2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #37279

Bio-Inspired Engineering Design: The Impact of Information Representation on Access to Inspiration from Outside One's Discipline

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Abstract

Engineering designs inspired by the natural world are often highly innovative, offering novel solutions to human problems where engineers had initially only seen trade-offs. Unlocking the full potential of biologically inspired engineering design can be difficult due to the need for knowledge transfer between biology and engineering. As a result, bio-inspired designs have been the result of either chance observation or dedicated studies. Efforts have been made to develop normative bio-inspired design processes and identify approaches that can aid non-biology experts to find and implement bio-inspired strategies; however, true accessibility is still lacking. Understanding connections between how biological information is represented (e.g., figures, terminology specialization, and age-based reading levels) versus the ability of an engineer (and especially a student) to produce successful bio-inspired designs is critical. This paper reviews a preliminary classroom study that sought to understand 1) how the source of biological information impacts resultant ideation success, 2) how the form of the biological representation influences resultant solutions, and 3) what the critical characteristics of a biological inspiration's representation are for it to be successfully transformed into an engineering idea. The long-term goal is to understand critical characteristics needed for successful knowledge transfer from non-engineering disciplines to create methods that broaden the prevalence of bio-inspired and other interdisciplinary designs.

1. Introduction

Bio-inspired design (BID) has long inspired designers and engineers to innovate solutions to the world's most challenging problems [1]. A bullet train in Japan inspired by kingfisher birds eliminated a sonic boom issue and decreased noise pollution [2]. George de Mestral invented Velcro after getting tired of continually removing burrs from his dog and himself after walking outside [3]. While successful examples of bio-inspired designs are numerous, the majority have either been a result of chance observations that eventually found a problem like Velcro or of very dedicated and problem-motivated studies like the bullet train. Despite the popularity of bio-inspired designs, it is challenging for designers and engineers to methodically learn and implement knowledge from biological fields to their own challenges. Understanding how the format of biological information can ease its use by engineers and designers for ideation can further advance the prevalence of successful and innovative bio-inspired designs. Bio-inspired design, and the broader field of Design by Analogy (DbA), have served as the foundation of countless innovations. However, much is still unknown about how to automate these design practices and their cognitive processing methods. Understanding how bio-inspired design can be taught to engineering students, in particular, those who have minimal biological knowledge, has been even less well-studied. A study found that most students gravitate towards familiar species and characteristics, a fixation that limits innovation and novel ideas that are often the result of working outside one's domain [4].

This work seeks to understand relationships between how biological knowledge is displayed (in this particular study, in terms of figures and technical complexity) and an engineer's (in this particular study, an engineering student's) ability to successfully identify and incorporate biological inspiration for solving an engineering problem. The specific characteristics of references have been found to influence engineering ideas in terms of quality, quantity, variety, and novelty [5, 6]. The study covered in this publication seeks to discover the relationship between stimuli representation and successful application of biological inspiration. The initial hypothesis was that biological text containing multiple basic images and simple language would be more preferable for engineering students working without the help of biologists and would facilitate the generation of ideas. The engineering problem was provided to the students and held constant for all participants. The ideation results are quantitatively measured using current best practices [5-13].

1.1. Bio-Inspired Design

Design by Analogy (DbA) is a methodology where designs are produced in a target domain inspired by an often-unrelated source domain. Analogical inferences are compelling cognitive mechanisms that have been found to improve both critical thinking and logical reasoning [14]. Biologically inspired design is a type of DbA that takes advantage of evolutionarily proven design principles to create new and innovative human-engineered solutions [15]. The initial popularization of bio-inspired design produced an exponential surge in papers and patents that has since tapered off to a lower, but still positive rate [16], suggesting that the potential of BID has not yet been fully discovered. Efforts have been made to develop normative BID processes and identify approaches that can aid non-experts to find and successfully implement biological strategies [17, 18], however, true accessibility is still lacking due to difficulties related to the required knowledge transfer from biology to engineering.

1.2. Bio-Inspired Data-driven Methods, Tools, and Databases

Hastrich developed the Biomimicry Design Spiral in 2005 that covers all steps from initial problem identification to the final product evaluation [19]. The model's spiral shape reinforces its iterative process. The International Organization for Standardization has a standard on Biomimetics that presents a 5-step model without an initial problem formulation and analysis phase [20]. Georgia Tech's BID formulated a 6-step design model similar to the design spiral until the last step where there is no mention of the final design evaluation [21]. The model introduces the Four-Box, which supports quick classroom projects by summarizing the four most important model categories (function, operational environment, constraints/specifications, and performance criteria) in 4 quadrants, and the T-Chart. The Technical University of Denmark employs a 5-step model that covers all steps from problem formulation to final evaluation and introduces the "bio card," which provides a description of the biological phenomena, related functions, mechanisms involved, a generalized principle, and a drawing [22]. The ParisTech group has created a 9 step biomimetics problem-solving process based on the TRIZ methodology from Masey and Wallace [23]. This methodology has the same design process as the design spiral but additionally subdivides some activities into separate actions. It is the only methodology that covers all 9 design steps. Lenau *et al.* compare these five design models for BID, finding how each methodology corresponds to one another [16]. Devesh *et al.* have also proposed a method to unify multiple models, creating an eight-step process with internal iterative loops [24]. Nagel *et al.* are currently working on creating new evidence-based educational resources to address analogy use/misuse, mapping, and transfer [25].

Data-driven tools, and databases generated in support of BID include an engineering-to-biology thesaurus created by mining biological text for meaningful keywords and translating those to engineering functional terms [26, 27]. A Design-by-Analogy to Nature Engine (DANE) provides a design case study library [28]. The Biomimicry 3.8 Institute created a popular web-based tool called AskNature [29] that employs a dedicated taxonomy to manage a large number of biological strategies, both untapped and those already used in engineering, based on functions. The T-Chart used here is an analogical tool developed by Helms and Goel [30] for biological analogy evaluation. The tool provides a side-by-side view of a design problem and a potential biological solution to rate the analogy between them in terms of 'same/similar/different.' Despite these tools created to overcome the challenge of understanding biological inspiration, no straightforward choice for bridging the divide between engineering and biology has emerged.

2. Methods

2.1. Classroom Study

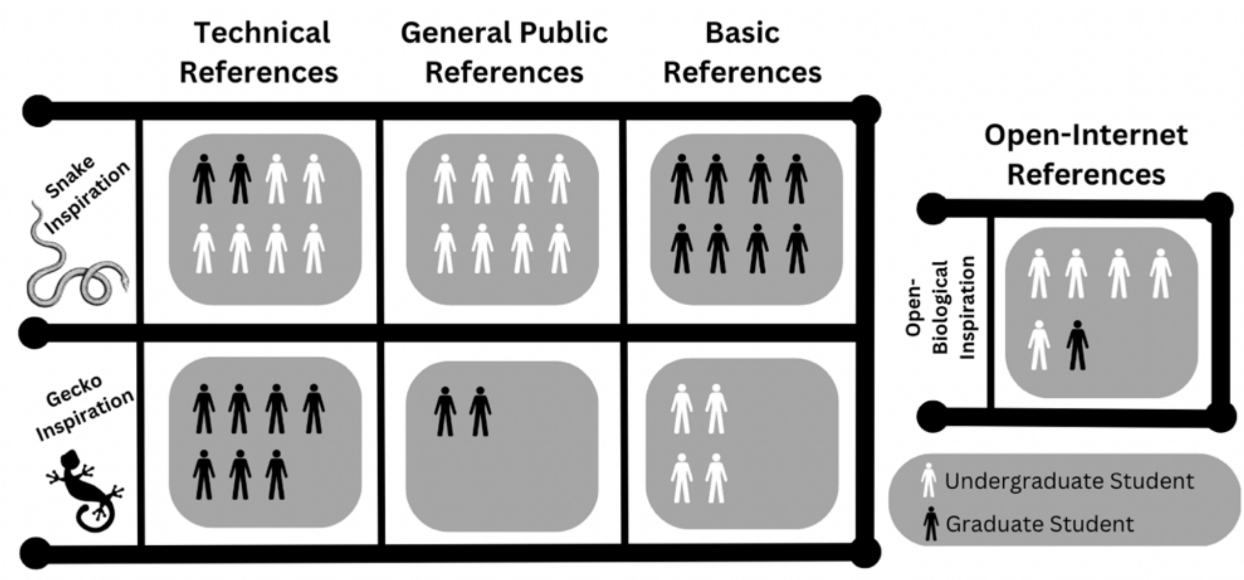

Figure 1. The seven student design group categories used for the study. Only one group wasn't given a fixed source of biological inspiration (gecko or snake) and was instead allowed an open internet search of everything outside of the website AskNature.org.

The study took place in a stacked undergraduate/graduate course of Bio-Inspired Engineering Design during the Spring 2022 semester. The classroom study consisted of 44 engineering students (mostly mechanical and a few biomedical). Twelve student groups of 2-4 students each were assigned the same design problem, in the form of a paragraph and a completed Four Box (seen in Table 1) and given the same basic problem background information. Each group was given one of 7 categories of generalized biological inspiration (snake, gecko, or open internet) and sources (basic, intermediate, or technical), as seen in Fig. 1. The biological inspirations were distributed randomly, resulting in 6 gecko-inspiration groups, 5 snake-inspiration groups, and 1 free internet group (with the limitation of not using AskNature). Figure 1 clarifies the three reference categories for the gecko and snake groups: basic – child level (e.g., zoo and national geographic kids-type publications), intermediate – general public level (e.g. Wikipedia and other online encyclopedias), and technical – researcher level (e.g. discipline-specific journal publications).

Students had most of a 75-minute class to read their resources, complete a T-Chart, and generate a bio-inspired design concept. The designs (sketches and notes) were collected at the end of class. The students were asked to complete a survey asking about the usefulness and helpfulness of their references to collect preliminary data on a possible connection between successful application of biological inspiration and the format of the biological information. The surveys and T-Charts were then analyzed using three different metrics: reading ease, image ease, and T-Chart accuracy.

Table 1. Four Box of the Problem Description: "Falls are ranked as the leading cause of death for older adults and the second leading cause of occupational-related deaths. Existing devices such as crampons and snow chains attach to the soles of shoes to increase grip but always protrude from the sole and may be tedious to attach and detach. There is thus a need for lightweight dynamic devices that can help prevent slips and falls through friction enhancement of footwear."

Operational Environment	**Function**
• Outdoors (Ice, Snow, Smooth Pavement) • Indoors (Carpet, Wood, Tile) • On existing wide variety of shoes (Dress shoes, Sneakers, Boots)	• Prevent slipping • Enhance friction • Modify shoes
Specifications	**Performance Criteria**
• Minimize damage to indoor surfaces • Attach to existing shoes • Low profile • Doesn't interfere with normal walking gate • Lightweight • Easy to attach/use	• Friction increased from regular shoes on both packed snow and ice

2.2. Data Processing (Text, Images, and Inspiration Application)

The Flesch Reading Ease (FRE) scale was used to assess the readability, or ease at which a text would be understood and engaged with, of the references given to the students (reading ease). This metric assigns a score between 1 and 100 to a text, with 100 being the easiest and 0 the hardest, based on sentence and word counts. Equation 1 shows the mathematical formula to compute this score [31], which determines the appropriate education level required to understand a reference. 100-60 is considered primary/middle school level (easy to read), 60-50 is high school level (fairly difficult to read), 50-30 is college level (difficult to read), and anything between 0-10 is professional level (extremely difficult to read) [32].

$$FRE = 206.835 - 1.105\left(\frac{Total\ Words}{Total\ Sentence}\right) - 84.6\left(\frac{Total\ Syllables}{Total\ Words}\right) \quad (1)$$

The visual aids (figures and images) within the references were also ranked based on technicality to understand how the figures may have made a reference more or less accessible and contributed to the bio-inspired solution. A Likert-type rating scale was developed to rank the technicality of the images, as shown in Fig. 2 [33]. The numerical rating scale used [34] ranged from 1-5, with 1 representing a basic figure showing an easily accessible/understandable image, often in color and of the entire biological phenomenon and 5 representing a highly technical figure with information that requires discipline specific knowledge and a clear reading of the text to use. The scale utilized is shown at the bottom of Fig. 2. Two hundred images were processed from the 37 references given across all 6 gecko (93 figures and images) and snake (107 figures and images) groups. Three of the researchers involved in the study scored (termed from here on out 'inter-raters') the images from 1 to 5, with 0.5 increments and their ranking results were averaged for each image to reduce the bias of a single organizer. The aggregate standard deviation of these scores was found to be ±0.21. The three inter-raters were two Ph.D. students and a recent Ph.D. graduate all specializing in the field of bio-inspired design. They had all taken the graduate-level course "Bio-Inspired Engineering Design," and one of them was serving as a Teaching Assistant for the course.

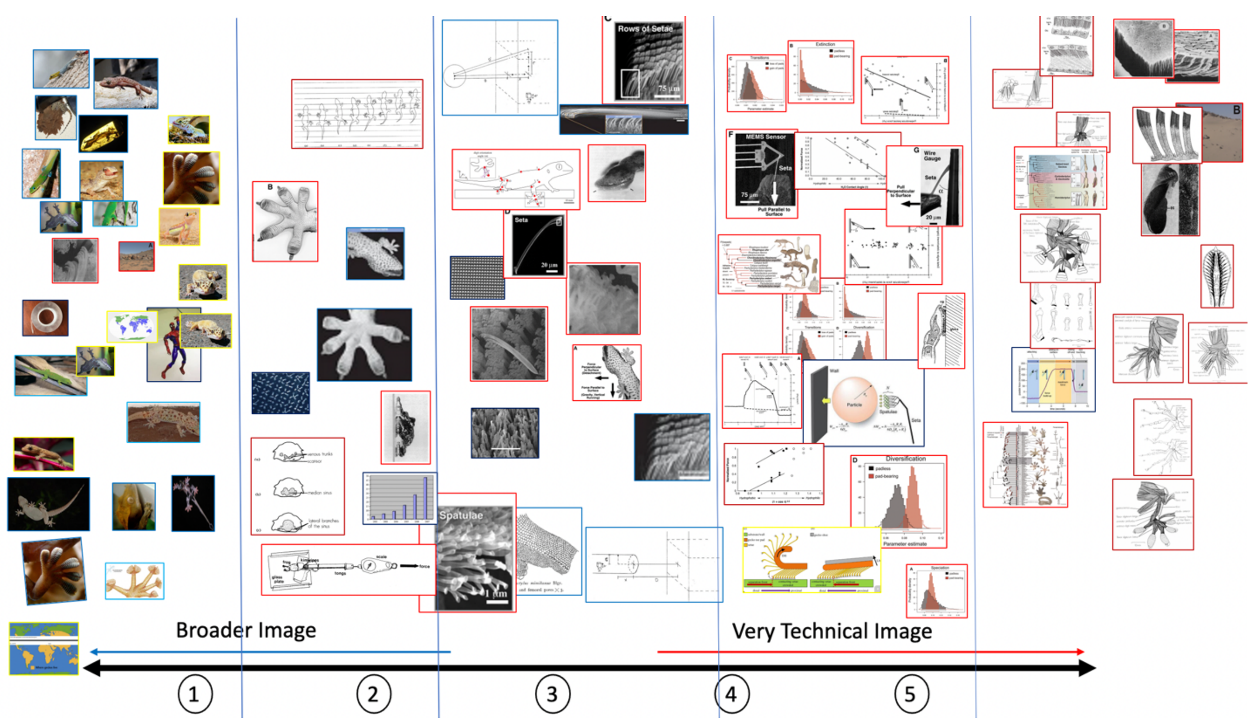

Figure 2. Unsorted images for Gecko (similar set up was used for Snake). The outline border color represents the reference from a particular team. Team A (red), Team B (blue), and Team C (yellow).

The team T-Charts were scored by the inter-raters using two criteria from the description of T-Chart *efficiency*, provided by Helms and Goel [30]: (a) the appropriateness of the analogy and (b) their agreement with the similarity ratings. The inter-raters assessed all entries in the student teams' T-Charts based on these two criteria. The T-Charts all had the same left columns, describing the problem, due to the same given Four Box being used by all the students. The inter-raters first considered whether the team's entry related to the potential bio-inspired solution was a fair comparison to the corresponding problem entry. For example, an entry regarding the nature of the terrain traversed by the organism from which the team is obtaining its bio-inspiration is a fair comparison to the operational environment problem description entry – "Outdoors (Ice, Snow, Smooth Pavement)." However, comparing this operating environment entry to the identified organism's risk from predators is not a fair comparison. Then, the inter-raters documented whether they, as experienced bio-inspired design researchers, agreed with the team's similarity ratings. An entry received a score of one if at least two inter-raters agreed with both the appropriateness of the analogy and the rating of similarity; otherwise, a score of zero was assigned. The overall efficiency score of a team's T-Chart was the sum of scores of all entries in their T-Chart.

3. Results and Discussion

The data is processed using the four metrics developed: (1) readings ease, (2) image ease, (3) quantity of images, and (4) T-Chart efficiency. Votes for specific references were normalized by number of students to ensure uniformity as the reference/inspiration groups had variable populations across the study.

3.1. Technicality of Biological Reference Text

Reading ease for the biological references is plotted against normalized votes for each reference to discover if a specific reference difficulty level was preferred by the students. Lower reading ease values (closer to zero) indicate a more technically advanced reference, while higher values (closer to 100) indicate an easier-to-read reference. Figure 3 displays the relationship for the advanced technical papers, Fig. 4 for the general public references, and Fig. 5 for the basic references.

Figure 3 shows that the reference (gecko inspiration) with a reading score below 10 (very difficult) was not preferred by any of the graduate students. This could suggest that texts that are technical to a professional level are difficult for engineering students to use and don't help them engage with the biological inspiration. A counter to that is that all four references (snake inspiration) were found to be of equal usefulness despite a range of reading ease scores from 27.9 to 51.9 by the graduate students, while the undergraduate students found the two most technical references they had (lower reading ease scores of 27.9 and 38.8) to be the most useful. This could be linked to the fact that these references had more descriptive or helpful images, a connection which is investigated later in Section 3.2. The references near the college-level reading score (reading ease of 30-50) are most useful to the college students. This usefulness could also be associated with the presence of certain engineering-associated topics in a paper. For example, one student noted *"Instead of generalized information, concentration on the* *mechanism helps rather than learning how it originated."* Another student found that the presence of *"description of mechanism and components and functions involved."* was useful for the generation of their final design.

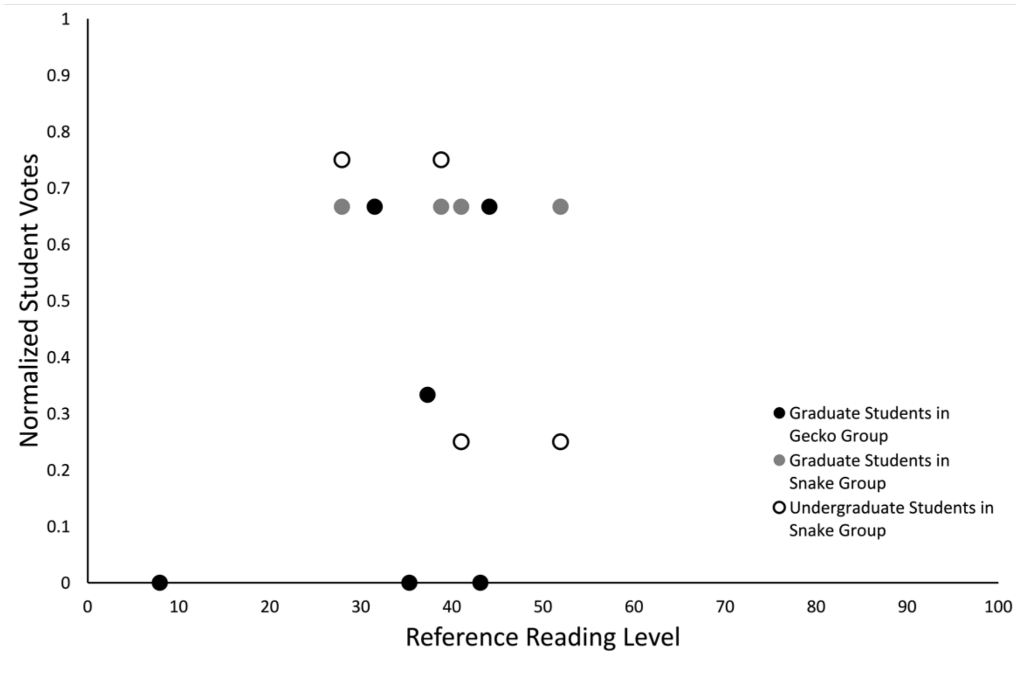

Figure 3. Reading ease for the advanced technical references about snakes and geckos given to 15 students (9 graduate and 6 undergraduate) making up 4 groups. These advanced references cover a reading ease score of 7.9 to 51.9. Lower reading ease indicates a more technically advanced reference.

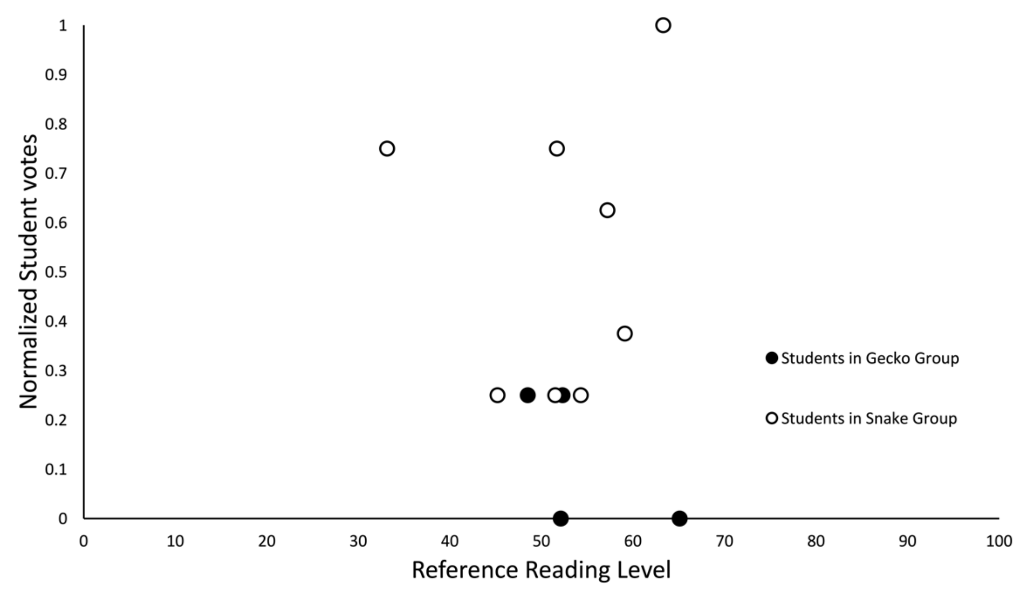

Figure 4. Reading ease for general public references about snakes and geckos, given to 10 students in 3 groups. These general references cover a reading ease score of 33.1 to 65.1. Lower reading ease indicates a more technically advanced reference.

Figure 4 suggests that students generally preferred the easier (higher reading ease) references, with one reference in the college level being the exception. A student further elaborated on what made a reference useful, stating that: *"I thought this was the most helpful because it talked about the anatomy of the scale and gave the most information about how they function and the structure of them."* This comment again suggests that terminology relating to engineering functions and structures may help engineering students use a biological reference.

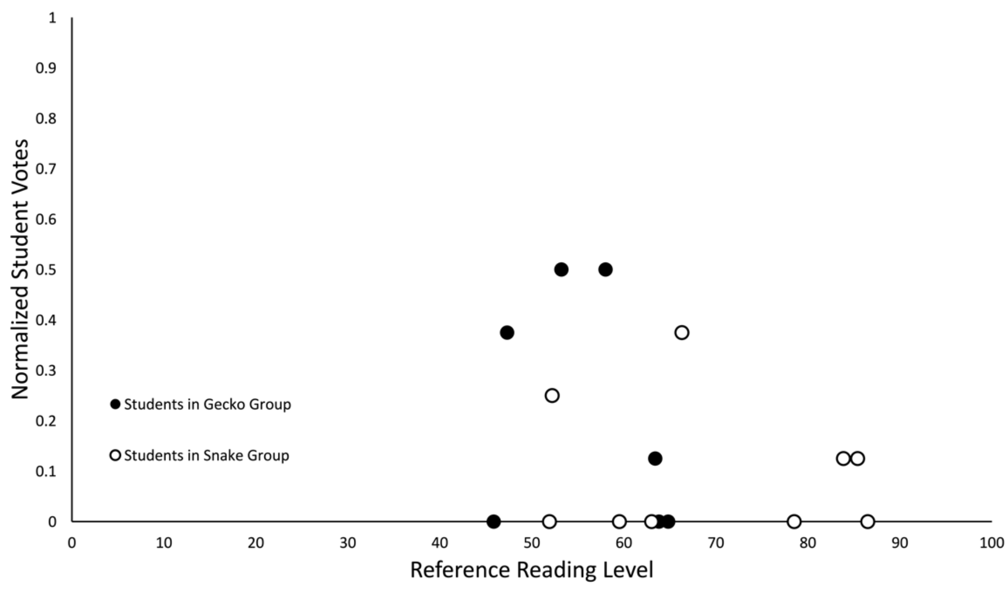

Figure 5. Reading Ease for Basic References, given to 12 students in 3 groups. These general references cover a reading ease score of 45.8 to 86.5 Lower reading ease indicates a more technically advanced reference.

A similar pattern to this reading ease range (50-65) can be seen in the *basic* references shown in Fig. 5, which reiterates the findings in Fig. 3 and 4 suggesting that a preferred reading level range *does* exist in the 45-65 range (college to high school reading level). In this category, students were provided with references that had very high reading ease scores (suitable for primary students). The students seem to have not preferred these easier references, suggesting that the oversimplification of biological phenomenon hinders biological inspiration for engineering applications.

3.2. Biological Reference Images

Results for the image ease (technicality) and the number of images in each reference are plotted against the normalized votes in Fig. 6-8. Figure 6 shows the image analysis for the *advanced technical* references, highlighting that images with an ease score higher than 4.4 (more technical) were *not* preferred by students. These high ease score images were very content heavy or contained scientific jargon that was difficult to understand without prior biological knowledge. A student elaborated more on this in the survey stating that *"There were lots of technical diagrams that were quite confusing or did not apply."* Interestingly, the references with the overall *largest number* of images were most preferred by students. These references contained a variety of pictures with different image ease scores ranging from 3.10 to 4.25. The reference with the *fewest number* of images (an image ease score of 3.17) was found by the largest number of students as the *most* useful.

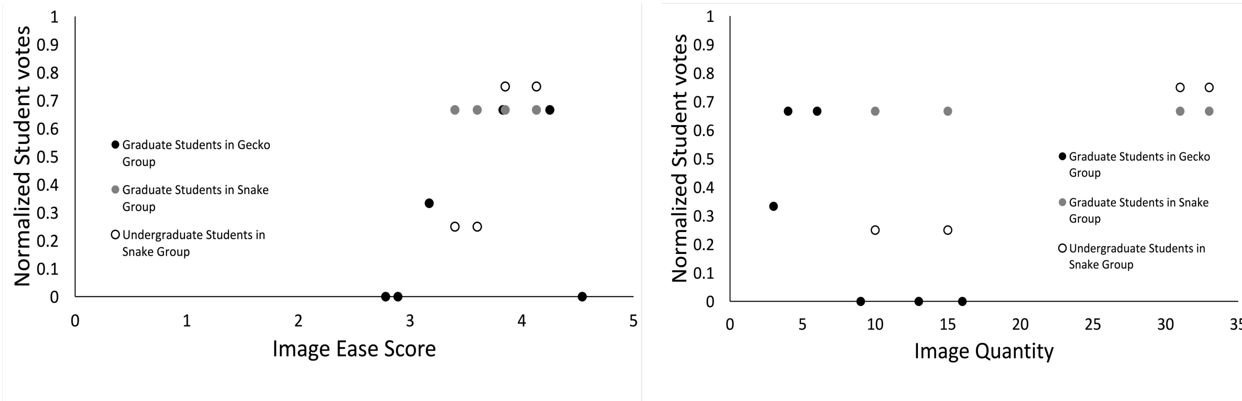

Figure 6. Reference image analysis for the *advanced technical* references, (right) image ease and (left) image quantity.

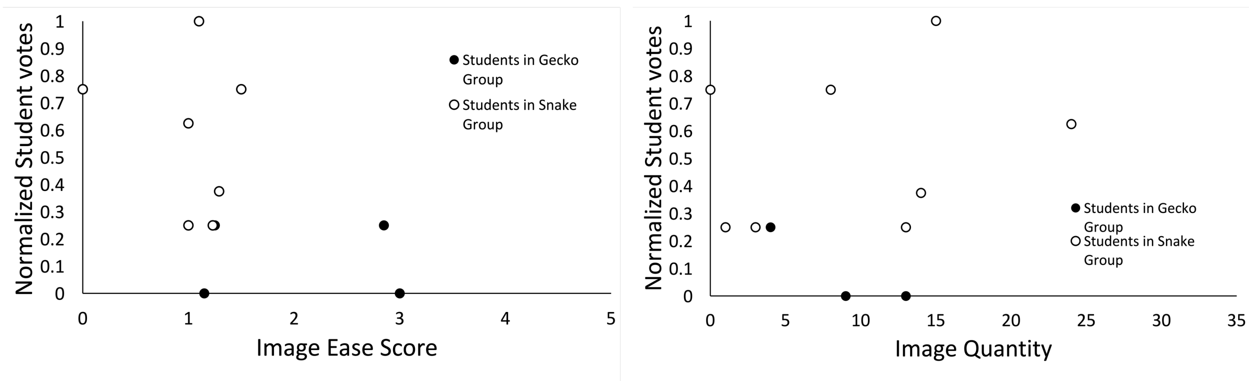

Figure 7. Reference image analysis for the *general public* references, (right) image ease and (left) image quantity.

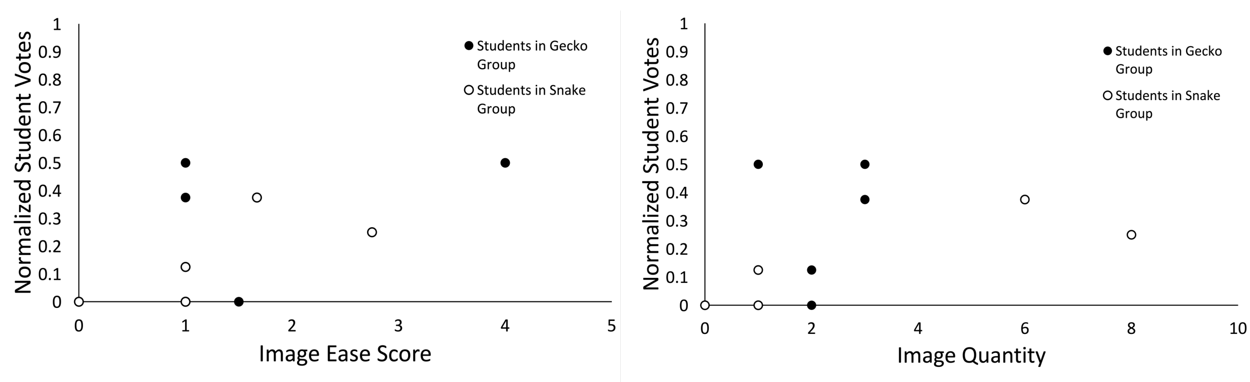

Figure 8. Reference image analysis for the *basic* references, (right) image ease and (left) image quantity. Please note that the number of images (left) in these references were significantly fewer than in the datasets shown in Fig. 6 and 7.

Figure 7 visualizes the image ease scores for the *general public* references, with the majority of the scores between 1 and 1.5 - making it difficult to extract information on student preferences. Zero students voted for the reference with an image ease score of 3, possibly due to the fact that this reference was one of the *simplest* in terms of reading ease. The *number* of images per references does again show however a correlation between a *more* images and student preference. A reference with *no* pictures and a large number of votes was found to be an exception to this hypothesis, possibly due to its *lower* reading ease score. These findings support the hypothesis that a certain amount of information is essential in an outside-discipline reference, whether in text or images.

Figure 8 shows the image analysis for the *basic* references, reiterating that that references with a *no* images are only preferred if they have a *low* reading ease. Additional work is required to further understand the preferred components of an image, but from this preliminary work it can be deduced that images containing descriptive images and microscopic pictures were most preferred. Examples of these preferred image types are shown in Fig. 9.

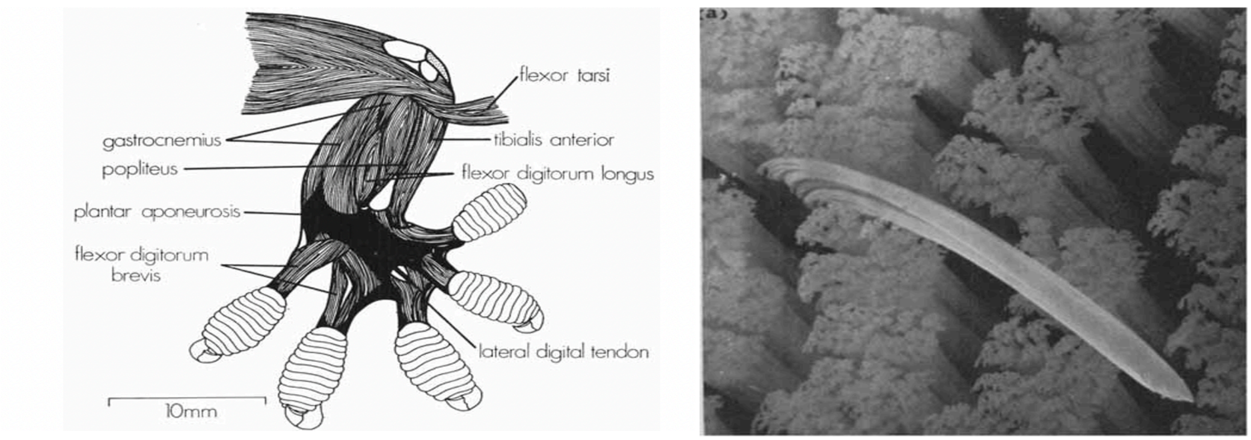

Figure 9. Student preferred image format (left) descriptive images (right) microscopic pictures. Figures taken from [35] with permission.

3.3. T-Charts

The overall accuracy of the student groups' T-Charts was calculated individually. The average of each of the three reference groups is displayed in Table 3. The T-Charts cannot be linked to one single reference or a single reference's reading ease or image ease, as the students used any/all references provided to them for the completion of the T-Chart. It is important to note that the students were very familiar with and had previous training from the same course on using T-Charts. Therefore, the T-Charts were analyzed based on the information from the reference rather than general correct use.

Table 3. Average T-Chart accuracy for each of the three main reference levels, provided with an average standard deviation.

Reference	T-Chart Average Accuracy ± Standard Deviation
Advanced Technical References	*80 ± 21.6 %*
General Public References	*55 ± 5 %*
Basic References	*50 ± 21.6 %*

The results show that there is a correlation between general reference ease (advanced, general, vs. basic) and T-Chart accuracy. The most technical references generated the highest T-Chart accuracies, all of the student groups except for one with the advanced technical references scored a near perfect score, although no concrete conclusions can be made yet due to the small dataset. The average accuracy score for the general public references was in the range of 50-60% and although the basic references had a similar average, they also had the highest prevalence of low accuracies in the 30-40% range (noted by the large standard deviation). One high ranking (potential outlier) increased the overall T-Chart accuracy for this group. Although more groups/data are needed to draw any concrete conclusions here, the results do suggest that for successful analogy evaluation students require detailed and more in-depth biological information than initially hypothesized. Given the limited sample sizes, a t-test analysis could not be performed to compare the groups. Future research efforts that generate additional data will use a t-test to better investigate differences. The T-Charts completed using the lower technical levels of references missed potential biological analogies. For example, most basic reference teams were unable to find the analogy for the “enhance friction” function despite understanding that their biological inspiration had that function. The teams from the more technical references were able to provide specific answers about these types of functions, such as the “setae” that can be found on a gecko’s toes.

4. Conclusion

This preliminary study sheds light on the impact of biological information technicality and presentation (text vs. images) on successful analogy application to engineering. Higher T-Chart accuracies were found to be produced by the more technical references, implying that detailed and advanced information is required – even when it’s from a foreign discipline – for identifying similarities and differences between a biological phenomenon and a needed engineering function. A reading score range of 50-60 seems to be preferred by engineering students, although no pattern could be extracted with the advanced technical references. This suggests that more generally, the oversimplification of biological phenomena does appear to hinder biological inspiration, possibly because there is simply not enough substantial information. This does not necessarily mean that more advanced technical papers are required for the "light bulb" moment of biological inspiration.

One hypothesis is that once a reference reaches a certain advanced level, students will shift to depend on pictures to generate inspiration, as there seems to be a trade-off between reading ease and image ease/quantity. The image analysis here suggests that references with the most pictures, as well as simple diagrams or microscopic pictures, are preferred by students. This could mean that there are key elements required to stimulate biological inspiration that need to be present, whether in terms of images or text.

5. Acknowledgements

The authors would like to acknowledge the participants of this study. We would also like to thank the J. Mike Walker ’66 Department of Mechanical Engineering Seed Grant program for funding this work.

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