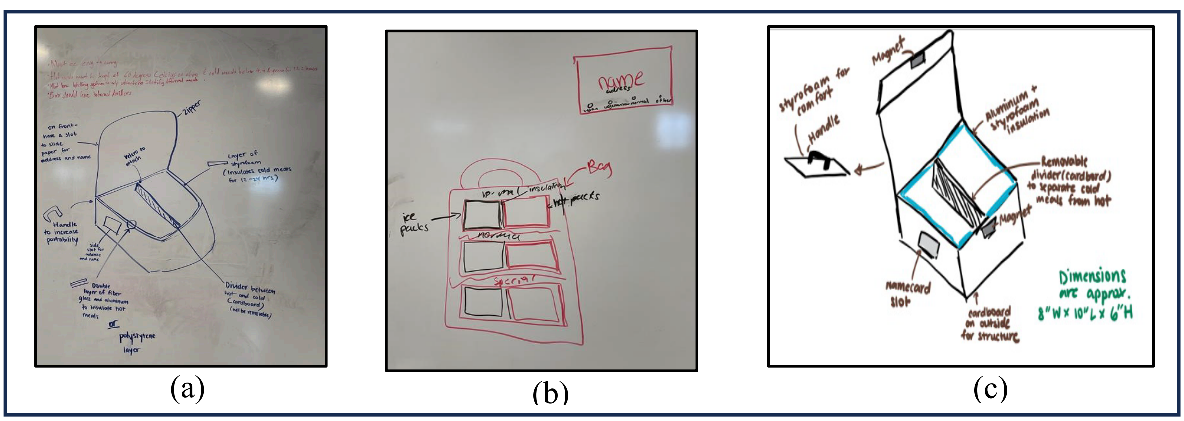


Figure 5. Lunchbox design ideas: (a) first prototype drawing, (b) second drawing, and (c) third design.

Team #10 engaged in ideation to conceptualize multiple ideas, many of which were modifications of the original idea and/or structural components of the lunch box design (Figure

6). Team #10 also prototyped and tested most of these ideas as well as explored various biological systems (i.e., whales, heater bees, and arctic hares). They indicated the changes they made to their design during their final presentation, as they explained,

> *The* [final prototype includes] *the handles, the hinge, the stoppers, the stopper locking mechanism to put this into here and have it not close, the flaps on these sides and here make the resistance more so that it is less likely to open. There is insulation between all of the cardboard, the actual outside of the cardboard, and between the sections so that the sections can be insulated from each other. This is our final product that's insulated, and it is much better than already existing solutions because it can hold both hot and cold items* (FP-Team #10).

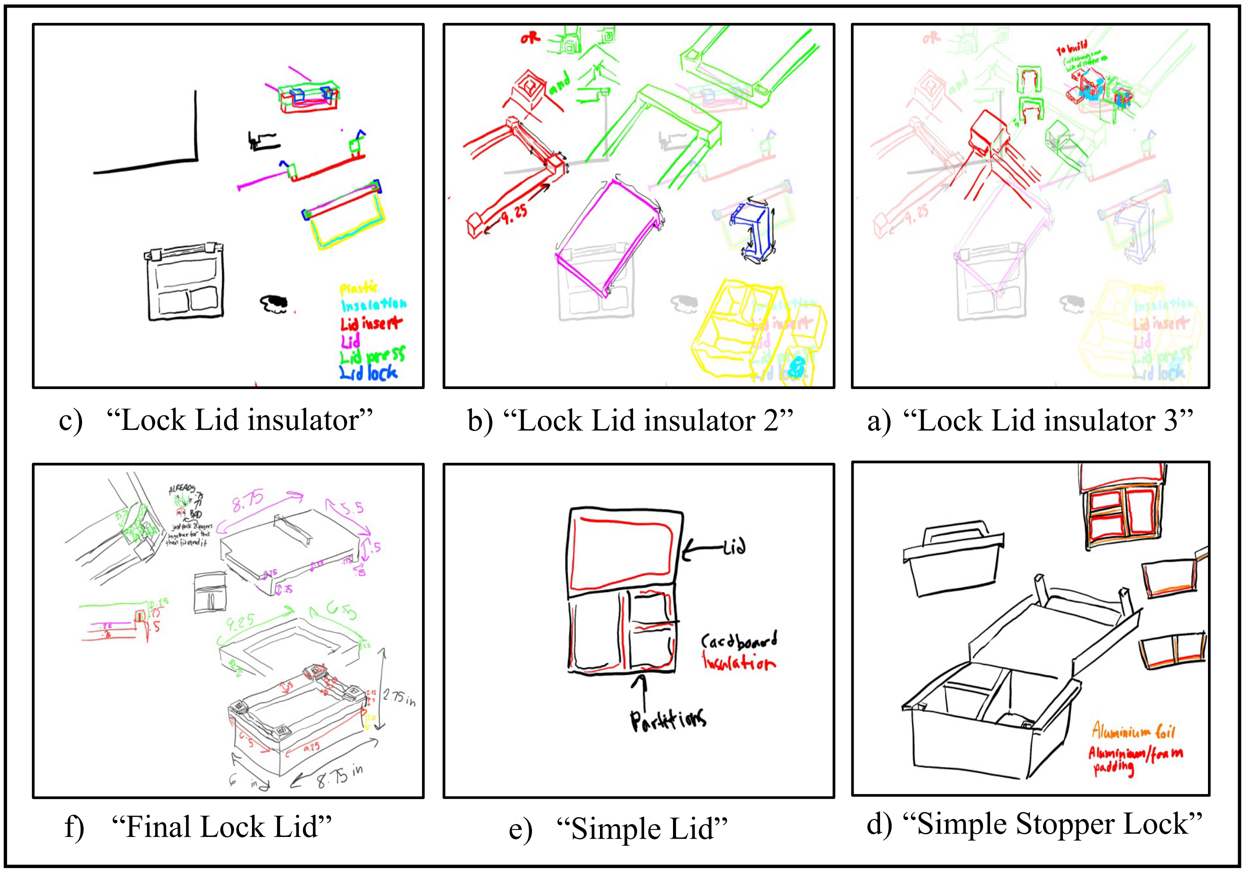
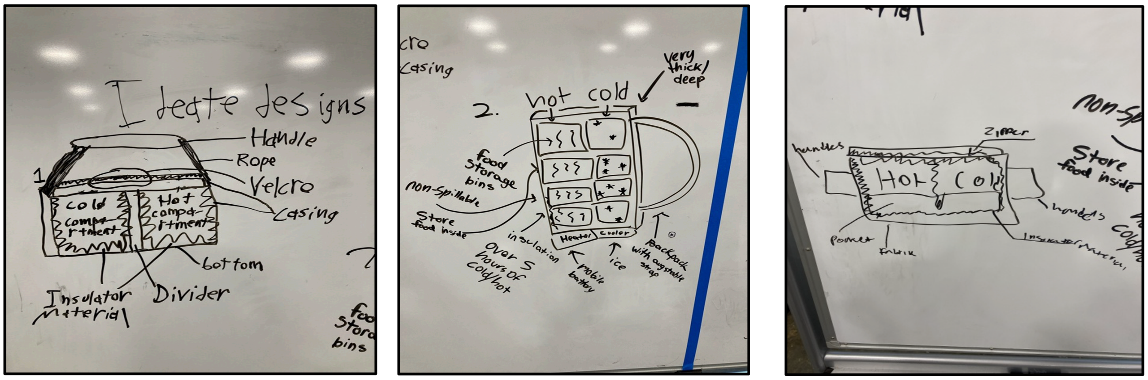


Figure 6. Ideas generated by the team (Team#10).

Team #8 generated three different ideas, which included a lunch bag, lunch backpack, and lunch box (Figure 7). The team also prototyped and tested each of these ideas, ultimately deciding that the box would be the best design solution. The lunch box design was inspired by the “layer of blubber that's underneath a polar bear's skin. The layer prevents heat from escaping from the polar bear, similar to Styrofoam” (EDPL-Team #8).



(a) (b) (c)

Figure 7. Different design ideas for a lunch: (a) bag, (b) backpack, and (c) box.

In some instances, teams did not develop a model of, prototype, and/or test many ideas that they may have ideated. However, during their final presentation, they discussed the multiple ideas generated and how these led to their final solution. For example, Team #13 claimed they made multiple sketches and even went on to point out how this design varied. However, they did not have actual drawings or images to share. Therefore, it is difficult to understand the variations in their designs.

> *We had a couple of different ideas, but finally went with this one, this one right here, which is the one that you can see upfront. That is the dimensions to hold two of the actual boxes that are going to be used to deliver food, so one hot and one cold meal, and they both have insulation in the middle. So, these are from the prototypes that we made, just right* [pointing to the divider they added to separate hot/cold] *from our second prototype, and this one right here* [the closing mechanism changed to a Velcro] *is the first prototype that we made before our final right here. It is made out of cardboard, felt tape, and cotton with a plastic lining and Velcro. The boxes can also regulate the temperatures of food, both warm and cold. The box closes with Velcro. The cotton lining is designed from most animal furs which trap heat that the animal gets off, and the Velcro is based on burrs which are a type of plant that will stick to your clothing or anything else* (sic, FP-Team #13).

Though students attempted to generate multiple ideas, they showed minimal signs of developing ideas further than a few (i.e., one to two). Further, students also did not attempt to explore different biological systems for each idea that they conceptualized.

Tending toward existing, well-understood solutions

The theme tending toward existing, well-understood solutions highlights students finding and using potential solutions from existing, similar products to generate solutions. This was the least common theme among the 18 teams. Nonetheless, it is important to note that this was not a result of teams not exploring existing solutions, as all 18 teams explored existing solutions as part of the curriculum. But rather, based on the data and analysis, only 4 out of the 18 teams explicitly referenced the existing solutions they explored for their design solution. For example, Team #2 stated that they explored the Stanley Steel boxes because,

> *The primary structure of the Stanley Steel Classic Lunch Box is a single layer of steel. It is not very thick, decreasing its insulation potential. However, steel is a dense material, meaning that heat energy must travel through much matter. These two aspects even outweigh the poor insulation that this lunchbox would provide. Due to this, our product should contain several insulating layers of preferably dense material* (EDPL-Team #2).

As a result, the team's (See Figure 8) design was inspired by a polar bear because a "polar bear [has] several layers of insulating material that reduce heat loss and also increase heat absorption. Due to this, we have included multiple layers of insulation in our design" (EDPL-Team #2).

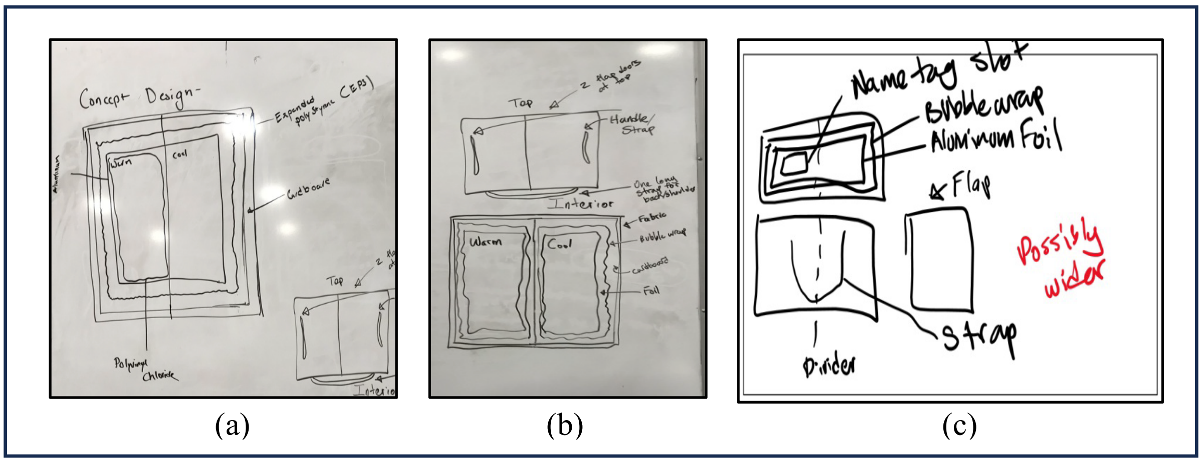
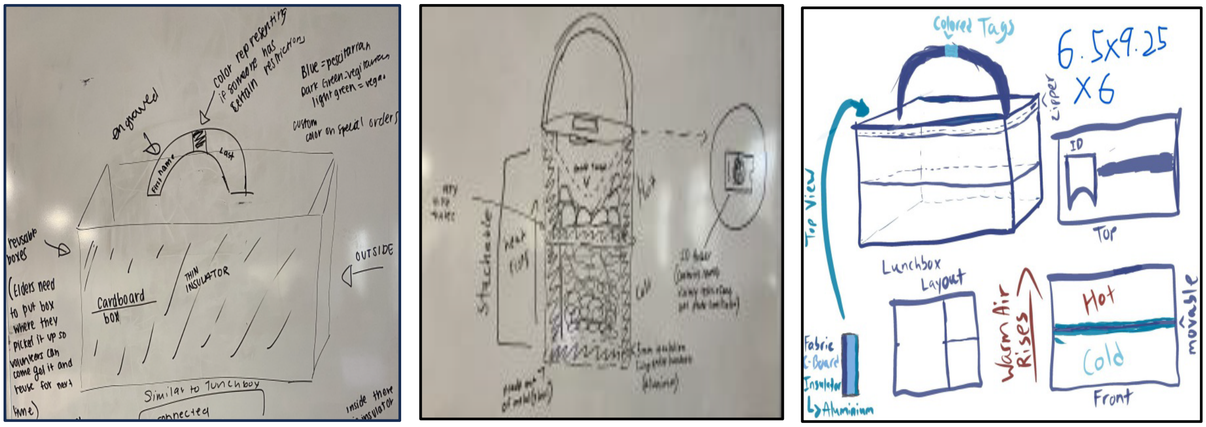


Figure 8. Lunch design: (a) multi-layer, two-compartment design 1, (b) multi-layer, two-compartment design 2, (c) Side-by-side compartment design, multi-layer insulation, and straps.

Likewise, Team #4 explored their lunchboxes to understand how they keep food insulated. They further explored the various design features the lunchboxes include. During their final presentation, a team member asserted, "I added a zipper because my lunchbox has a zipper" (FP-Team #4). Figure 9 illustrates the different designs team members conceptualized. Concept A is the "cardboard box," which has multiple layers and is separated into two compartments. Concept B is the "Indian lunchbox," which includes multiple layers (trays) that can easily be removed. Concept C is the "combination bag AB" that includes multiple insulated layers and a strap for easy carry. The team's final prototype, concept C, was a combination box that met all the design requirements. It was inspired by "feathers and used the thermal concept of radiation to preserve heat to keep food warm and cold" (EDPL-Team #4).



(a) (b) (c)

Figure 9. Team #4 lunch box designs: (a) a cardboard box, (b) an Indian lunchbox, and (c) a combination bag AB.

Some students also explored existing biological systems, going beyond what was covered in the curriculum, that would be appropriate for the design solution. For instance, Team #6's final design (Figure 10) was inspired by a "sheep" due to its ability to "insulate with cotton wool" (FP- Team #6). Thus, cotton was used as their main insulator. As the team claimed,

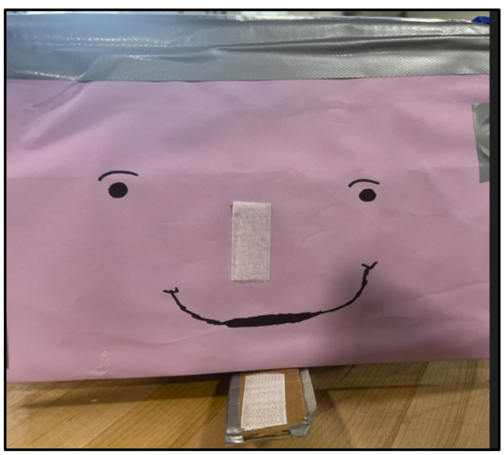


Figure 10. The final design of the lunchbox.

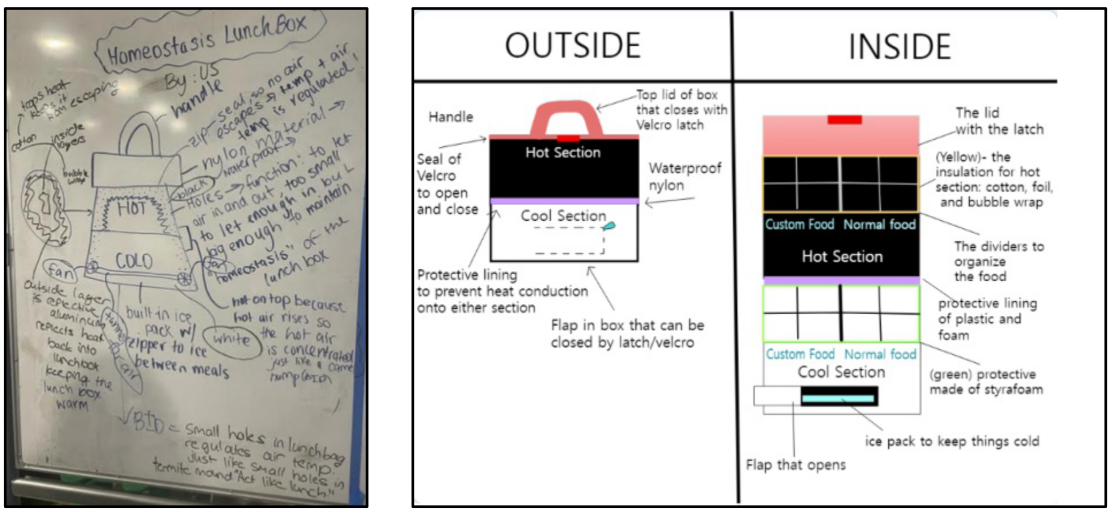
> *So, the final product has a fun and quirky design with a ton of colors. There is a Velcro strap on the edge of the lunchbox that connects to the top of the box for holding. The lunchbox includes sturdy handles, and Velcro makes for a unique nose on the face of the lunchbox once it is removed. The unique container... The inside contains a divider down the middle for hot and cold sides to enjoy delicious meals at varying temperatures. Each side contains thorough insulation to maintain the temperature* (FP-Team #6).

Similarly, another team explored existing biological systems not covered in the curriculum and methods of heat transfer (i.e., conduction, convection, radiation) for their design solution. The team highlighted in their EDP logs,

> *Camels try to use as little energy as possible to conserve water and energy. This information could be used to implement it into our lunch bag because we could add something like a hump to increase the coolness of the cold sections and make sure the cold does not mix with the warm* (Team #15).

These well-understood solutions were then included in their final design (Figure 11) as they claimed,

> *We add little lumps of aluminum foil into the hot section to help conserve heat, similar to how camel humps concentrate heat inside their hump. We also added extra layers of cotton foil, just like how whales use their layers of blubber to keep warm, by making sure outside air does not get inside the lunchbox. We also added plastic in the holes of the box, which traps light waves, keeping the food warm. This idea came from polar bears who have thick coated fur, which they can use to absorb heat* (Team #15).



(a) (b)

Figure 11. Lunch box design: (a) first design and (b) second design.

These examples demonstrate that students relied on current, existing solutions, some of which they had prior knowledge of, and minimally diverged, limiting their consideration of many alternatives. Since student participants were allowed to use any resource they needed, they searched on Google for existing solutions to the problem, which led to conventional solutions.

Students' perception of the value of BID

Further investigation of the individual value of BID items on the student survey was conducted to determine if any changes occurred in students' perception of the value of BID from pre-to-post as a result of their engagement in the curriculum, specifically pertaining to learning about BID and biological systems. In Table 5, we present the survey items again to make it convenient for the reader to review the results.

Table 5. Value of biologically inspired design engineering items.

Questions	Items
BID-Q1	Using concepts from biology is useful for developing engineering solutions.
BID-Q2	It is easy to find inspiration for engineering designs in the natural world.
BID-Q3	When working on engineering design problems, nature is a good source of ideas.
BID-Q4	Biology-inspired designs are an important part of engineering.
BID-Q5	Using biology-inspired designs to solve engineering problems is exciting.

The survey results revealed modest shifts in students' views regarding the value of BID from pre to post (See Figure 12). These results corroborated the qualitative findings to some degree.

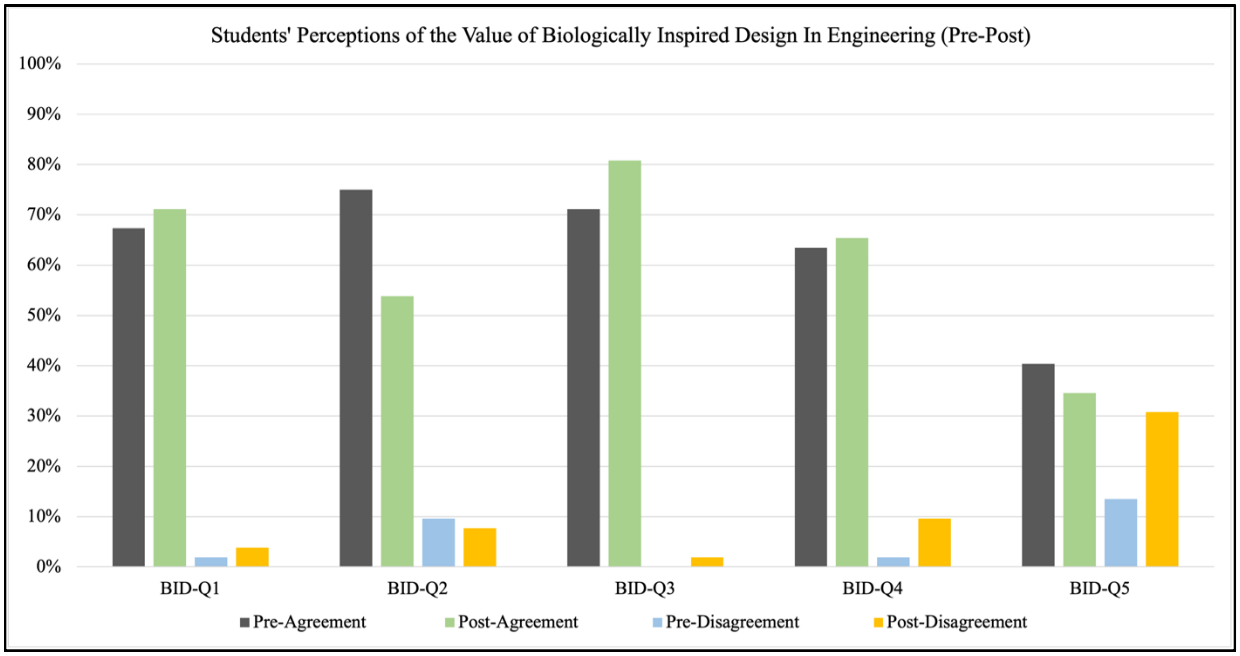


Figure 12. Students *(n*=52) perceptions towards the value of BID (pre-post).

After the course, slightly more students agreed that using concepts from biology (BID-Q1) is useful for developing engineering solutions (67% to 71%). Similarly, a marginal shift (63% to 65%) was observed among students who agreed that biology-inspired designs are an important part of engineering (BID-Q4).

In contrast, students who believed biology was a good source for engineering ideas (BID-Q3) showed a larger increase (71% to 81%). Interestingly, while many initially agreed that finding biological inspiration was easy (BID-Q2), fewer believed so after the curriculum (75% to 54%). A lower percent of the students initially concurred that using biology-inspired designs to solve engineering problems is exciting (BID-Q5), but even fewer felt so after engaging in the curriculum (40% to 35%). These last two points are particularly informative for our discussion.

Discussion

The results of this study contribute to engineering education as a whole and, more specifically, to the knowledge base of pre-college engineering. These findings offer insights into high school students' engagement in the ideation stage of the EDP and the impact of this engagement on students' perceptions of the value of BID for engineering design. It was hypothesized that including biological inspiration would have a positive effect on ideation, and indeed, many prior design studies on biologically inspired design have shown increases in idea generation [22], [23]. The analysis above demonstrates several patterns in students' design ideation behavior.

First, research suggests that equipping students with ideation techniques can support the generation of a greater number of varying ideas [20], [38]. The curriculum, therefore, included various ideation techniques documented in the literature (i.e., SCAMPER, morphological analysis) in addition to biologically inspired design. To aid in idea generation, teachers were trained on these techniques, and supporting lessons and worksheet scaffolds were provided. Nonetheless, no student team documented more than two initial design concepts, and most (14 out of 18) generated only one. Any design concepts documented beyond the first one or two were always derivative of the original(s).

Second, every design concept was derived from an existing solution, for example, by splitting an existing lunchbox design into two halves. The emergent decision variables that resulted in design variation were the orientation of the halves (top/bottom, left/right), amount, type and placement of insulation, and closure mechanism. In all other respects, the design concepts were derived from available lunch box examples and constrained by materials available in class.

Third, even where multiple design concepts were documented, the majority (9 out of 18) of the students fixated on their first idea and did not evaluate the second. The lack of ideation technique use and subsequent fixation is similar to previous studies [39] and [40]. Furthermore, most student teams (15 out of 18) appeared to follow a linear path with little or no iteration, similar to Crismond and Adams's [41] study.

By these accounts, introducing biologically inspired design appeared to have little to no effect on the students' ideation. Moreover, the student surveys suggest an adverse result. While many students initially concurred that biological inspiration was easy, fewer believed so after the curriculum (75% to 54%). Similarly, many initially agreed that using biology-inspired designs to solve engineering problems is exciting (40% to 35%) but felt differently afterward.

While our research does not explain these results directly, our experience in the context of an introductory high school engineering course suggests several factors. For purposes of this discussion, we believe the course was well designed pedagogically [14], that the student's ability to learn and the teachers' pedagogy and course delivery were within generalizable expectations, and that the classroom setting was not a factor [12], [13], [14]. We offer the following conjectures as possible factors inherent to teaching BID in high school engineering that may have influenced the results.

Factor 1, **time.** In an introductory high school engineering course, the focus of the curriculum was the design of an engineering-first learning experience that ensured the students met the standards for the basics of the engineering design course; biologically inspired design is strictly an add-on from this perspective. While meeting the standards was accomplished, the time available for including the more difficult biological content was reduced [42], [43]. If time is a limiting constraint on design ideation, then including additional methods and content that reduce that time will, therefore, limit ideation as well, even if the method intends to increase it.

Factor 2, expectations. Convergent, interdisciplinary learning in the context of an introductory engineering course with expectations and outcomes that are engineering-focused motivates focus on engineering course content. This applies to students in terms of motivating their grading and progression in the course sequence and to teachers in terms of their evaluation [44], [45].

Factor 3, cognitive dissonance. We believe that simultaneously learning biology and learning the new engineering design content in an engineering classroom created dissonance and cognitive overload [26]. This is especially true where EDP process steps like ideation overlap but are slightly different from the biologically inspired design version of that process step. For example, in EDP ideation, students can rely on their own lived experience about how devices work. In contrast, biologically inspired design requires finding and understanding biology before using it effectively for design. We support the BID-Q2 survey result, which showed a reduction in students' belief that finding biological systems to use for design was easy.

Factor 4, design problem. In an introductory high school course, students have limited knowledge of engineering, biology, and physical science to begin with. The problem selected must be one for which the fundamental scientific or engineering principles are approachable for the student and for which the biology that could be used to support those fundamentals are likewise approachable [46], [47]. The choice of a thermodynamics problem met these criteria, including a five-hour lesson and experiment on the basics of heat transfer. However, the biology that students and teachers were comfortable with (e.g., insulation) and the level of understanding of how those systems worked were so similar to existing solutions that the students found no new solutions in biology (from their perspective). Those solutions that might be novel (e.g., phase-change, boundary layer disruption, thermal windows) were likely beyond the grasp of students and possibly the teacher; thus, all of the solutions leaned into biological solutions that already looked like an existing solution. It may be that at this level, novel biologically inspired solutions are unlikely to be understood and found for most problems.

While the results do not demonstrate increased ideation in the form of student conceptual designs, as hypothesized, they do indicate that students made critical connections between biological and engineering design concepts. In nearly all design cases, students were able to articulate one or more patterns in biology and how their design mimicked those patterns. We also saw evidence that students made modest structural changes in design revisions that resembled those found in biological patterns, including (a) adding IR reflective material to reflect or contain heat and (b) adding layers of different functional insulators. While these changes were also present in existing solutions and could have been copied from there, many student teams explicitly connected (and credited) the biology when documenting the change.

Conclusion and Implications

This research is unique in its focus on exploring ideation and novice high school student designers' perceptions of biologically inspired design after a 7-week experience. The research suggests that while potentially valuable, questions remain about fixation, setting student expectations, and lesson timing with respect to both prior engineering and biological knowledge. These findings are consistent with previous literature documenting the challenges novice versus informed designers encounter when generating multiple ideas [23], [48]. Further, while many ideation strategies were explicitly taught in the curriculum, students failed to leverage any of these strategies to support alternative ideas; rather consistent with other studies, students showed signs of fixation. Ideation is a critical stage in the EDP for successful innovation [19]. Therefore, to ensure that students can engage in ideation effectively, students' design practices need to be supported by providing them time to engage in design strategies to help with idea generation.

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