Understanding Analogical Reasoning in Biomimetic Design: An Inductive Approach

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Abstract This paper reports insights gained from observing groups of novice designers apply biological analogies to solve design problems. We recorded the discourse of fourth-year mechanical engineering students during biomimetic design sessions. We observed that the availability of associations from superficial or functional characteristics of biological knowledge led to fixation, which affected the designers' ability to identify the relevant analogy. In addition, even after identifying the analogy, the designers fixated on mapping irrelevant characteristics of biological knowledge, instead of developing additional solutions based on the previously detected analogy. The paper also presents initial work towards quantifying analogical reasoning in a design study.

Introduction

Analogical reasoning involves the comparison of similarities between two concepts. Abstracting and transferring knowledge from one concept to another allows designers to develop novel design concepts. Design researchers, e.g. Goel [1] agree that analogical reasoning plays a key role in creative design.

In biomimetic or biologically inspired design, designers use analogical reasoning to compare similarities between biological phenomena and design problems, and then transfer analogous strategies to develop design solutions. Shu et al. [2] observed that although several innovative solutions to engineering problems have been inspired by biological phenomena, challenges still exist in developing generalized methodologies for biomimetic design. In particular, a number of

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obstacles prevent novice designers from correctly applying biological analogies, and effective methodologies that overcome these obstacles are still being developed.

We believe that analogical reasoning in the context of biomimetic design is still not fully understood. Therefore, our research goal is to gain a better understanding of the analogical reasoning process during biomimetic design. We used an inductive approach and observed groups of novice designers, working in a natural setting, apply biological analogies to solve design problems. The designers' dialogues were recorded and analyzed qualitatively.

The following sections provide background in biomimetic design and analogical reasoning. In addition, previous observational studies and protocol analyses in design research are reviewed to preface our methodology.

Relevant Work in Biomimetic Design

Mak and Shu [3] studied cognitive factors that influence the application of biological analogies to engineering problems. The authors observed that text descriptions of biological phenomena that included principles and behaviors in addition to forms, tended to be more easily used by students as design stimuli. In later work, Mak and Shu [4] found that novice designers tend to fixate on irrelevant features of biological phenomena and incorrectly apply biological strategies to design problems.

Cheong and Shu [5] observed that text descriptions of biological phenomena containing causal relations are more likely to serve as useful analogies for design problems. Causal relations often explain how functions are achieved by behaviors. For example, "break down" enables "absorb" in the description "Humans absorb amino acids by breaking down proteins from food". Cheong et al. [6] developed a template to help designers extract strategies from causal relations contained in descriptions of biological phenomena. However, when novice designers used the template in a controlled experiment, the correctness of analogical transfer only improved marginally.

Vattam et al. [7] and Helms et al. [8] studied the cognitive account of biomimetic design in the context of students working on projects in a biologically inspired design course. Helms et al. reported a number of common errors made by designers, including solution fixation, misapplied analogy, and improper analogical transfer. Vattam et al. developed a conceptual framework of compound analogical design that extends existing models of analogy-based design to better represent biologically inspired design, and studied the distribution of analogies across different design phases. Both Helms et al. and Vattam et al. focused on understanding the process of biologically inspired design through an in situ study on the practices of novice designers. While their research had a broad context to observe novice designers' work over the course of a term project, we aim to identify insights through detailed analyses of designers' dialogues during 20-min design sessions.

Other previous research in biomimetic design has focused on developing models to support the access and use of biological information. The SBF model from Goel et al. [9] represents causal processes between states using the structure-behavior-function framework. Helms et al. [10] observed that the SBF model of biological systems helped designers understand complex relations in systems, such as causality. Vattam et al. [11] reported that DANE, a library of SBF models of biological systems, could potentially be used as a conceptualization tool.

Sartori et al. [12] used SAPPHiRE constructs to represent mechanisms of transfer in 20 biomimetic examples in the literature. SAPPHiRE, developed by Chakrabarti et al. [13], defines multiple levels of abstraction in order to explain how a biological system works to fulfill its goals. The authors found that successful biomimetic examples usually involve systems that share similarities at higher levels of abstraction.

Nagel and Stone [14] developed a framework that is primarily based on functional-modeling of biological systems with a set of terms from the "engineering-to-biology thesaurus". Although the authors provide a detailed description for using their technique, they do not empirically study its direct benefits to designers, or how designers use it in practice.

The above biomimetic design models, primarily developed to represent and index biological information, are effective at formally representing complex biological systems. However, their utility in the concept generation process requires further validation. For instance, Vattam et al. [11] reported the challenges of using SBF modeling in concept generation; novice designers were not willing to build models without seeing the direct benefits and were not convinced of DANE's usefulness and value.

We propose that better understanding of the cognitive processes in biomimetic design can help improve these models and corresponding heuristics, and ultimately lead to more effective biomimetic concept generation. In the following section, we discuss background research in analogical reasoning, which is fundamental to biomimetic concept generation.

Background in Analogical Reasoning

Analogical reasoning is considered to be central to creative thought. For instance, Boden [15] claims that the creation of novel ideas often involves the transformation of existing knowledge into something new. In design, analogical reasoning allows individuals to find similarity between an existing knowledge base and a target design space, and transform that existing knowledge into new design solutions.

Gentner et al. [16] identify two levels at which similarities can be found in analogical reasoning: superficial and relational. The superficial level refers to object attributes. The relational level can be further decomposed into two levels: relation between objects and relation between relations, i.e., "higher-order relation".

In the context of biomimetic design, the superficial level corresponds to the attributes of biological entities (objects). The relation between objects then corresponds to the functions of biological entities, and the relation between relations can correspond to the causal or temporal relations between the functions of biological entities. The following example describes the different characteristic levels of enzymes.

Superficial	Enzymes are *ribbon-shaped*
Functional	Enzymes *bind* to substrates
Causal	Enzymes *bind* to substrates to *form* enzyme-substrate complexes.

Many researchers agree that successful analogical transfer occurs at the relational levels. Gentner et al. [16] note that finding similarities between higher-order relations is crucial to successful analogical reasoning. In the context of design, Goel [1] states "analogical transfer requires the use of generic abstractions, where the abstractions typically express the structure of relationships between generic types of objects and processes". In biomimetic design, designers must abstract biological knowledge to identify its relational similarities to design solutions.

Observational and Protocol Studies

While experimental studies test the validity of hypotheses or interventions, observational studies are well suited to formulate hypotheses and develop interventions for future experiments. Dunbar [17] notes an important benefit of an observational study is that researchers can observe more natural and real-world behaviors of people, whereas those behaviors may be restricted in experimental studies. The use of observational studies in biomimetic design [3, 4, 7, 8] include our past work, and Vattam et al. [7] and Helms et al. [8], who observed students working in natural settings on a biologically inspired design project over an extended period.

However, one limitation of observational studies is the difficulty of collecting data. For this reason, many researchers use "think-aloud" techniques to elicit verbal dialogues from participants. Encouraging designers to verbalize their thoughts is presumed to reflect the designers' underlying cognition. The verbal dialogues are then transcribed to generate protocols, which offer useful data for both qualitative and quantitative analyses. Cross [18] discusses a number of observational protocol studies in design research, including their advantages and limitations.

Chiu and Shu [19] reported some limitations of verbal protocol studies. Verbalizing thought processes can be perceived as unnatural and adds a cognitive workload on designers, which can lead to results that may not reflect real-world performance. To address this, designers can be encouraged to participate in design processes naturally, speaking aloud to one another as they normally would. While this approach may not capture cognitive mechanisms in as much detail, the process is more natural and may better reflect actual design practices.

Protocol Analysis

Once verbal protocols have been generated they can be analyzed qualitatively and quantitatively. Merriam [20] recommends that the analysis of qualitative data, such as design protocols, should ultimately be tailored towards the needs of the researcher. One of the most common methods of analyzing protocols in psychological and design research, and the most relevant to our approach, is qualitative coding. Qualitative coding segments a protocol based on categories of interest to the researcher.

Miles and Huberman [21] suggest that researchers should develop meaningful and clearly defined categories for coding. Goldschmidt [22] used design "moves", which identify ideas that transform the design situation and reflect the development of ideas. Kvan and Gao [23] adopted Schön's definition of design processes ("framing", "moving", and "reflecting"), in order to study the problem-framing process in design. Kan et al. [24] used a coding scheme based on the FBS (function-behavior-structure) ontology. Gero [25] suggests that the FBS coding scheme provides a common framework to represent design knowledge and allows consistency in protocol analysis.

Linkography, developed by Goldschmidt [22], is performed by linking related design "moves" and graphically represents protocol data. Linkography has been used to examine a wide variety of phenomena in design, including problem framing effects [23], visuo-spatial working memory load [26], and design fixation [27]. The analysis of linkographs has also progressed to include applying statistical models, cluster analysis [26], and entropy models [28]. These techniques help researchers quantify the relationships found in linkographs.

Computational linguistic methods are also used to analyze design protocols. Dong [29, 30] used latent semantic analysis to quantify coherent thinking and lexical chain analysis to evaluate concept formation in design teams. These computational linguistic models provide more objective and standardized ways to analyze protocols. However, Wang and Dong [31] point out that computational models still require the resource-intensive preparation of training data. They took a more efficient, yet sufficient approach, of using statistical patterns of relevant semantic features, e.g., keywords, to compute appraisals in design text.

Both the linkographic and computational linguistic approaches are used to quantify design protocols. These approaches help mitigate researcher bias and allow the application of various numerical/statistical analysis techniques. Our current research chooses instead to manually review protocols, as we learned that this process could lead to valuable insights. We agree with Brown's [32] observation that studying transformational creativity such as analogical reasoning can be challenging, and that we should "work upwards towards creativity," i.e., take an inductive, bottom-up approach. Therefore, we initially focused on using qualitative observation to better understand analogical reasoning in biomimetic design.

While the research approach was primarily qualitative, we also worked towards the quantitative/graphical representation of our design protocols. The results of the protocol analysis will be discussed after presenting the research method and qualitative observations.

Methods

Participants

The data for this experiment were collected from 30 engineering students (28 males and 2 females), during a design-by-analogy laboratory exercise in a fourth-year mechanical design course at the University of Toronto. All data collected came from students who consented to have their design session audio-recorded and to have the data used for research purposes.

Procedure

The laboratory exercise required students to generate solutions for an engineering design problem by using a biological analogy as a source of inspiration. Three design problems were used, and each problem was paired with a description of a biological phenomenon as the source of analogy.

For practical reasons, three to four students were assigned to a group and each group worked on a single design problem. There were three laboratory stations with three groups at each station (see Table 1).

Each group was given 20 min to generate solutions for the design problem. One group (Group 9) used only 12 min and stated they could not generate any more solutions. At the beginning of each 20-min session, each member of the design group was provided with a written copy of the design problem and relevant biological phenomenon.

The order of problems was counterbalanced in a 3 × 3 *Latin square* matrix to control for problem effects. However, it is reasonable to expect the presence of a learning effect for the second and third design groups at each station, since they had the benefit of observing the preceding groups.

Design Problems and Biological Phenomena

The following design problems and corresponding descriptions of biological phenomena were created by the researchers and provided to the design groups.

Table 1 Details on experimental groups and design problems assigned

Lab station	Design group #	# of students	Design problem
A	1	4	Promotional mailing
	2	3	Authorized disassembly
	3	3	Wet scrubber
B	4	3	Wet scrubber
	5	4	Promotional mailing
	6	3	Authorized disassembly
C	7	3	Authorized disassembly
	8	4	Wet scrubber
	9	3	Promotional mailing

1. *Promotional Mailing Problem*

You are a marketing director for a credit card company. You are looking for an effective strategy to distribute sign-up promotional mailings within a city. You would like to distribute promotional mail to selected neighborhoods in the city so that a large proportion of the promotional mail actually results in people signing up. In other words, you don't want to waste resources on sending promotional mail to neighborhoods where people are not likely to sign up. Assuming that you don't have any demographic information of the city, how would you optimize the use of promotional mailings?

Biological Phenomenon (Ant): An ant colony can identify the shortest path between its nest and food source with the following strategy. Ants depart the colony to search randomly for food, laying down pheromones on the trail as they go. When an ant finds food, it follows its pheromone trail back to the nest, laying down another pheromone trail on the way. Pheromones have more time to dissipate on longer paths, and less time to dissipate on shorter paths. Shorter paths are also travelled more often relative to longer paths, so pheromones are laid down more frequently on shorter paths. Additional ants follow the strongest pheromone trails between the food source and the nest, further reinforcing the pheromone strength of the shortest path.

2. *Authorized Disassembly Problem—From Saitou* et al. [33]

Original equipment manufacturers (OEM's) want easy disassembly of their products to reduce disassembly cost and increase the net profit from reuse and recycling at product end of life. However, OEM's are also concerned with protecting high-value components from theft and access by competitors. How can you allow disassembly that is easy but only by those authorized? [33].

Biological Phenomenon (Enzymes): Enzymes are complex proteins that bind to specific substrates (molecules) and form enzyme-substrate complexes that perform biochemical activities. The specific binding is achieved when the active site of an enzyme geometrically matches its corresponding substrate. However, an enzyme changes its shape with environmental factors such as pH and temperature. This shape change alters the conformation of the enzyme's active site to the point where substrates can no longer fit, thereby disabling the function of the enzyme-substrate complex.

3. *Wet Scrubber Problem*

Wet scrubbers are air pollution control devices that remove pollutants from industrial exhaust systems. In conventional wet scrubbers, exhaust gas is brought into contact with a liquid solution that removes pollutants from the gas by dissolving or absorbing them into the liquid. The removal efficiency of pollutants is often improved by increasing the contact time or the contact area between the exhaust gas and the scrubber liquid solution. What other strategy could be used to increase the removal efficiency of wet scrubbers?

Biological Phenomenon (Penguins): Penguins are warm blooded yet keep their un-insulated feet at a temperature close to freezing to minimize heat transfer to the environment. The veins that carry cold blood from the feet back to the body are located closely to the arteries that carry warm blood from the body to the feet. The warm blood flows in the opposite direction as the cold blood, which allows the penguins to transfer the most heat to the cold blood. This reduces both the amount the returning blood can drop the core body temperature, and the amount of heat lost through the feet.

Design Session Mediators

A research assistant was assigned to each laboratory station to facilitate and audio-record the design sessions. To control for any confounding effects introduced by the research assistants, they were provided with a script to handle potential questions from students, and were instructed not to contribute to the design process. The research assistants only interceded when design progress slowed or the students had settled on a design solution. After 20 min, the research assistants stopped the design session and provided the next group with the corresponding design problem.

Design Protocols

Students in each design group were instructed to verbalize their ideas during the design process; these verbalizations were audio-recorded and transcribed for analysis. However, students were not asked to verbalize all of their thoughts. Because this was a group exercise and there was only one audio-recording device at each laboratory station, having a true talk-aloud experiment would have made transcribing the audio files very difficult.

Table 2 Examples of each coding category for the wet scrubber problem

Code	Example
Entity	"Veins have a lot of surface area so we can make sure that…I mean…the liquid we are using for the scrubbing, it can go through like really narrow pipes or whatever to increase the surface area"
Function	"We also did kind of blood circulation, 'cause uh, we are re-circulating [scrubber solution and exhaust gas]"
Strategy	"It says the opposite direction allows, like, most flow of gas exchange […] so make, I don't know, maybe we could make the […] liquid scrubber run in one direction, and […] gas run in the other direction. That increases the flow [exchange]"

Two authors of this paper transcribed the audio files for each design group. After each transcript was generated, it was cross-reviewed by the other researcher to verify its accuracy. Some audio data was not interpretable, e.g., multiple designers speaking at once, designers murmuring very quietly, etc., and this data was excluded from further analysis.

Protocol Coding

We coded participants' ideas that involved some type of comparison into three different categories:

Entity A comparison to superficial characteristics of entities of the biological phenomenon

Function A comparison to functions of the biological phenomenon

Strategy A comparison involving a higher-order relation (strategy) from the biological phenomenon.

The method of coding design protocols into a set of defined categories is in line with other protocol analyses discussed previously in the introduction [23–25]. Creating mutually exclusive segments, however, was not possible for this coding scheme. Higher-level comparisons, such as the strategy level comparison, often invoke comparisons at the functional and superficial levels. In addition, segmenting the protocol based on participants' utterances or ideas was difficult due to multiple interruptions from other group members and many instances of incomplete ideas. To avoid bias in the segmentation and coding process, each protocol was segmented into 10-s units. This coding scheme allowed us to code occurrences of each type of similarity comparison and plot their occurrence over the time of the design protocol. Two of the authors individually coded the protocols, after which cases of disagreement were discussed until an agreement was reached. Table 2 shows examples of segments that contain each coding category.

Table 3 Examples of analogous elements between the ant phenomenon and the promotional mailing problem at three levels of comparison

Level of comparison	Ant phenomenon	Promotional mailing	Similarity
Strategy	Target food source based on feedback obtained from random travel	Target sign-ups based on feedback obtained from random mailing	✔
Functional	Traveling to food source	Sending out mail	×
Superficial	Food source	Sign-ups	×

Only the strategy level of comparison features a high degree of similarity

Qualitative Observations

We first drew qualitative observations from the protocols. While some of the observations agree with previous research in design and cognitive psychology, there were new insights that could contribute towards a better understanding of the analogical reasoning process in biomimetic design.

Detection of Analogies

All three groups that worked on the promotional mailing problem were able to identify the relevant strategy from the ant phenomenon within the first 5 min of problem solving. However, two of the three groups that worked on the authorized disassembly problem could not identify the relevant strategy from the enzyme phenomenon in the 20-min period. This result was surprising. The promotional mailing problem required participants to detect an analogy that was mostly based on the similarity at the strategy level, with the analogous elements present at the functional level and the superficial level having little similarity (see Table 3). On the other hand, the authorized disassembly problem was paired with the enzyme phenomenon. The phenomenon featured analogous elements that may seem similar at all three levels, which could have helped participants identify the relevant analogy (see Table 4).

For the authorized disassembly problem, many participants fixated on making associations at the functional or superficial level and were not able to identify the analogous strategy. We suspect that the apparent similarity between analogous elements at the functional and superficial levels prevented the participants from detecting the relevant analogy. When the participants observed similarity at the low levels of comparison, which are more easily found than at the strategy level, they focused on implementing particular characteristics of functions and entities in their design solutions. On the other hand, the participants who solved the promotional mailing problem may have been able to easily identify the strategy because they could not find similarity between analogous elements at the

Table 4 Examples of analogous elements between the enzyme phenomenon and the authorized disassembly problem at three levels of comparison

Level of comparison	Enzyme phenomenon	Authorized disassembly	Similarity
Strategy	Bind based on specific substrate; temperature changes the shape of enzyme to release	Assemble based on specific part interface; temperature changes the shape of part interface to disassemble	✔
Functional	Binding of enzyme to substrate	Attaching of one part to another	✔
Superficial	Specific shape of substrate	Specific shape of part interface	✔

All three levels of comparison feature some degree of similarity

functional and superficial levels. This finding is contrary to Gentner's [34] proposal that having similar analogous elements at the low levels of comparison helps people map higher-level relations.

The biological descriptions for these two problems did differ in length, and the effect of this difference can be complex. A longer description may provide additional context that can aid designers to identify higher-level relations. However, the same information also provides more stimuli that could distract designers from identifying the higher-level relations.

Influence of Readily Available Associations

We suspect that readily available associations at the functional and superficial levels of comparison for the authorized disassembly problem caused participants to fixate on those particular levels. Participants were able to match analogous solutions from their knowledge with the concept of enzymes binding to specific shapes of substrates. The solutions developed by the students involved using or modifying various types of fasteners or interfaces such as mechanical screws, snap-fits, power supply interfaces, etc.

Most of these solutions were highly relevant to the student's domain knowledge in mechanical engineering. This tendency to develop solutions based on the familiar domain knowledge may be similar to Purcell and Gero's [35] finding that mechanical engineers tend to fixate on using familiar principles to solve design problems. We observed the tendency to depend on domain knowledge, especially if associations to the domain knowledge are readily available at low levels of comparison, prevented novice designers from identifying the analogy. This hypothesis might also explain why the participants were more successful in solving the promotional mailing problem. The problem goal involved logistic optimization and was different from conventional mechanical design problems; therefore, the participants may have been more open to applying the new knowledge gained from the ant phenomenon. In summary, domain knowledge was more likely to induce fixation, rather than help detect the analogy. This observation differs from Novick's [36] finding that domain expertise may help people access potentially useful analogies.

Some participants almost exclusively found associations at the superficial level. For the wet scrubber problem, one particular participant persistently tried to apply superficial characteristics of a penguin's feet, e.g., texture, color, in developing new types of mechanical scrubbers. Mak and Shu [4], Helms et al. [8], and Cheong et al. [6] also reported on novice designers' frequent fixation on superficial characteristics in biomimetic design. Interestingly, another participant within the same group pointed out twice that the analogy should be based on the countercurrent exchange of flows, not on superficial characteristics of penguins. This suggestion, however, did not stop the first participant from fixating on the superficial similarity. The following section discusses this failure to properly evaluate analogies in more detail.

Evaluation and Mapping of Analogy

In some groups, participants fixated on their existing ideas and failed to realize the analogy even when another participant explicitly stated the analogy. What we found interesting was that "structural alignment and consistency", which Gentner [34] lists as important factors of analogy evaluation, had little effect on some participants' likelihood to move away from their fixated ideas. In other words, the fixation on initial ideas was so significant that the participants were no longer properly evaluating the analogies they used. A number of design researchers, including Rowe [37], Ball et al. [38], and Cardoso and Badke-Schaub [39], also report strong fixation effects on initial ideas.

In some cases, participants developed solutions based on the relevant strategy, but expressed that they were not sure if their analogies were correct and complete. This lack of confidence led to either abandoning the strategy or trying to force-fit non-analogous elements that seemed relevant to the strategy. Essentially, the detection of the analogy did not guarantee correct mapping of the analogy. In fact, two promotional mailing groups started to make irrelevant associations between the ant phenomenon and their solutions, e.g., identifying the optimal path to deliver mail or comparing a CEO to a queen ant, *after* they had detected the relevant strategy. One group that solved the wet scrubber problem also showed a similar tendency. After agreeing on using the countercurrent flow exchange, the group tried to elaborate their solution with irrelevant inferences from the penguin phenomenon, e.g., using vein-like channels and considering the distance between the penguin's heart and feet.

Once designers find the relevant analogy, they may be likely to look for new one-to-one mappings from the analog source, instead of performing one-to-many inferences. In other words, designers focus on using multiple features of the source analog, some of which may not be relevant, and fail to develop multiple solutions based on the analogous strategy. This observation suggests that designers may have fixated too much on *mapping* the analogy instead of *projecting* multiple inferences. Gentner [40] and Holyoak and Thagard [41] have reported one-to-one mapping as a constraint in analogical reasoning and we have indeed observed that it has a significant effect in design-by-analogy.

Some of these effects may be partially due to the structure of the experimental design task. The designers were given 20 min to generate concepts, but were not specifically asked to generate multiple solutions.

Facilitating Analogical Reasoning

We observed one particular group overcome fixation, which could provide insights for facilitating analogical reasoning. The group was assigned the authorized disassembly problem, and one participant repeatedly asked questions to himself and other group members about whether they were fixating on specific aspects of the biological phenomenon, as well as how they could apply the biological phenomenon in new ways. These types of questions evidently shifted the group's focus from one particular level of comparison to identifying the relevant analogy. Based on this observation, we believe that the awareness of fixation and its effect on identifying the analogy is a key requirement for effective analogical reasoning in biomimetic design. Winkelmann and Hacker [42] also noted that design performance is increased through the use of interrogative questions, which stimulate reconsideration of the problem. Participants who ask these types of questions without external prompting might be demonstrating enhanced awareness, with the additional benefit that the questions promote increased problem solving among group members.

Lack of awareness of fixation during design problem solving is apparent not only amongst novice designers. Linsey et al. [43] reported that even experienced designers, mostly the engineering faculty members in the authors' study, were not able to accurately perceive the degree of fixation that they were experiencing. Most design-by-analogy methodologies generally do not seem to provide a means for participants to identify fixation effects. Chrysikou and Weisberg [44] provided defixation instructions that helped participants avoid fixating on pictorial examples; however, their instructions were problem specific and may not be transferrable to general design-by-analogy problems. Also, we observed a variety of fixation effects on familiar domain knowledge, superficial attributes, and initially inspired solutions. In complex design tasks including biomimetic design, these multiple types of fixation mean that any one specific mediation approach is unlikely to improve the design process in general. Methods that support biomimetic design [9, 13, 14], most of which are based on modeling biological knowledge, may help designers understand the complex biological information of interest. However, the methods do not fully support mitigating fixation during concept generation.

An effective solution to address this challenge may be to educate or train novice designers to better identify and apply analogies with enhanced awareness of fixation effects. In a meta-analysis of 70 studies on the effects of training programs on creativity, Scott et al. [45] concluded that the most effective programs were the ones that fostered the development of cognitive skills and the necessary strategies to apply them. Specific to biomimetic design, Nelson et al. [46] found that students who took a biologically inspired design course were able to develop more novel and diverse concepts than those who did not take the course and solved the same design problem. Nelson et al. concluded that increased novelty and variety might be due to the students' improved analogical reasoning capabilities from the biologically inspired design course.

Training could also work in congruence with existing methodologies of biomimetic design; therefore, we suggest those researching these methodologies study how designers use the tools. Observational studies on using the tools, such as the one conducted by Vattam et al. [11] would be an effective approach for this purpose. For our research, we are interested in conducting more observational studies to identify characteristics that allow designers to effectively perform analogical reasoning, and develop training materials or strategies to help designers take better advantage of biological analogies.

Graphical Representation of Similarity Comparisons

After the initial review of our experimental transcripts, we performed a protocol analysis to examine trends in participants' similarity comparisons. The goal was to graphically represent different levels of similarity comparison, i.e., entity, function, strategy, occurring over time and see if those representations support our qualitative observations.

Figure 1 depicts the results of the protocol analysis. The y-axis represents a similarity comparison index; the index value is calculated using a rolling average of instances of similarity comparisons over five time segments (50 s). The graphs visually represent the distribution of similarity comparisons made over time.

In general, more functional-level comparisons coincided with the detection of relevant strategies. In most cases, the strategy-level comparison occurred right after or during an increase in functional-level comparisons.

For Groups 5 and 9 of the promotional mailing problem and Groups 4 and 8 of the wet scrubber problem, entity-level comparisons increased following strategy-level comparisons. This trend supports our observation of participants trying to map entity features of the analog, instead of exploring different solutions based on the detected strategy.

Groups 6 and 7 of the authorized disassembly problem made most comparisons at the functional-levels. These two groups fixated on the domain knowledge that was associated with functional aspects of the biological phenomenon. Group 4 of the wet scrubber problem had a large number of entity-level comparisons. The

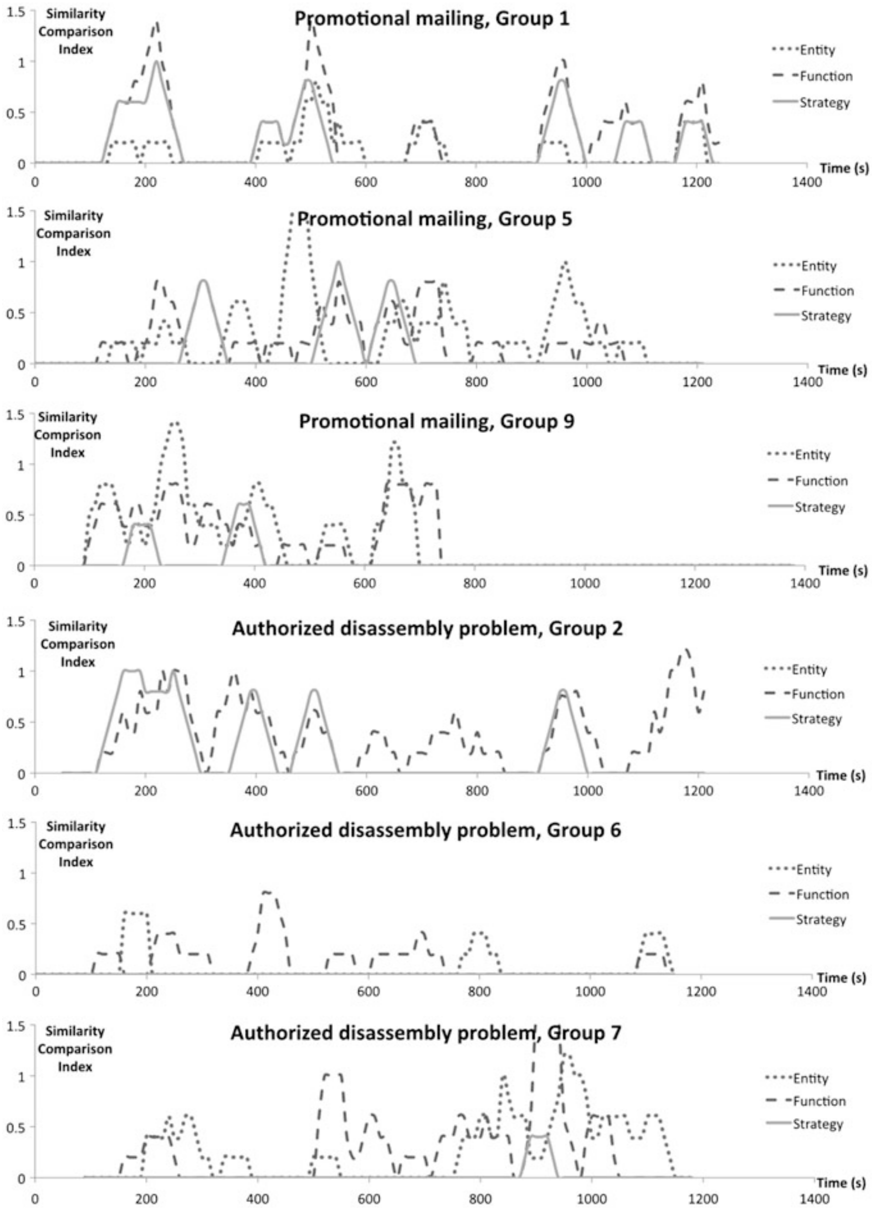

Fig. 1 Distribution of similarity comparisons (entity, function, or strategy) over time. The similarity comparison index on the y-axis is the rolling average of instances of similarity comparisons over five time segments

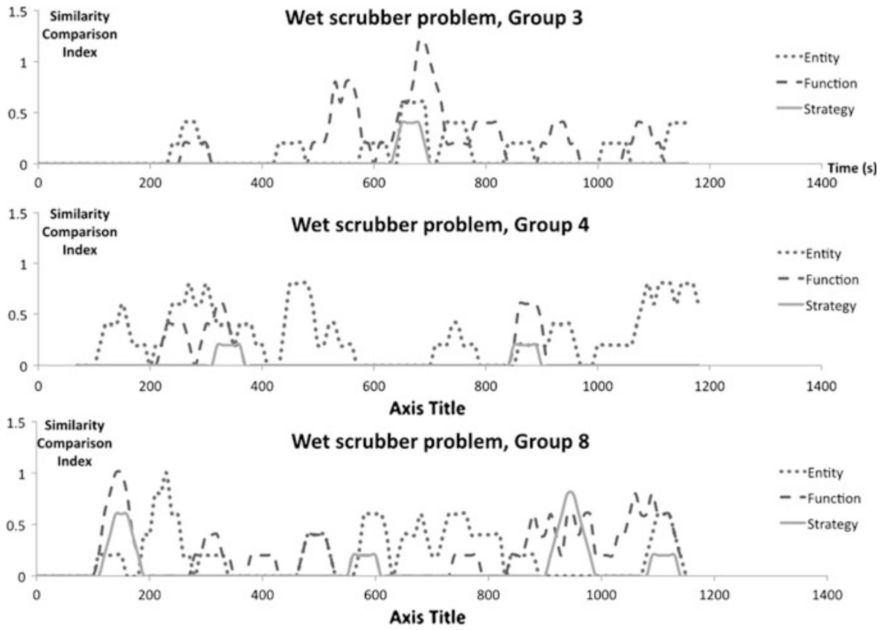

Fig. 1 (continued)

participant who fixated on superficial characteristics of a penguin's feet was part of Group 4.

While the graphs were able to support some of our qualitative observations, the protocol analysis requires refinement. A particular aspect to address is the subjective and inferential nature of the qualitative coding. Adopting formal coding schemes such as Gero's [25] FBS could enable more consistent identification of coded segments. Computational linguistic and statistical analyses could also be used to perform more in-depth quantitative analysis.

Conclusion

The current study took a qualitative, inductive approach to understand analogical reasoning in biomimetic design. The interesting observations include:

- Similarity between analogous elements at low levels of comparison, e.g., superficial and functional, prevented novice designers from detecting the overall analogy.
- Domain knowledge can provide readily available associations at low levels of comparison and induce fixation.

- Novice designers focus on mapping multiple features of the source analog, instead of projecting multiple inferences from the identified analogy, perhaps due to lack of confidence in the analogy.

We believe that analogical reasoning, used in practice for complex design tasks such as biomimetic design, can be influenced by many cognitive biases. For instance, we observed that fixation significantly influences the design process, perhaps more so than the ability to reason with analogy.

Another factor that influenced the results could be that our study involved novice designers. To generalize these findings to a larger population and wider context, more natural design situations should be considered for future research, e.g., include expert designers, perform longer design sessions, allow external reference sources and personal selection of analogies.

While the current research focused on qualitative observations, we also value the benefits of quantitative analysis. A number of researchers have well demonstrated the advantages of numerical and statistical analyses on design protocols. In particular, Dong [29] suggests quantitative analysis supported with computational tools opens the possibility of assessing design processes in near real time. Our future research will also explore different methods of quantitative protocol analysis.

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