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Biologically Inspired Design for Engineering Education: A Multiple Year Evaluation of Teachers' Professional Learning Experiences (Evaluation)

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Biologically Inspired Design for Engineering Education: A Multiple Year Evaluation of Teachers' Professional Learning Experiences (Evaluation)

Abstract

This evaluation paper focuses on how high school engineering teachers' professional learning experiences advance their understanding of bio-inspired design integration into engineering as a result of the professional learning environment. Participants included engineering teachers from local school districts, who participated in professional learning (PL) in the summer of 2020 and summer of 2021. Design-based research (DBR) methodology guided the development and refinement of the PL experiences across the two summers, and conjecture maps were developed to reflect our high-level conjectures (overall goals of the PL), the embodiment of the learning design (the PL experience), the mediating processes, and the outcomes associated with the PL. The findings illustrate that during the 2020 PL, teachers' overall experiential learning promoted exploration fostering conceptual understanding of BID integration into engineering. However, the specifics of drawing inspiration from nature, such as identifying structure, function, and mechanism (SFM) of biological entities were points of confusion. Challenges were potentially compounded by the virtual PL learning environment, which negatively impacted teachers due to lack of personal interaction and limited hands-on activities. Comparatively, the 2021 PL offered an experientially more enjoyable hybrid platform, through which teachers were able to master detailed SFM analysis. However, due to the emphasis on SFM and specific curriculum activities, the guiding theme that biology can serve as inspiration for engineering design was diminished.

Introduction

Engineers have often used nature as an inspiration to find solutions and develop products that benefit society, a process termed biologically inspired design (BID). BID is an emerging academic discipline, also referred under similar names as biomimicry, bionics, and biomimetics, that prepares students with the interdisciplinary knowledge and skills to combine scientifically studied biological systems and functions with engineering to create more economic, efficient, and sustainable solutions to human challenges [1], [2]. In fact, integration of BID in engineering has shown to increase students' interest in engineering and can be a means to attract women within engineering, due to its interdisciplinary nature [3]–[5]. Students exposed to BID are not only well-prepared to face modern engineering design challenges but have also expressed an appreciation for nature and the knowledge yet to be discovered about the natural world [6], [7]. Consequently, undergraduate, and graduate engineering programs have begun to place greater emphasis on integrating bio-inspired design in their engineering curriculum to prepare their graduates to work across disciplinary, cultural, and economic boundaries. However, integration of bio-inspired engineering has not translated to pre-college education. Given the advantages observed by integrating BID concepts in higher education, it seems promising to design curricula for pre-college education that introduces students to BID multidisciplinary learning. As with curricular innovation, conceptual understanding must be achieved by teachers before they are able to thoughtfully instruct their students, reinforcing the need for high-quality professional learning experiences.

Our research is centered within the K-12 (high school) setting and is focused on teacher experience resulting from a BID professional learning program. Specifically, we investigate how the professional learning environment designed within the professional learning experience led to integration of BID within engineering teachers' preexisting schema for engineering education. This study is part of a larger project, which aims to create socially relevant, accessible, and highly contextualized high school engineering curricula focusing on bio-inspired design. To effectively implement the curriculum, robust professional learning (PL) were designed for high school engineering teachers during the summers of 2020 and 2021. The lessons learned from these previous teacher PL experiences are intended to guide the development of the final PL experience for summer of 2022 and ultimately a scalable, online PL. More importantly, these lessons learned can be further translated into future change efforts to improve engineering education.

Background & Literature

Bio-inspired Design (BID) in Pre-College Education

BID is a developing concept, especially in pre-college education [2], [7]–[9]. Nonetheless, from the limited research garnered, integrating biological functions within the engineering design process in K-12 education appears to hold strong benefits [6], [7], [9]. As students enter the continually evolving job market, equipping them with multidisciplinary appreciation for STEM better prepares them for professional success. Biologically inspired design combines disciplines of biology and engineering, requiring students to utilize all components of STEM: science, technology, engineering, and math [7]–[9]. Using nature as inspiration for engineering design also serves to offer students a heightened appreciation for the natural world and sustainability. Instead of viewing nature as something to only enjoy and experience, students begin viewing living organisms as a resource for providing efficient and eloquent design solutions [6]. Thus, as research has demonstrated, BID assimilation has shown to lead to more complete STEM integration, as well as increased student appreciation for nature, STEM engagement, and understanding of the engineering design process [3], [6], [8], [10]–[12].

The incorporation of BID into the engineering design process is also engaging and exciting for young individuals [10]. Abaid et al. [10] discovered that students had more favorable perceptions of engineering after engaging in a BID activity, in which participating students were tasked with creating the most efficient swimming robots based off various types of fish fins and testing different robot designs. Moreover, explicit teaching of BID can assist students to develop a deeper understanding of the engineering design process through intentionally integrating BID, and then working iteratively to develop and build their engineered solution [3], [11].

In addition to students, teachers' engagement in BID learning has also demonstrated unique benefits. Previously conducted research on teacher professional learning focusing on bio-inspired design implementation was shown to increase teachers' self-efficacy and outcome expectancy, as well as heighten their understanding of the material [13], [14]. As Han et al. [13] asserts, beliefs held by the teachers can impact student learning and student attitudes toward STEM and ultimately student academic achievement. Consequently, it is critical to provide teachers with rich and meaningful experiential learning experiences that can strengthen their understanding of BID integration in engineering. As research indicates, experiential learning experiences help to develop teachers' understanding by experimenting, reflecting and adapting new practices and content in their own professional context [2], [15].

For this evaluation paper, conjecture mapping was applied in conjunction with design-based research (DBR) to reflect on and evaluate the professional learning environment designed for the Biologically Inspired Design for Engineering Education (BIRDEE) project across the two summers and its impact on teachers' professional learning experiences.

Theoretical Framework: Conjecture Mapping and Design-Based Research

Conjecture mapping is used as a means of "specifying theoretically salient features of a learning environment design and mapping out how they are predicted to work together to produce desired outcomes" [15, p. 19]. Conjecture mapping has been previously used within education research to articulate goals for projects and final outcomes [17]. In accordance with Sandoval's original structure, conjecture maps consist of four main elements. The first element involves a *high-level conjecture* that is the overall objective for the learning environments' design. The high-level conjectures are abstract ideas about the learning principles consciously selected in the design of the learning environment. That high level conjecture is expected to be met through specific *embodiments*, the second element. High-level conjectures are further reified into *embodiment* in the learning environment as shown by the arrows between high-level conjecture and embodiment. According to Sandoval (2014), the embodiments comprise of tools and materials, task structures, participants structure, and discursive practices. The embodiments generate *mediating processes* (third element), that involve observable interactions, though artifacts generated through learning activities can be used as well, between participants and the design of the environment. Analysis of artifacts can demonstrate how participants interpret designed activity structures and tools to explain their interactions, learning and engagement. These mediating processes ultimately produce *outcomes* [16]. A learning environment is deemed successful if the outcomes generated support the high-level conjecture initially set for the project. Such learning environment, in which formal and informal learning occurs in rich contexts are best examined using a pragmatic approach, such as design-based research. Conjecture mapping plays an important role in design-based research (DBR) since conjectures support the iterative testing used to examine and revise the learning environment, as it is designed and subsequently implemented [18].

Design-based research (DBR) is an emerging paradigm for the study of learning in context through the systematic design of instructional strategies and tools [19]. DBR aims at producing new theories and practices that potentially impact learning and teaching in naturalistic settings. DBR is often employed in research to understand contexts, design effective systems, and make meaningful changes for the subjects of the studies [20]. Traditional methods of research generate refined understandings of how the world works, which may indirectly affect practice. In DBR there is an intentionality in the research process to both refine theory and practice [20]. In essence, the fundamental guiding principle of design-based research is the study of "learning as situated within a learning ecology" [21]. The learning ecology in this project is the professional learning environment, which comprised of activities, tools, resources, and the participatory and pedagogical processes in which the engineering teachers engaged.

Design-based research operates at an intermediate level of theory to produce useful explanations that extend beyond the context in which the study is situated [22]. Additionally, the design research process purposefully facilitates interactions in order to produce useful explanations [20]. In essence, combining conjecture mapping with DBR serves as a promising tool for program evaluation for development projects. For this study, conjecture mapping in conjunction with DBR was applied to reflect on and evaluate the goal of the professional learning experiences in relation to the learning environment outcomes across the two summers of professional learning.

Methods

Research Design

In this qualitative study, design-based research (DBR) methodology guided the development and refinement of the PL experiences across the two summers. DBR involves interactive cycles of testing and research-informed revisions of an innovative educational practice that has the potential for long term sustainability [16], [23]. In addition, conjecture mapping, a design-based research method, was employed to evaluate the design of the professional learning environment and teachers' experiences as a result of each PL. We analyzed how the tools and materials, task and participant structures, discursive practices, and mediating processes used across the PL supported a trajectory of teacher development and understanding over the two years.

Participants

The aim of this paper was to investigate whether the PL resulted in four participating engineering teachers being able to integrate their new understanding of BID into their preexisting schema for engineering design. Three of the teachers are formally certified to teach 6-12 engineering and one is permitted to teach engineering based on professional background [2]. The teachers varied in terms of their teaching experience ranging from a first-year teacher to more veteran teachers. The four participating teachers represent three high schools from two school districts in a large southeastern metropolitan area. In two high schools, the majority of students are Black or African American, representing between 89% and 96% of the student population. In the remaining high school, the student community is more diverse, where a small majority of students are white (53%), and the remaining students are Asian (23%), Black (11%), or Hispanic (8%) [8]. These teachers were recruited from school districts that had agreed to participate in the project. Thus, the participants were only those teachers' that accepted our invitation and were willing to implement the curriculum in their classrooms.

Setting & Context: Teacher Professional Learning

The professional learning experience evaluated within this paper is nested within a larger project focused on increasing female interest in engineering, through development and implementation of BID curriculums that are more interdisciplinary and human focused [2]. Thus, the project included developing three curricular units to incorporate BID within the engineering design process, as well as designing and hosting an effective professional learning experience for high school engineering teachers to help them develop their own understanding of BID incorporation within the engineering design process, as well as gauging potential student interest in BID. Ultimately, the final goal was the implementation of designed curriculums within high school engineering classrooms [2].

The PL for this project was initially designed to be face-to-face as part of a six-week summer internship at university research laboratories focused on biology and bio-inspired design [2]. However, due to COVID-19 and research lab closures in the summer of 2020, the project team had to transition the summer PL experience to an online setting. BlueJean online meeting platform was used for the PL meetings, and all PL artifacts/assignments and readings were shared with teachers via Canvas. Though online, the goal of each summer online PL was to connect engineering teachers to the natural world through immersive experiential learning activities to improve teachers' knowledge of bio-inspired design integration in engineering. The first PL in the summer of 2020 was completely virtual and the second PL in summer of 2021 was hybrid.

For each year of PL (2020 & 2021), a synchronous, quasi-facilitated online course was developed and delivered to teachers over six weeks [2]. Across the two years, primary elements of the online PL design and function of each course were the use of inquiry, experiential learning, and highly collaborative assignments and discussions. In year one, teachers attended the live PL two days a week (Tuesdays and Thursdays) for two hours, in addition to offline, asynchronous assignments (See Table 1 & 2 for the topics discussed across the two years of the PL).

For the first year of the PL, activities included found object investigations, in which teachers identified objects in nature and determined functional properties of those objects. Structure, function, mechanism was introduced to aid in evaluating biological solutions to engineering design problems, and a final design challenge culminated in teachers applying what they learned to produce a biologically inspired vaccine transport device.

Table 1

Professional learning activities for summer 2020

Weeks	Module Topic	Learning Activities
Week 1	Intro to Bio Inspired Design	Found Object – exploration of a natural object virtual zoo walk
Week 2	Design Challenge Part A: Problem Definition and Understanding	Discussion of applicability BID to solving engineering problems
Week 3	Design Challenge Part B: Ideation, Biological Analogies, and Low Fidelity Prototypes	Introduction to structure, function, mechanism (SFM) and biological analysis to evaluate biological solutions

Week 4	Independent Work: Nature Walk and Test Planning	Found object investigation in relation to SFM
Week 5	Design Challenge Part C: Prototype Planning, Fabrication and Curriculum Review	Prototype development
Week 6	Design Challenge Part: Testing and Final Presentation	Testing and evaluation of prototypes

For year two, teachers, attended PL activities each day of the week for approximately two hours over four weeks with a two-week hiatus in the middle. Over the duration of both PLs, a similar amount of content was delivered, although spaced differently due to teacher availability.

Activities for the second PL included more specific curriculum activities, including a never-wet experiment, robotic arm design, explicit SFM review, found object analysis, and many field trips to locations such as botanical garden, zoo, and research laboratories. Teachers participated in such activities from the student perspective, completing written reflective questions and presenting their work within the classroom sessions.

Table 2

Professional learning activities for summer 2021

Weeks	**Module Topic**	**Learning Activities**
Week 1	Exploration of Nature: Curriculum Overview, Reflection on Teacher Practices and Experimental Activities	Project Kickoff, Botanical Gardens, Curriculum Overview and Activities
Week 2	Curriculum Overview and Activities	Unit 1 review continued, completion of curriculum activities, discussion of women in engineering, structure, function, mechanism (SFM) analysis
Week 3	**BREAK**	
Week 4		
Week 5	SFM Analysis and Reflection	Zoo visit, Found Object Activity - exploration of a natural object SFM overview
Week 6	Other Engineering Activities and Field Experiences	Lab visits, reflection on found object, pedagogical training, Engineering Log (EDPL) completion

Data Sources

The data sources for this paper include teacher interviews, PL artifacts, field notes, and video recordings of all the PL sessions. The video recorded sessions allowed us to capture teachers and PL facilitators' virtual interactions as PL activities were being implemented, and the assignments were being discussed. As such, our data sources included many hours of video data, one and a half hours of focus group discussion with the four teachers and teachers' assignment submissions, and field notes.

Data Analysis

Data analysis involved qualitative content analysis of teacher interviews, PL artifacts, field notes, and video recordings to inform our assertions. Content analysis is a systematic and robust method of qualitative data analysis that can help make sense of all forms of data including auditory and visual data when context is important [24]. An inductive process of analysis was conducted for coding the data. This helped to synthesize, summarize, and generate summaries of the data. The summaries of the data were then used to develop a conjecture map based on our high-level conjecture, a commonly used approach in DBR. Conjecture mapping can articulate changes in knowledge gained from design research. Thus, conjecture maps were developed after the data was examined holistically to reflect our high-level conjectures (previously outlined overall goals of the PL), the embodiment of the learning design (the PL experience), the mediating processes, and the outcomes associated with the PL for each year.

To create the conjecture maps, the high-level conjecture and the desired outcomes were articulated [16]. The high-level conjecture was *that teachers will integrate BID into their pre-existing teaching engineering schema* by engaging in experiential learning experiences and interactive discussions. The conjecture captures aspects of the goal of transforming teacher practice, conceptual understanding of BID integration, and appreciation of nature as a result of the context in which the designed learning environment was situated.

This was followed by articulating our desired outcomes of the PL experience. These outcomes were that the experiential learning experience would: (1) foster engineering teachers' conceptual understanding of BID integration into engineering, (2) be effective in increasing teachers' appreciation for nature, (3) increase teacher comfort with integrating BID in their engineering teaching, and (4) enhance teachers' ability to critically evaluate their own pedagogical practices for BID integration and student engagement. The desired outcomes reflected not only the goal of the project but also research which supports experiential learning pedagogy in which purposeful engagement via experiences and focused reflection increase knowledge and develop skills [15].

The embodiment of our conjectures, the designed learning environment also termed as "learning ecology" were then described [22]. Cobb et al., [18, p. 9] describes learning ecology as "a complex, interacting system involving multiple elements of different types and levels". Following Sandoval [16] and Cobb et al. [22], suggest four features of the learning environment: (1) tools and materials, (2) task structures, (3) participant structure, and (4) discursive practices. Finally, the mediating processes were articulated which were generated through the content analysis of various data sources discussed previously.

The analysis and interpretation of data, as well as the construction of the conjecture maps, was strengthened by following the trustworthiness criteria suggested by Guba and Lincoln [25]. Credibility was achieved through data and researcher triangulation. Data in this case comprised of video recordings of the PL, field notes, teacher interviews transcripts, and artifacts, which were first analyzed by two researchers, who were part of the research and evaluation team individually, then as a group. Agreements and disagreements were discussed through deep conversation among multiple researchers at different stages of the analysis and conjecture maps' development and refinement [26].

Results

In the summer of 2020, the project's first professional learning experience (PL 1) for participating teachers was launched. The high-level conjecture (See Figure 1) was to design a PL for engineering teachers that fostered their connection to the natural world through immersive experiential learning activities to improve teachers' knowledge of bio-inspired design integration in engineering. This conjecture was projected to be met by our embodiments, which included various activities, interactions, and discussions, including coaching cycles that the teachers engaged in during the professional learning experience. Through completing the various embodiments, mediating processes resulted, which ultimately led to our intended outcomes. Arrows connecting embodiments, meditating processes, and outcomes show which facets of the learning environment directly led to one another.

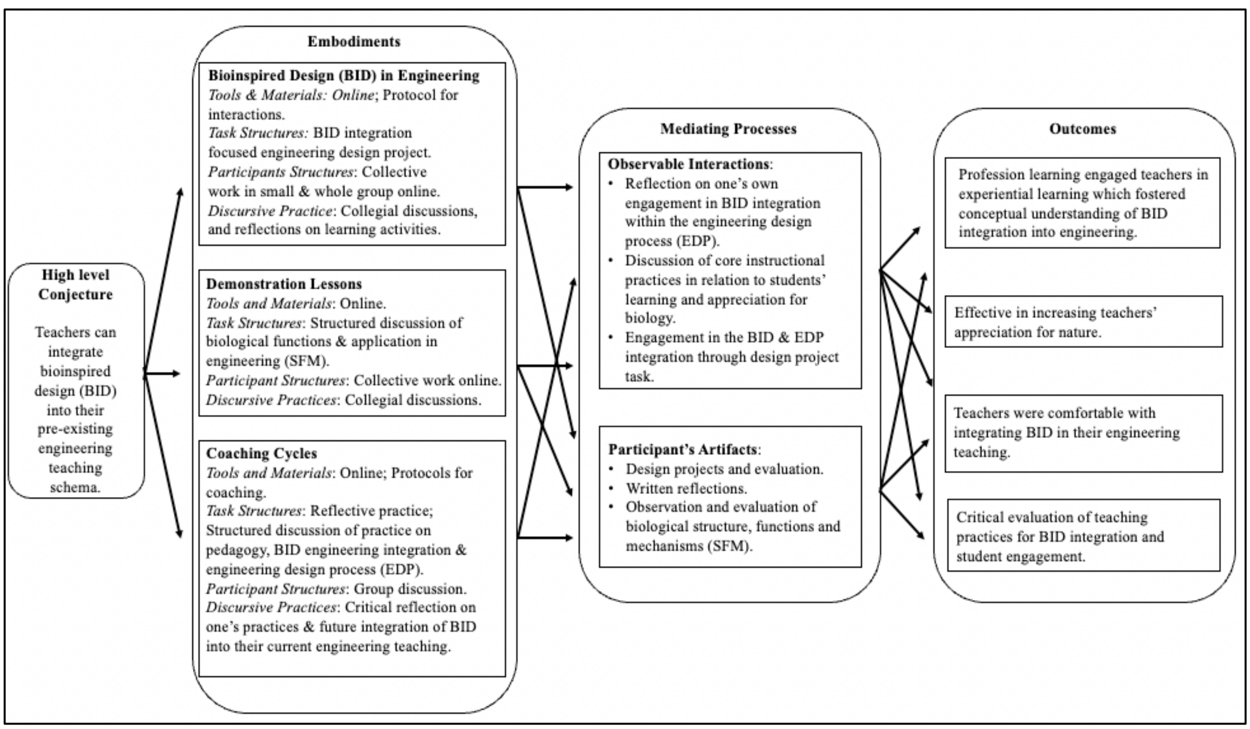

Figure 1. *Conjecture map of 2020 professional learning environment.*

As is evident within Figure 1, the PL experience in summer 2020 resulted in high levels of connection between embodiments, mediating processes, and outcomes. Embodiments occurred in the form of specific activities, including a virtual zoo and nature walk experience, as well as engagement in engineering planning and iterative prototyping for each teacher's own engineering design project. Through engaging with the natural environment and explicit discussion of BID application to engineering, mediating processes resulted as teachers reflected on their own engagement in BID integration, as well as core instructional practices and implications for student engagement. Additionally, as teachers completed engineering design projects of their own, they were required to engage from the student perspective and further reflect on the integration of BID within the engineering design process. The outcomes produced from the embodiment-derived mediating processes that left teachers by the end of the PL with a conceptual understanding for the integration of BID within engineering, although teachers expressed hesitancy in being able to breakdown specific functions of natural objects and apply them to engineering design. Additional outcomes included enhanced teacher appreciation for nature, as well as newly acquired teaching practices and greater comfort teaching BID material. Ultimately, the desired outcomes intended were reached. This also supported the high-level conjecture set for the PL prior to its start, demonstrating that PL1 was successful in helping teachers to integrate BID into their pre-existing teaching and engineering schemas.

Leading into summer of year two, the PL was conducted within a hybrid format in which 2-3 days each week occurred through in-person discussion and activities, and the remaining days of the week were held in a virtual environment. During this PL, teachers also engaged in field trip experiences such as zoo, botanical gardens, and research labs. The high-level conjecture and the desired outcomes remained the same as from the previous year to nurture teachers' connection to the natural world through immersive experiential learning activities to strengthen teachers' knowledge of BID integration in engineering. However, embodiments and mediating processes were adjusted to address the need for additional teacher support in more technical BID applications, such as understanding structure, function, and mechanism (SFM) of biological entities. As a result, teachers developed a sound understanding of and were able to conduct SFM analysis of a natural object. Figure 2 shows the conjecture map created for the second summer PL (PL 2).

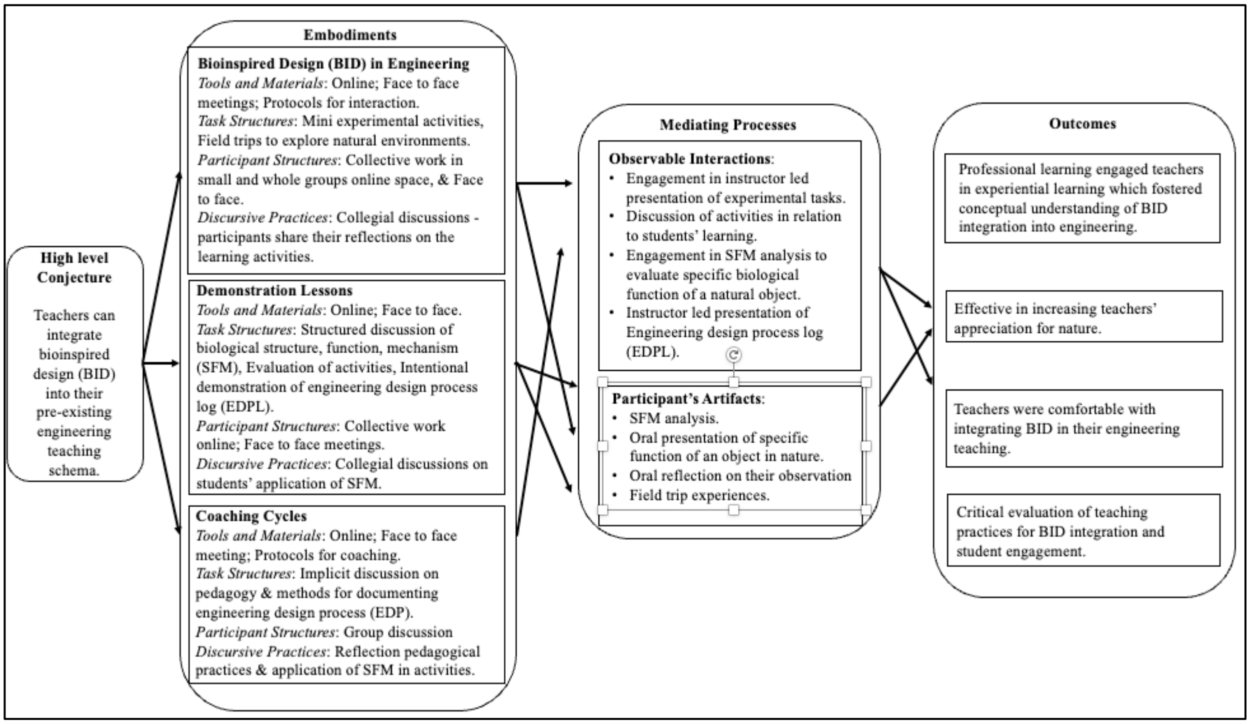

***Figure 2**. Conjecture map of 2021 professional learning environment.*

For Figure 2, connecting arrows indicate the PL experience was not as enriching as the previous year. Embodiments, conducted in the form of specific activities, included in-person zoo, botanical gardens, and research lab tours, as well as repeated SFM analysis for natural objects, various curriculum activities, and practice with an engineering design process log (EDPL) [27]. Mediating processes resulting from these embodiments included teacher reflection on projected student engagement in curriculum activities, as well oral reflection on field observations and presentation of specific biological function analysis for objects found in nature.

As is evident, major differences between PL 1 and PL 2 emerged within the embodiments and mediating processes, as teachers were more involved during the second PL with instructor led experimental tasks, SFM analysis and engineering design process log (EDPL) completion. The largest difference in activities between the two PLs was the culminating design project within PL 1 that required teachers to engage first-hand from the student perspective in integrating BID into the engineering design process. For the second PL, this was not the case as teachers instead participated in extensive SFM practice and isolated curriculum design activities and did not engage in the engineering design process from start to finish.

As the embodiments and mediating processes for the two PLs were different, so too were the actual outcomes, thus the initial desired outcomes intended for the PL were not all met. PL 2 was effective in increasing teacher appreciation for nature, as well as increasing teacher comfort and ability to conduct structure, function, and mechanism analysis. However, unlike that of the first PL, the teachers did not gain extensive practice integrating BID into the engineering design process, and thus did not meet the outcome to foster conceptual understanding for BID integration within the engineering design process. Lacking such conceptual understanding, they also failed to incorporate it into their own engineering and teaching schema. Instead, they gained technical practice at breaking down and identifying specific biological functions.

Discussion and Lessons Learned

The findings illustrate that during the 2020 PL, teachers' overall experiential learning promoted exploration fostering conceptual understanding of BID integration into engineering. However, the specifics of drawing inspiration from nature, such as identifying structure, function, and mechanism (SFM) of biological entities were points of confusion. Challenges were potentially compounded by the virtual PL learning environment, which negatively impacted teachers due to lack of personal interaction and limited hands-on activities. Comparatively, the 2021 PL offered an experientially more enjoyable hybrid platform through which teachers were able to master detailed SFM analysis. However, due to the emphasis on SFM and specific curriculum activities, the guiding theme that biology can serve as inspiration for engineering design was diminished.

There were important lessons to be learned from each of the professional learning experiences held over the past two years. Going into our third year, we plan to take all that we have learned and apply it into our final teacher professional learning experience.

From PL 1, teachers were presented the information to integrate BID into the engineering design process and were also equipped with the tools to articulate this integration to their students. Yet, teachers were left unprepared for completing specific technical aspects of understanding the biological material for BID application, such as extracting specific functions, mechanisms, and structures of biological entities for use within an engineering design [28].

Alternatively, for PL 2, teachers were well-prepared with the technicalities of breaking down specific biological functions and their resulting structures and mechanisms, yet the PL lacked in the general overview and aspirational goals of integrating BID into the engineering design process and discussion of best pedagogical approaches within the classroom.

Looking ahead to year 3, we can combine key experiences of the past two years to create a more effective PL, one that will address the overarching high-level conjecture to provide teachers with the ability to adequately integrate BID into their engineering and teaching schemas while also providing them with the technical expertise necessary in structure, function, and mechanism breakdown in order to be able to use their BID knowledge to its full potential. We believe this would best be achieved by requiring the teachers to work on a design project throughout the duration of the PD and simultaneously including more explicit instructor led discussion on SFM breakdown and application to the engineering design process.

Additionally, we learned from the hybrid format of PL 2 that including in-person components to the professional learning experience is important for increasing teacher enjoyment and engagement yet does not appear to be critical for teacher learning. For instance, we observed that in-person field trips fostered teachers’ appreciation for nature and generated enthusiasm for BID, yet such experiences still need to be connected back to the goals of professional learning to increase teachers’ conceptual understanding of BID integration in engineering. Thus, it would be ideal to incorporate in-person aspects going forward, including immersive field experiences, but it is still critical to bridge the connections between knowledge generated across settings.

Conclusion

The COVID-19 pandemic significantly impacted the originally planned PL experiences designed for this project. Nonetheless, the lessons learned from the two years of PL (virtual and hybrid) are applicable within this new pandemic context for future BID PL for summer of 2022 and for BID- related PL more generally. The results of this evaluation can serve to identify further resources or support, that teachers may need in order to effectively integrate BID into their engineering teaching. Further, this evaluation can serve as a grounding for rethinking teacher professional development in terms of providing teachers with immersive learning experiences (e.g., research lab visits, nature walks) to advance their understanding of bio-inspired design integration in engineering.

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