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EFFECTS OF ABSTRACTION ON SELECTING RELEVANT BIOLOGICAL PHENOMENA FOR BIOMIMETIC DESIGN

Tao Feng, Hyunmin Cheong, L.H. Shu*
Dept. of Mechanical & Industrial Engineering
University of Toronto
5 King's College Road
Toronto, ON, M5S 3G8, Canada
***Corresponding author email:** shu@mie.utoronto.ca

ABSTRACT

The natural-language approach to identifying biological analogies exploits the existing format of much biological knowledge, beyond databases created for biomimetic design. However, designers may need to select analogies from search results, during which biases may exist towards: specific words in descriptions of biological phenomena, familiar organisms and scales, and strategies that match preconceived solutions.

Therefore, we conducted two experiments to study the effect of abstraction on overcoming these biases and selecting biological phenomena based on analogical similarities. Abstraction in our experiments involved replacing biological nouns with hypernyms. The first experiment asked novice designers to choose between a phenomenon suggesting a highly useful strategy for solving a given problem, and another suggesting a less-useful strategy, but featuring bias elements. The second experiment asked novice designers to evaluate the relevance of two biological phenomena that suggest similarly useful strategies to solve a given problem.

Neither experiment demonstrated the anticipated benefits of abstraction. Instead, our abstraction led to: 1) participants associating non-abstracted words to design problems, and 2) increased difficulty in understanding descriptions of biological phenomena. We recommend investigating other ways to implement abstraction when developing similar tools or techniques that aim to support biomimetic design.

1. INTRODUCTION

Biomimetic, or biologically inspired design, uses biological phenomena as inspiration to solve problems. To support biomimetic design, our research group has developed a natural-language approach [1,2] that directly searches biological information already available in natural-language format, e.g., text, papers, etc. We pursued this approach because the most popular alternative, developing databases of biological phenomena to support design, involves significant effort, expertise and potential bias.

For over a decade, we developed tools and techniques to support the natural-language approach. For example, by analyzing co-occurring words, we identified biologically meaningful keywords [3,4] that may retrieve more relevant matches from the domain of biology than functional keywords used in engineering. We also categorized matches to reduce effort required to evaluate them [5], used meta-data to reduce irrelevant matches [6], and identified matches that likely describe functional relations in biology [7].

Despite the above, we continued to observe persistent challenges in the selection of analogous biological phenomena identified by natural-language search. We believe that designers may select non-analogous biological phenomena due to biases toward superficial characteristics of biological entities [8-10]. We also observed a tendency to select familiar analogies, where the familiarity may be with the organism, organization level, physical scale of the phenomena, etc.

We hypothesized that abstraction is one technique that could support designers in selecting analogous biological phenomena. A number of researchers demonstrated the benefits of abstraction in design contexts, e.g., artificial intelligence for analogical reasoning [11-12], recalling analogies in conceptual design [13], and considering different analogous problem scenarios [14].

Our research group has previously studied one-to-one application of biological analogies, i.e., applying a strategy described in a single biological phenomenon to solve a given design problem. For such a scenario, past work confirmed the potential value of text-based templates in assisting designers to apply functional strategies abstracted from biological phenomena to design solutions [8-9]. We also confirmed that for specific problems, abstracting nouns in a description of a biological phenomenon helps designers find the analogy between the phenomenon and the design problem [15].

Our current research aims to investigate the effect of abstraction in evaluating the relevance of one biological phenomenon relative to another phenomenon. Descriptions of biological phenomena were abstracted by replacing biological nouns with their hypernyms, i.e., more general forms of the biological nouns. This method was chosen because hypernyms can be automatically identified using a lexical database such as WordNet [16]. We hypothesized that abstraction of nouns would reduce designers' bias towards superficial characteristics and familiarity of biological phenomena. We also predicted that such abstraction would help designers recognize the relevance of biological phenomena based on analogical similarities to design problems.

The rest of the paper is organized as follows. Section 2 reviews relevant work in abstraction for analogical reasoning and biomimetic design. Sections 3 - 4 report the results of two experiments that examine the effect of abstraction. In Sections 5 - 7, we discuss our findings, limitations, and conclusions.

2. BACKGROUND

We first present research that confirmed the benefit of abstraction in various contexts related to conceptual design. Next, we review cognitive studies of biomimetic design to describe the challenges involved in using biological analogies. Finally, we identify the main contribution of the current study.

2.1. Reported benefits of abstraction in design

Abstraction is understood as an essential process that enables designers to apply solutions from one situation to another, i.e., design-by-analogy. Abstraction has long been the central idea behind enabling computational design-by-analogy [11,12], which benefits from generalized knowledge about design situations, such that similarities can be found at more abstract, e.g., functional, levels. A number of knowledge representation schemes that support reasoning at multiple levels of abstraction have been developed, including Gero's function-behavior-structure ontology (FBS) [17], Goel's structure-behavior-function model (SBF) [18], Umeda et al.'s function-behavior-state model [19], Chakrabarti et al.'s State-Action-Part-Phenomena-Input-oRgan-Effect model (SAPPhIRE) [20], etc.

Various experiments confirmed that abstraction also facilitates human reasoning in different scenarios of design. Linsey et al. [13] found that retrieval of analogous solutions from memory is enhanced if the example products that suggest analogous solutions are provided to designers in abstract representation. Zahner et al. [14] confirmed that participants were more likely to use divergent thinking to explore multiple analogous design scenarios that are described abstractly. Linsey et al. [21] developed the WordTree method to abstract desired functions of concepts and demonstrated that the method increased the use of analogies.

2.2. Cognitive studies of biomimetic design

Mak and Shu [22] observed that novice designers use different types of analogical transfer to relate biological phenomena to design problems. Some of these participants focused on transferring a specific entity from biology, either only its superficial or both its functional and superficial characteristics. Designers who rely on such tendencies when looking for relevant biological phenomena may be less likely to select meaningful analogies.

Helms et al. [23] reported common errors made by students using two approaches to biologically inspired design: 1) solution-driven, which seeks problems to be solved using specific biological phenomena, and 2) problem-driven, which seeks biological phenomena to solve given design problems. The errors specific to biomimetic design include "using off-the-shelf biological solutions," "misapplied analogy," and "improper analogical transfer." Such errors could significantly influence how novice designers select biological analogies.

Vattam et al. [24] developed a conceptual framework of compound analogical design. The framework characterizes biologically inspired design as often involving opportunistic interaction between problem decomposition and analogical transfer. In other words, biological analogies identified during problem solving can reformulate the problem, which in turn may locate new types of biological analogies. Their finding suggests a strong interlink between the selection of biological analogies and the designer's understanding of the problem.

To support identification and application of biological analogies, our research group has developed text-based templates. Mak and Shu's [8] template provides the relevant strategy suggested in a biological phenomenon and supports the mapping of corresponding objects between the phenomenon and the design problem. Cheong and Shu's template [9] focuses on identifying causally related functions from a biological phenomenon, which establishes the framework for analogical transfer (Figure 1). The template was paired with one-to-one mapping instructions that assist in the transfer of causally related functions. Both templates aim to help designers abstract underlying strategies from descriptions of biological phenomena.

Instead of providing templates to assist designers in performing abstraction, Cheong and Shu [15] abstracted descriptions of biological phenomena by replacing nouns with either hypernyms or arbitrary letters. Next, the effect of such abstraction was examined on novice designers' ability to identify analogies between biological phenomena and design problems. Abstraction was found useful for a problem that involves an analogy based on functional relations, but not useful for a problem that involves an analogy based on spatial relations. In addition, too much abstraction, e.g., replacing biological nouns with letters, prevented the understanding of certain biological phenomena.

2.3. Contribution of current study to existing work

Our current research aims to quantitatively evaluate how abstraction supports designers in determining relevance of biological phenomena.

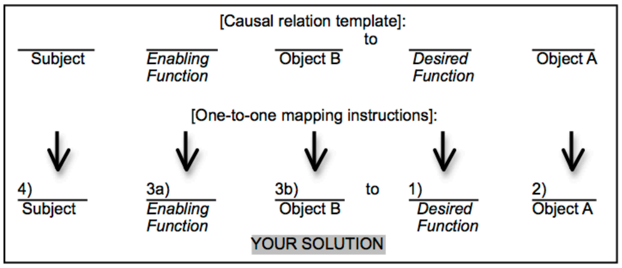

Fig. 1 Casual relation template with one-to-one mapping instructions (numbers suggest sequence), adapted from Cheong & Shu [9].

Helms et al. [23] and Vattam et al. [24] observed students working on biologically inspired design projects over the duration of a course. They describe how designers interact with SBF models, which are abstract representations of biological phenomena, to explore biological analogies. However, the effect of SBF abstraction on selecting analogies in an experimental setting has not been quantified.

Chakrabarti et al. [20] and Sartori et al. [25] studied the effectiveness of the SAPPhIRE framework, which aims to represent biological systems in multiple levels of abstraction. Results were compared between using the framework and another generic design guideline, but not how SAPPhIRE helps designers choose between multiple biological phenomena.

All of our previous work involving templates [8,9] and abstraction [15] studied the situation where a designer was given a single biological phenomenon for a single design problem. Therefore, those experimental tasks did not involve the choice between multiple phenomena.

Therefore, we conducted two experiments to investigate the effect of abstraction in different scenarios of selecting biological phenomena. Abstraction consisted of replacing biological nouns in descriptions of biological phenomena with hypernyms, i.e., more general forms of nouns. We predicted that such abstraction would help designers associate fewer superficial characteristics of biological nouns to design problems, and instead focus on finding functional similarities.

In Experiment 1, participants were given two biological phenomena and asked to determine which is more relevant to the given problem. The biological phenomena were selected such that one phenomenon suggests a solution strategy useful to the problem. The other phenomenon suggests a solution strategy ill suited for the problem, but that would be preferred by designers given past, informal observation. We wanted to examine whether abstraction has a positive effect in helping designers select the more useful biological phenomenon. In Experiment 2, participants were asked to rate the relevance of two biological phenomena that suggest similarly useful solution strategies to the given problem. However, one phenomenon contains features towards which we expected designers would bias. Experiment 2 aimed to examine whether abstraction affects participants' bias, e.g., toward favored organisms from past observations, when choosing between two similarly useful biological phenomena.

3. EXPERIMENT 1: THE EFFECT OF ABSTRACTION ON THE CHOICE BETWEEN USEFUL AND NON-USEFUL BIOLOGICAL PHENOMENA

Two descriptions of biological phenomena were provided as options for the source of analogy for each of four design problems. We selected biological phenomena such that one suggests a useful solution strategy while the other suggests a non-useful solution strategy. We examined whether abstracting nouns in the descriptions of biological phenomena can help designers choose the phenomenon with the useful solution strategy. We hypothesized that abstraction reduces the bias of using superficial similarities to determine relevance of biological phenomena.

3.1. Experiment method

3.1.1. Participants. The participants were 21 4th-year engineering students in a mechanical design course at the University of Toronto. Participants received two one-hour lectures that summarized the research and application case studies of the natural-language approach to biomimetic design. Therefore, participants were informed on the types of biases that occur during selection of biological analogies, and the suggested approach of finding analogical similarities in biomimetic design. However, we deliberately avoided discussing the specific problems and phenomena used in the experiment. Participants also received lectures on conceptual design topics such as problem definition, fixation, design-by-analogy, etc. These lectures were part of the course from which the participants were recruited. In addition, participants had experience with multiple design projects in an academic setting, and no participant had extensive training in biology.

3.1.2. Design problems and experimental conditions. All participants received four design problems involving (1) fuel cells, (2) drag reduction, (3) clean clothes, and (4) recycling, shown in Tables 1-4. Each problem was paired with two biological phenomena selected by the authors. One phenomenon suggests a strategy we found more useful in solving the corresponding problem than the other. We will refer to corresponding phenomenon as "relevant" or "irrelevant" hereafter. To identify relevant biological phenomena, we used verb keywords that describe desired functions of each problem to search the text, *Life, the Science of Biology* [26]. For the irrelevant phenomena, we searched Wikipedia (http://en.wikipedia.org) for specific biological organisms. Tables 1-4 show the two conditions under which phenomena were presented as one of two choices in parentheses, and why we deemed one phenomenon irrelevant.

We created two conditions for the experiment. The control condition received full descriptions of biological phenomena, i.e., using the first term in parentheses. The abstraction condition received the same description with biological nouns replaced with hypernyms of those nouns found from WordNet [16], i.e., using the second term in parentheses. For example, "fish" would be replaced with "organism" and "heart" would be replaced with "organ". From multiple hypernyms that could be found based on different levels of abstraction in WordNet, we tried to pick the most general forms of hypernyms without loosing biological connotation. For example, the hypernym chosen for "cilia" was "body part", which is one level below "part." Participants were randomly assigned to one of the two conditions (n=11 for control and n=10 for abstract).

Table 1 Experiment 1: Fuel-cell problem and corresponding biological phenomena.

Fuel cell problem:
Proton exchange membrane (PEM) fuel cells are used in low-temperature power-generation applications. Water created from the fuel cell reaction must be removed to prevent congestion, or flooding, in the oxidizer flow channels. Develop solutions to passively remove water out of the flow channels.
Fish (Irrelevant: Strategy uses active mechanism of pumping)
(Fish / Organism-A) has (heart / organ-A1) (chambers / cavities) that are sequentially arranged. The first (chamber / cavity) collects (blood / body fluid) from the body and sends it into the second (chamber / cavity) where the main pumping action takes place. The (blood / body fluid) is pumped through the final (chamber / cavity) and is transported to the (gills / organ-A2), where gas exchange takes place.
Xylem (Relevant)
(Xylem / Tissues) in (plants / organism-B's) transport water from (roots / parts) throughout the (plant / organism-B). Water flows through (xylem / tissues) with the evaporation of water from the surfaces of (leaves / organ-B's) to the atmosphere. Due to the cohesive and adhesive properties of water, as water molecules evaporate from the (leaves / organ-B's), additional water molecules are pulled from the lower part of the (plant / organism-B) through (xylem / tissues).

Table 2 Experiment 1: Drag-reduction problem and corresponding biological phenomena.

Drag-reduction problem:
Drag reduction is an important problem in making fuel-efficient ships. Traditionally, naval engineers have tried to optimize the size and shape of ships to reduce form drag (or profile drag). An alternate approach is to reduce the contact between water and ships. Develop new solutions to reduce drag on ships.
Aquatic fern (Relevant)
(Aquatic fern / An organism-A) has surface characteristics adapted to living on water. The (leaf / organ) surface contains a series of (hairs / filaments) that are mostly coated with hydrophobic (wax / substance) except on the tips that are hydrophilic. This results in the tips holding water while a layer of air is trapped below. The air layer enables (aquatic fern / organism-A) to float freely on water.
Squid (Irrelevant: The strategy is based on moving quickly rather than reducing drag)
(Squid / An organism-B) can move at slow speeds with gentle, rhythmic pulses of water pushed out of the (mantle / layer) cavity. When (squid / organism-B) has to move quickly, the (muscles / tissues) within the (mantle / layer) inflate the cavity to increase the amount of water that can be filled in and expelled. Expelled water propels the (animal / organism-B) to reach speeds of 40km/h.

Table 3 Experiment 1: Clean-clothes problem and corresponding biological phenomena.

Clean-clothes problem:
Washing or cleaning clothes requires energy and often environmentally harmful detergents. Develop solutions to keep clothes clean without focusing on improving washing/cleaning processes.
Bacteria (Relevant)
A variety of (bacteria / organism-A1's) on our body surfaces form normal (flora / groups) and live in great numbers without causing (disease / conditions). These natural occupants of our bodies compete with (pathogens / organism-A2's) for space and nutrients, so normal (flora / groups) are a form of innate defense.
Cat (Irrelevant: The strategy describes a cleaning process)
(Cat / An organism-B) regularly cleans themselves to keep its (fur / covering) in good condition. The (cat's / organism-B's) (tongue / organ) has tiny, (rigid spines / body parts) that remove foreign objects from (fur / covering). (Cats / organism-B's) also participate in social grooming, in which they clean each other's (fur / covering).

Table 4 Experiment 1: Recycling problem and corresponding biological phenomena.

Recycling problem:
One of different systems used for curbside recycling is a "mixed waste collection," in which all recyclates are collected mixed and the desired material is then sorted out at a sorting facility. One difficult sorting task is separating paper and plastic, which is usually done by hand. Develop solutions that will enable removing paper or plastic from the mixed collection.
Blue jays (Irrelevant: The strategy does not involve separating materials)
A pair of (blue jays /organisms) begins to build their (nest / unit) after the (courtship / event) period. (Blue jays / organisms) incorporate everything from (branches / plant parts) to (hair / filaments) in their (nests / units).
Mucus (Relevant)
(Mucus / Body fluid) in the (respiratory tract / system) traps airborne (pathogens / microorganisms). (Mucus / Body fluid) and trapped (pathogens / microorganisms) are removed by rhythmic motion of (cilia / body parts) in the (respiratory tract / system).

Individual participants in both conditions were asked to identify which biological phenomenon was more relevant to the design problem, and to provide reasons for their choice.

A repeated-measures design was used where each participant underwent each condition to solve two of the four problems. While the order of the problems was consistent, the order of the conditions was randomized to counterbalance learning effect due to condition order. We gave participants 10 minutes per problem, which included time to read the problem and corresponding phenomena, make a choice and provide a reason. We observed that this time is adequate for selecting the more relevant biological phenomenon without actually generating concepts.

3.1.3. Evaluation. First, we wanted to compare between conditions, the proportion of participants who correctly chose the relevant biological phenomenon for each problem. We hypothesized that more participants in the abstraction condition would pick the relevant biological phenomenon. To examine the dependency between the choice made (correct or incorrect) and the experimental conditions (control or abstract), we created 2x2 contingency tables and conducted Barnard's tests [27] to test our hypothesis.

Second, we analyzed the reasons that participants provided in selecting biological phenomena. We predicted that fewer participants would give reasons related to associating superficial similarities in the abstraction condition. We also wanted to investigate what other reasoning is involved in designers' choice of one biological phenomenon over another.

Table 5 shows the categories of reasons provided by participants. The lead author created the categories after reading all participants' responses and also categorized the responses. A single participant comment could be classified under multiple categories. For example, a comment "The biological strategy [of the xylem] is infeasible because [the fuel cell] works in low temperature environment" is classified into two categories: 1) "found the strategy suggested is not feasible" and "considered similar working environment". We asked a second independent rater to classify 30% of the concepts according to the categories created by the lead author. An inter-rater agreement of 92.5% was obtained.

For statistical analysis, we again conducted Barnard's test to examine the dependency between the reasons made (yes or no for a particular category) and the experimental conditions (control or abstract). We used alpha = 0.05 for all tests.

3.2. Results and discussion

3.2.1. Effect of abstraction on choosing relevant biological phenomenon. Figure 2 compares between conditions for each problem, the number of participants that made correct versus incorrect choices of biological phenomena. Table 6 presents the statistical test results.

Table 5 Categories of reasons provided by participants in choosing biological phenomena

Made association based on specific words (noun/verb): Using superficial characteristics of a specific noun, or the function described by a specific verb, to associate the biological phenomenon to the design problem.
Considered similar working environment: Choosing biological phenomenon based on how the environments of the biological phenomenon and the design problem are similar/dissimilar.
Found the strategy suggested feasible/infeasible or useful/not useful.
Could not transfer strategy/biological entity: Wanting to use underlying strategy or particular entity directly to solve the problem, but not finding a way to make the strategy/entity work in the solution.
Could not understand the phenomenon.
Did not provide reason: Not justifying selection.

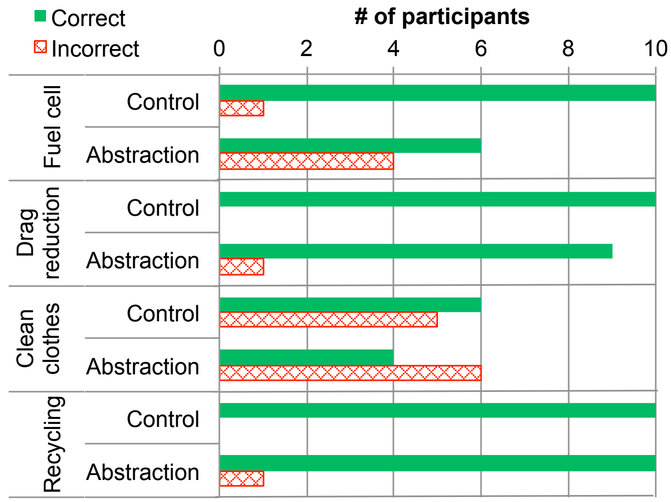

Fig. 2 Number of participants who made correct vs. incorrect choice of relevant phenomena

Table 6 Analysis of condition effect on making correct choice of relevant biological phenomena

Problem	Control (Correct/ Incorrect)	Abstract (Correct/ Incorrect)	Barnard's test (*p*-value)
Fuel cell	10 / 1	6 / 4	.112
Drag reduction	10 / 0	9 / 1*	.327
Clean clothes	6 / 5	4 / 6	.310
Recycling	10 / 0	10 /1	.327

*One participant did not complete

For the drag-reduction and recycling problems, almost all participants in both conditions made the correct choice. In hindsight, the irrelevance of one biological phenomenon for each of these two problems may have been too obvious. Therefore, we were unable to examine the effect of the abstraction condition for these two problems.

For the fuel-cell and clean-clothes problems, more participants in the abstraction condition tended to make the incorrect choice. We were surprised to see that abstraction did not have any positive effect, but in fact some negative effect, although not statistically significant. The next section examines the frequency of reasons that participants provided for their choice, and details the negative effects of abstraction.

3.2.2. Effect of abstraction on the types of reasoning involved in analogy choice. We examined the reasons provided by participants in selecting biological phenomena. Figure 3 compares the frequency of reasons between the control and abstraction conditions. Table 7 shows the statistical test results. We found that instances of making associations based on specific words were significantly higher for the abstraction condition (*p*=.039).

These results suggest that abstracting nouns could have simply caused the participants to turn their attention to, and thus fixate on, other non-abstracted words in the descriptions.

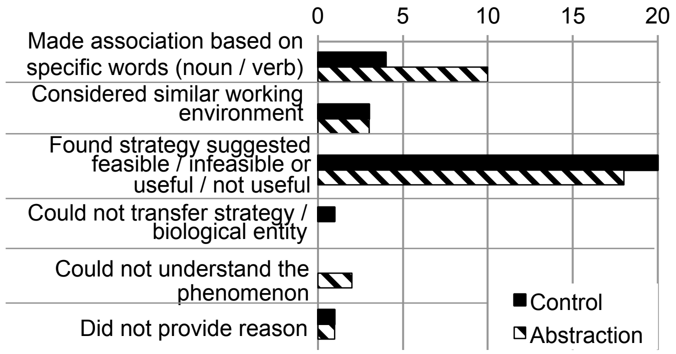

Fig. 3 Frequency of reasons for choosing biological phenomena

Table 7 Reasons for choosing biological phenomena

	Control (Y / N)	Abstract (Y / N)	Barnard's test (*p*-value)
Made association based on specific words (noun/verb)	4 / 17	10 / 11	**.039**
Considered similar working environment	3 / 18	3 / 18	.996
Found the strategy suggested feasible / infeasible or useful / not useful	20 / 1	18 / 3	.209
Could not transfer strategy / biological entity	1 / 20	0 / 21	.361
Could not understand the phenomenon	0 / 21	2 / 19	.154
Did not provide reason	1 / 20	1 / 20	.996

Participants often made associations with individual verbs, without considering the biological phenomenon's overall strategy. For example, for the clean-clothes problem, one participant remarked that the cat phenomenon (irrelevant) was more relevant because it contained the verb "clean". Similarly, for the drag-reduction problem, a participant selected the fern phenomenon (relevant) because of the verb "float". Floating may be relevant to the overall function of the ship mentioned in the problem description, but by itself, is not directly relevant to the specified problem of reducing drag.

3.3. Summary of Experiment 1

Experiment 1 did not support that abstraction of biological nouns facilitates the choice of relevant biological phenomena. In fact, abstraction of biological nouns increased the likelihood of participants fixating on non-abstracted words, which led to choosing the irrelevant biological phenomenon.

4. EXPERIMENT 2: THE EFFECT OF ABSTRACTION ON THE CHOICE BETWEEN SIMILARLY USEFUL BIOLOGICAL PHENOMENA

Experiment 2 investigated the scenario that asks designers to decide on which one of two similarly useful biological phenomena is more relevant. We selected phenomena that suggested as similarly useful strategies as we could accomplish with two different phenomena. We predicted that biases, such as preferences for familiar phenomena at familiar scales, would create differences in participants' perception of relative relevance, and thus choice. Given these biases, we hypothesized that abstraction would reduce the differences in the participants' biases toward one phenomenon over another.

4.1. Experiment method

4.1.1. Participants. Twenty 4th-year engineering students in the same mechanical design course at the University of Toronto participated in the experiment in a subsequent year. Participants received the same types of lectures on biomimetic design and conceptual design as in Experiment 1. We assumed a similar amount of experience in design and biology. Data from three participants were discarded because they wished to withdraw from the experiment, reducing the sample size to 17.

4.1.2. Design problems and experimental conditions. We used the same four design problems as in Experiment 1, and repeated their statements in Tables 8-11 to facilitate examination of the new biological phenomena provided in Experiment 2.

A pair of biological phenomena was again provided as the potential source of analogies for each problem. The irrelevant phenomenon from Experiment 1 was replaced with one that the authors deemed similar in usefulness to the original relevant phenomenon. Our goal was to reduce the obviousness of relevance, i.e., almost all participants picking one phenomenon as for the drag-reduction and recycling problems in Experiment 1. Therefore, participants received two similarly relevant biological phenomena for each problem. We did not externally confirm that the two phenomena were similarly relevant. Our results, presented in Section 4.2.1, did confirm that the choice between the two phenomena was not as obvious as in Experiment 1. Tables 8-11 show the problems and corresponding biological phenomena.

We again created two conditions: control and abstraction. Participants were randomly assigned to one of the two conditions (n=9 for control and n=8 for abstraction). As with Experiment 1, the control condition received full descriptions of biological phenomena. The abstraction condition received the same description with biological nouns replaced with hypernyms of those nouns found from WordNet [16]. Some of the abstract nouns used in Experiment 2 were modified in an attempt to reduce difficulty in reading and comprehension. In addition, we provided Table 12, containing definitions and examples of different organizational levels in biology, to clarify the nouns used in the abstraction condition.

Instead of asking participants to choose the more relevant analogy as in Experiment 1, we asked participants to rate how relevant they find each phenomenon to the problem. A Likert-scale rating between 0 and 10 was used. Zero corresponded to a phenomenon deemed completely irrelevant to the problem, and 10 corresponded to a phenomenon deemed completely relevant. We decided to use this measure over a simple binary choice to quantify the difference in participants' bias toward one phenomenon over another. We then asked participants to provide reasons behind their ratings of biological phenomena. As in Experiment 1, a repeated-measures design was used. The problem order was kept the same while the condition order was randomized to counterbalance learning effect due to condition order. We again gave participants 10 minutes to complete each problem.

Table 8 Experiment 2: Fuel-cell problem and corresponding biological phenomena.

Fuel-cell problem:
Proton exchange membrane (PEM) fuel cells are used in low-temperature power-generation applications. Water created from the fuel cell reaction must be removed to prevent congestion, or flooding, in the oxidizer flow channels. Develop solutions to passively remove water out of the flow channels.
Osmosis (anticipated biases: animal-based, familiar organ)
The water and solutes moved into the tissue fluid are taken up by the (peritubular capillaries / tissue-A's) and returned to the (venous blood / fluid-A) leaving the (kidney / organ-A). High levels of (blood glucose / molecule-A's) cause water to move from cells into the (blood / fluid-A) by osmosis, and the (kidneys / organ-A's) increase urine output to excrete excess fluid volume from the (blood / fluid-A).
Xylem
(Xylem / Tissue-B's) in (plants / organism-B's) transport water from (roots / organ-B1's) throughout the (plant / organism-B's). Water flows through (xylem / tissue) with the evaporation of water from the surfaces of (leaves / organ-B2's) to the atmosphere. Due to the cohesive and adhesive properties of water, as water molecules evaporate from the (leaves / organ-B2's), additional water molecules are pulled from the lower part of the (plant / organism) through (xylem / tissue-B's).

Table 9 Experiment 2: Drag-reduction problem and corresponding biological phenomena.

Drag-reduction problem:
Drag reduction is an important problem in making fuel-efficient ships. Traditionally, naval engineers have tried to optimize the size and shape of ships to reduce form drag (or profile drag). An alternate approach is to reduce the contact between water and ships. Develop new solutions to reduce drag on ships.
Aquatic fern
(Aquatic ferns / organism-A's) have surface characteristics adapted to living on water. The (leaf / organ-A) surface contains a series of (hairs / tissue-As) that are mostly coated with hydrophobic (wax / molecule-A) except on the tips that are hydrophilic. This results in the tips holding water while a layer of air is trapped below. The air layer enables (aquatic ferns / organism-A's) to float freely on water.
Water strider (anticipated bias: insect-based)
(Water striders / organism-B's) use the high surface tension of water and long, hydrophobic (legs / organ-B's) to help them stay above water. (Hydrofuge hairs / Tissue-B's) line the body surface of the (water strider / organism-B). There are several thousand (hairs/ tissue-B's) per square millimeter, providing the (water strider / organism-B) with a hydrofuge body. The tiny (hairs / tissue-B's) on the (legs / organ-B's) provide both a hydrophobic surface as well as a larger surface area to spread their weight over the water.

Table 10 Experiment 2: clean-clothes problem and corresponding biological phenomena.

Clean-clothes problem:
Washing or cleaning clothes requires energy and often environmentally harmful detergents. Develop solutions to keep clothes clean without focusing on improving washing/cleaning processes.
Bacteria
A variety of (bacteria / organism-A's) on our body surfaces form normal (flora / population-A's) and live in great numbers without causing disease. These natural occupants of our bodies compete with (pathogens / population-A's) for space and nutrients, so normal (flora / population-A's) are a form of innate defense.
Ground cover (anticipated bias: familiar scale)
(A ground cover / population-B) should spread by itself. Ideally, they will develop rapidly into a dense (cover/ population-B). Some, however, grow so fast they can become invasive. A (ground cover / population-B) should be sufficiently dense to inhibit competition from (weeds / organism-B's).

Table 11 Experiment 2: Recycling problem and corresponding biological phenomena.

Recycling problem:
One of different systems used for curbside recycling is a "mixed waste collection," in which all recyclates are collected mixed and the desired material is then sorted out at a sorting facility. One difficult sorting task is separating paper and plastic, which is usually done by hand. Develop solutions that will enable removing paper or plastic from the mixed collection.
Baleen whale (anticipated bias: familiar scale, animal-based)
(Baleen whales / Organism-A1's) take in large volumes of water that contain tiny (ocean creatures / organism-A2's) and squeeze the water out through the (baleen / tissue-A's), leaving the (food / substance-A) caught on the (baleen / tissue-A's). Then they use their (tongue / organ-A) to wipe the (baleen / tissue-A's) clean before processing the (food / substance-A).
Mucus
(Mucus / Substance-B) in the (respiratory tract / organ system-B) traps (airborne pathogens / microorganism-B's). (Mucus / substance-B) and trapped (pathogens / microorganism-B's) are removed by rhythmic motion of (cilia / tissue-B's) in the (respiratory tract / organ system-B).

Finally, we wanted to reduce the occurrence of noun/verb matching in Experiment 2, as we suspected that such behavior could have masked the positive effect of abstraction in Experiment 1. Therefore, we asked participants to use the causal relation template and one-to-one mapping instructions shown in Figure 1. Our previous work demonstrated that the template and mapping strategies reduced the instances of non-analogous association when using descriptions of biological phenomena as the source of biomimetic design [9].

4.1.3. Evaluation. We collected participants' relevance rating on each biological phenomenon provided. To compare the relevance ratings of biological phenomena, as well as the difference in relevance ratings between biological phenomena, we used independent samples t-tests.

Table 12 Levels of biological organization to help clarify terminology of abstracted terms

Level	Examples
Molecule	Protein, DNA, enzyme
Organelle One of several formed bodies with specialized functions suspended in the cytoplasm found in eukaryotic cells.	Mitochondrion, Cell Nucleus
Cell The lowest level of organization where all the properties of life appear.	Neuron, red blood cell
Tissue An integrated group of cells with a common structure and function.	Brain tissue, muscle tissue, bone
Organ A specialized center of body function composed of several different types of tissues.	Brain, kidney, heart, leaf
Organ System An organized group of organs that carries out one or more body functions.	Nervous system, digestive system
Organism A complete living being composed of one or more cells.	A deer, pine tree, single-cell organism
Population A group of individuals of one species that live in a particular geographic area.	A bacterial culture, all the deer in forest
Community All the organisms that inhabit a particular area; an assemblage of populations of different species living close enough together for potential interaction.	All organisms in a particular area (animals, plants, bacteria, fungi etc.)
Ecosystem A level of ecological study that includes all the organisms in a given area along with the abiotic factors with which they interact; a community and its physical environment.	A forest, a pond
Biosphere The entire portion of the earth that is inhabited by life. The sum of all the planet's ecosystems.	Planet Earth

To analyze the reasons behind their ratings, the same set of categories used for Experiment 1 was found adequate and used again. The same independent rater was asked to classify 30% of the concepts according to the categories, resulting in an inter-rater agreement of 91% with the lead author's ratings. Finally, we analyzed the errors made by participants in completing the causal relation template and one-to-one mapping instructions. We used Barnard's tests to examine the dependency between the frequency of errors and the experimental conditions, and used alpha = 0.05 for all statistical tests.

4.2. Results and discussion

4.2.1. Effect of abstraction on reducing bias in identifying relevant biological phenomenon. Figure 4 shows average participant ratings for the relevance of each biological phenomenon. Not much difference in the ratings between biological phenomena can be observed in either control or abstraction conditions. Therefore, we could not demonstrate significant sources of bias that caused participants to rate one phenomenon higher than another in the control condition. We also could not demonstrate that abstraction was able to mitigate bias. Only the drag-reduction problem suggests some difference between perceived relevance of biological phenomena for the control condition that was reduced in the abstraction condition. However, large variances in average ratings for the abstraction condition prevent us from concluding that the reduction in difference was due to abstraction.

Figure 5 specifically compares the differences of between-phenomena ratings, between the abstract and control conditions. Again, t-tests performed on these measures, shown in Table 13, did not find any significant difference.

4.2.2. Effect of abstraction on types of reasoning in rating relevance of biological phenomena. Figure 6 compares the distribution of the reasons for rating phenomena, reported by participants, between the two conditions. Table 14 shows the results of Barnard's tests.

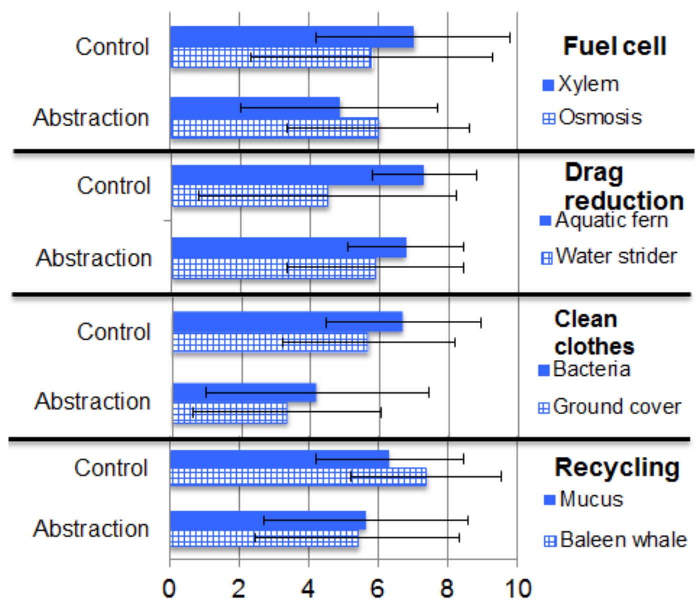

Fig. 4 Relevance ratings of biological phenomena. Error bars represent standard deviations.

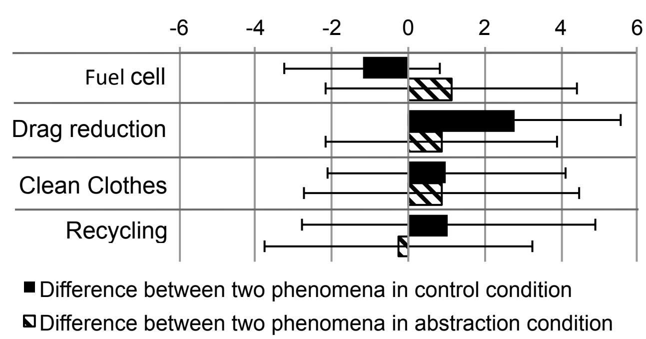

Fig. 5 Comparison of the differences in relevance ratings between phenomena. Error bars represent standard deviations.

As expected, the instances of noun/verb association in both conditions were reduced after the causal relation template and one-to-one mapping instructions were introduced in Experiment 2. However, a greater proportion of participants in the abstraction condition than in the control condition could not understand the biological phenomenon. This difference was statistically significant (p=.010). In fact, all the cases of participants not understanding the biological phenomenon were in the abstraction condition. In hindsight, abstraction of nouns likely made it more difficult for participants to comprehend the descriptions of biological phenomena, which offsets any potential benefit we intended through abstraction.

Figure 6 shows that 88% (15/17) and 82% (14/17) of participants, in the control and abstraction condition respectively, reported their reason in determining relevance as whether the strategies suggested were feasible or useful. A main factor in determining relevance could be whether participants could develop concepts based on the phenomena.

4.2.3. Effect of abstraction on correct completion of causal relation template and one-to-one mapping instructions. We analyzed the causal relation template and one-to-one mapping instructions completed by participants. Figure 7 and Table 15 show that more errors occurred under the abstraction than control condition, although the differences are not statistically significant. The results suggest that abstraction likely led participants to make incorrect use of additional support tools provided. This is not surprising, considering comments provided during the debriefing session. Specifically, many participants reported that abstraction of nouns made the phenomenon and thus the biological strategy more difficult to understand.

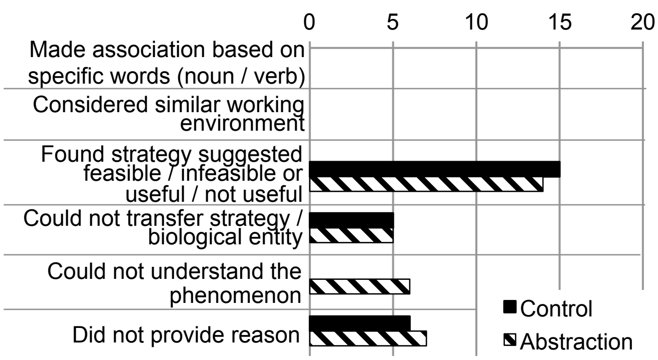

Fig. 6 Frequency of reasons for rating biological phenomena

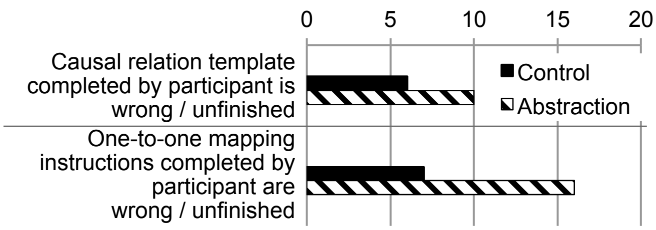

Fig. 7 Frequency of errors made in using the causal relation template and one-to-one mapping instructions

Table 13 Analysis of difference in relevance ratings between biological phenomena

	Difference b/w two phenomena		t(15)	p-value
	Control (Mean +/- SD)	Abstract (Mean +/- SD)		
Fuel cell	-1.20 +/-2.03	1.12 +/- 3.30	1.72	.106
Drag reduction	2.79 +/-2.78	0.88 +/- 3.02	1.35	.197
Clean Clothes	1.00 +/-3.12	0.88 +/- 3.60	.767	.940
Recycling	1.06 +/-3.84	-0.25 +/- 3.51	.728	.478

Table 14 Analysis of reasons for rating biological phenomena

	Control (Y / N)	Abstract (Y / N)	Barnard's test (p-value)
Made association based on specific words (noun/verb)	0 / 17	0/ 17	1.00
Considered similar working environment	0 / 17	0 / 17	1.00
Found the strategy suggested feasible / infeasible or useful / not useful	15 / 2	14 / 3	.474
Could not transfer strategy/biological entity	5 / 12	5 / 12	.998
Could not understand the phenomenon	0 / 17	6 / 11	**.010**
Did not provide reason	6 / 11	7 / 10	.415

Table 15 Analysis of errors made in using causal relation template and one-to-one mapping instructions

	Control (Y / N)	Abstract (Y / N)	Barnard's test (p-value)
Causal relation template completed by participant is wrong/unfinished	6 / 62	10 / 58	.174
One-to-one mapping instructions completed by participant are wrong/ unfinished	7 / 61	16 / 52	.075

4.3. Conclusions of Experiment 2

Experiment 2 showed that the abstraction implemented increased the likelihood of novice designers not understanding the descriptions of biological phenomena, leading them to perceive the phenomena as not relevant to the design problem. The same reason could also explain why abstraction increased the likelihood of novice designers making errors in completing the causal relation template and one-to-one mapping instructions.

5. GENERAL DISCUSSION

The abstraction we implemented, by replacing biological nouns with hypernyms, did not reduce participants' bias in evaluating relevance of biological phenomena. We wanted to approximate the abstraction that could be automatically performed on natural-language text. In hindsight, such abstraction could have prevented any potential benefits. However, other possible explanations follow.

A human preference for specific examples over abstract representation has been observed in education research. Prince and Felder [30] state that traditional engineering instruction methods are deductive, i.e., a generalized concept is provided first, followed by specific examples of the concept. However, the authors reported that a number of inductive teaching methods, e.g., problem/project/case-based learning, were at least as effective, and in general more effective than, traditional deductive methods. Therefore, when designers must learn unfamiliar information, e.g., biological phenomena, abstraction itself may prove an obstacle.

More evidence on the human tendency to prefer specific representation has also been found during concept generation. Design researchers and educators advocate that problem definition should be performed at the abstract level by focusing on the functions of the product [31]. However according to Gero et al. [32], a common behavior amongst designers across disciplines, expertise, and geographical regions is that they start thinking about specific structures (forms) at the onset of the conceptual design process.

In addition, the negative effects of abstraction we observed could be specific to the task of evaluating the relevance of analogies. As reported by a number of design researchers [13,14,21], abstraction has positive effects in certain design scenarios. We also agree with Qian & Gero [11] and Goel [12] that abstraction is necessary to enable creative/analogical reasoning in computational design. Our previous abstraction study [15] provided a single phenomenon to solve a given problem, so participants may have assumed the relevance of the phenomenon and tried harder to apply it. When given two phenomena, the task of comparing them may lead participants to be more critical of their relevance. Our current studies suggest the benefits of abstraction may be limited when analogies are derived from a domain unfamiliar to the designer, and the task involves a selection of an analogy amongst options. Specific to biomimetic design, Vattam et al. [24] reported that many students who used their SBF models, an abstract representation of biological systems, had difficulty in seeing the value of the models.

Another plausible explanation could be that the hypernyms chosen for our study may have been overgeneralized forms of the original nouns. Bhatta and Goel's work on analogical learning [29] and Fu et al.'s study on analogical stimuli [30], as well as our own previous study on abstraction of biological nouns [15], suggest that there is an appropriate level of generalization best for analogical reasoning. Future research could investigate finding these appropriate levels of abstraction for biomimetic design.

6. LIMITATIONS AND FUTURE WORK

Our sample size was limited by the number of students enrolled in an elective upper-year course. We could have recruited more participants beyond the course. However, those participants would have been sufficiently different from our main population to introduce other effects, e.g., from a different year in school, not having had the same lecture material on biologically inspired design, cognitive biases, fixation, etc. Although our sample sizes are smaller than those of other design studies, our conclusion is that our initial hypotheses on the benefits of abstraction are unsupported. Because we observed that abstraction in fact tends to have negative effects, even a greater sample size would not likely support our initial hypotheses.

Instead, future studies could look into the effects of other implementations of abstraction on populations with different expertise, educational background, and context. The participants used for our study were undergraduate students, mostly trained in engineering at a single university, without extensive design expertise or biological knowledge. Future studies could be conducted with expert designers, ideally from various domains and backgrounds, or even with biologists. Finally, more training on biomimetic design and design-by-analogy could enable novice designers to take advantage of abstraction and reduce the negative effects reported in this paper. Longitudinal studies that examine the effect of training, as performed by Gero et al. [33], could be considered as well.

7. CONCLUSION

We investigated the effect of abstraction on how novice designers perceive the relevance of biological phenomena to design problems. Our abstraction involved replacing biological nouns in descriptions of biological phenomena with their hypernyms. Two scenarios for which we investigated the effect of abstraction were: 1) Identifying the biological phenomenon that offers a more useful strategy over one that features common sources of bias, and 2) Evaluating the relevance of two biological phenomena that offer two similarly useful biological strategies, where one features common sources of bias. We were unable to demonstrate the benefits of abstraction. In the first scenario, abstraction of nouns appeared to simply redirect participants' non-analogous association to non-abstracted words in the descriptions. In the second scenario, abstraction simply made it more difficult for participants to understand the descriptions of phenomena.

While other design studies have confirmed the benefits of abstraction [13,14,21], our work suggests that abstraction may also have negative effects. We recommend investigating other ways in which abstraction can be implemented when designing similar tools or techniques that aim to support biomimetic design, or any other design-by-analogy method.

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