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Reducing cognitive bias in biomimetic design by abstracting nouns

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ABSTRACT

Biological analogies can increase creativity in design by providing related, yet distant-domain stimuli, which have been reported to lead to more innovative concepts than within-domain stimuli. However, over the past decade, we have observed that designers are influenced by cognitive biases in their selection and application of biological analogies. We propose that abstraction of biological nouns in descriptions of biological phenomena can reduce such cognitive bias and support analogical reasoning. Experiments confirmed the promising effect of this objective and automatable intervention on novice designers. The cognitive biases and fixation we aim to reduce are relevant to conceptual design in general.

1. Introduction

Biomimetic, or biologically inspired design, is gaining prominence as a design method, and has produced a number of innovative engineering solutions [1–6]. One approach developed to support biomimetic design takes advantage of the abundant biological information readily available in natural-language format, e.g., texts, papers, online resources, etc. [7,8]. In this approach, designers use keywords to locate relevant biological phenomena from text describing biological information.

Over the past decade, we have observed that designers' cognitive biases often impede the identification of analogous relationships between text descriptions of biological phenomena and potential design solutions [7].

1.1. Analogical application of biological phenomena

Biomimetic design aims to develop engineering solutions based on strategies found in biological phenomena. Identifying relevant strategies requires analogical reasoning, which involves finding similarities in *higher-order relations* between two concepts [9]. One type of a higher-order relation is a causal relation.

For example, in "Enzymes destroy bacteria to protect animals," a causal relation formed between the functions of "destroy" and "protect" identifies how a certain action is enabled in the phenomenon. This enabling strategy can be transferred to solve a design problem with the goal of achieving protection.

Identifying and transferring causal relations are essential to more general design-by-analogy methods in engineering [10,11]. These methods are often extended to model biological systems and support biomimetic design [12,13].

1.2. Non-analogous application of biological phenomena

We often observed that novice designers, e.g., final-year undergraduate engineering students participating in biomimetic design exercises, use non-analogous association to apply suggested biological phenomena in their design solutions [14–17]. This is often initiated by fixation on specific words and phrases, referring to either entities or functions, in the descriptions of biological phenomena. For example, a student presented with the above description of enzymes may develop solutions based on other perceived or known characteristics, e.g., ribbon shape, of enzymes. In this case, the student fixates on enzymes over other entities or functions present in the description. The student then uses prior knowledge, i.e., ribbon shape, of enzymes, to develop a solution that is not analogous to the provided phenomenon.

In addition to the above obstacle, other cognitive biases reported include the tendency by novice designers to develop the same concept multiple times in response to different analogies intended to solicit different solutions [15,16]. Analogies are also often matched with existing and widely known solutions, rather than used to develop new solutions, even by experts, i.e., collaborators in academia and industry. Goel et al. [13] report similar cognitive biases by student designers conducting biomimetic design projects. Such cognitive biases and fixation are obstacles that are relevant to conceptual design in general.

1.3. Previous methods to support application of biological analogies

Mak and Shu first proposed the use of "templates" to aid students in analogical transfer [15,16]. Cheong and Shu developed a template that asks designers to identify causally related functions from descriptions of biological phenomena [17].

Cheong and Shu [18] then developed a computational technique to automatically identify causally related functions based on grammatical relations. This enabled a search tool to sort descriptions of biological phenomena by the enabling functions of the desired function. This technique is intended to help designers focus on functional relations rather than specific entities that could cause fixation or non-analogous association.

However, in 96 concepts developed by final-year engineering students using the above tool, 43% still exhibited fixation on specific entities. For example, using the above phrase describing

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enzymes, concepts were developed based on superficial associations such as the ribbon shape of enzymes.

While 30% of the concepts demonstrated correct analogical transfer, fixation on specific functions, e.g., concepts developed based solely on "destroy", rather than "destroy to protect" accounted for 21% of concepts. A remaining 6% had other uncategorized difficulties.

1.4. Abstraction as an approach to reduce cognitive bias

The above results motivated us to consider another approach to complement the identification of causally related functions. In design by analogy, abstraction is considered to be key in transferring knowledge from one domain to another [11]. In biomimetic design, abstraction could be used to remove the identity of specific entities, thereby reducing fixation on the entities and the non-analogous associations that follow. For the enzyme example above, an abstraction could be:

"Entity-A **destroys** entity-B to **protect** entity-C."

With the above abstraction, the designer would unlikely make any association from words other than the functional verbs, "destroy" and "protect." We hypothesized that abstraction of biological nouns would reduce cognitive bias and support the transfer of biological analogies. The following section describes the experiment conducted to test this hypothesis.

2. Experimental method

2.1. Participants

Experimental data were collected from two groups. The first group consisted of 21 undergraduate engineering students in a final-year mechanical design course at the University of Toronto. The second group consisted of 15 MASc/PhD graduate students recruited from the Mechanical and Industrial Engineering Department at the same university. It is reasonable to expect group differences between the two populations; the first group received lectures on biomimetic design and design fixation prior to the experiment, while a few members of the second group had industry experience and may have more extensive design knowledge. However, examination of the data showed only minimal differences between the groups, and therefore group effect is not further discussed in this paper.

2.2. Experimental design and conditions

Participants were provided with design problems and asked to write down or sketch solutions based on descriptions of biological phenomena as the source of analogy. Each participant individually solved three problems that involved (1) promotional mailing, (2) authorized disassembly, and (3) wet scrubber. Each problem was paired with a single biological phenomenon, which was presented in one of three different experimental conditions. Tables 1–3 show the three problems, and how the description of the corresponding biological phenomenon was modified for each condition.

The control condition used the full description of a biological phenomenon. The hypernym condition used the same description with biological nouns replaced with hypernyms of those nouns found from WordNet [19]. WordNet is a lexical database that organizes lexical and semantic relations, e.g., hypernyms, hyponyms, antonyms, etc., between groups of words. The hypernym of a word can roughly be considered the superset of the word, e.g., "plant" is a hypernym of "tree". The letter condition used the same description with biological nouns replaced with arbitrary letters. The hypernym and letter conditions represent different levels of abstraction applied to the descriptions; hypernyms bear more general meanings of the original nouns, while letters do not bear any meaning at all but are simply used to indicate equivalent entities in the description.

A repeated-measures experimental design was used where each participant underwent every condition, i.e., solving each design problem under a different one of the three conditions. While the order of the problems was constant, the order of the conditions was randomized to examine the effect of abstraction.

2.3. Concept rating

For each condition/problem, we counted the number of participants that generated at least one analogous concept. We rated neither quality nor novelty of the concepts, as our goal is to examine if abstraction supports the transfer of biological analogies.

Table 1
The promotional mailing problem, presentation of corresponding biological phenomenon for each condition, and expected solution.

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 sign-up promotional mailings?
Ant foraging:
Control: Ants can identify the shortest path between the 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.
Hypernym: An organism can identify the shortest path between the unit and food source with the following strategy. The organisms depart the unit to search randomly for food, laying down body fluid on the trail as they go. When an organism finds food, it follows its body fluid trail back to the unit, laying down another body fluid trail on the way. Body fluid has 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 body fluid is laid down more frequently on shorter paths. Additional organisms follow the strongest body fluid trails between the food source and the unit, further reinforcing the body fluid strength of the shortest path.
Letter: A can identify the shortest path between the B and food source with the following strategy. A's depart the B to search randomly for food, laying down C's on the trail as they go. When A finds food, it follows its C trail back to the B, laying down another C trail on the way. C's 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 C's are laid down more frequently on shorter paths. Additional A's follow the strongest C trails between the food source and the B, further reinforcing the C strength of the shortest path.
Expected analogous solution: Randomly send out some mail to several neighborhoods; Target future mailing based on response obtained.

Table 2
The authorized disassembly problem, presentations of corresponding biological phenomenon, and expected solution [3].

Authorized disassembly problem:
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?
Enzyme-substrate interaction:
(Enzymes/Compounds/A's) bind to specific (substrates/substances/B's) and form (enzyme-substrate/compound-substance/A-B) complexes that perform biochemical activities. The specific binding is achieved when the (active site/part/C) of (an enzyme/a compound/A) geometrically matches its corresponding (substrate/substance/B). However, (an enzyme/the compound /A) changes its shape with environmental factors such as (pH and temperature/chemical/physical property/D). This shape change alters the conformation of the (enzyme's active site/compound's part/A's C) to the point where (substrates/the substances/B's) can no longer fit, thereby disabling the function of the (enzyme-substrate/compound-substance/A-B) complex.
Expected analogous solution: Fasten parts with specific interfaces whose shapes are changed by environmental factors to disassemble the parts.

Table 3
The wet scrubber problem, presentations of corresponding biological phenomenon, and expected solution.

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?
Penguin's circulatory system:
(Penguins have/ An organism has/A has) warm (blood/body fluid/B) yet keep their/its un-insulated(feet/body part/C) at a temperature close to freezing to minimize heat transfer to the environment. The (veins/tubes/D's) that carry cold (blood/body fluid/B) from the (feet/body part/C) back to the body are located closely to the (arteries/tubes/D's) that carry warm (blood/body fluid/B) from the body to the (feet/body part/C). The warm (blood/body fluid/B) flows in the opposite direction as the cold (blood/body fluid/B), which allows the (penguins/organisms/A's) to transfer the most heat to the cold (blood/body fluid /B). This reduces both the amount the returning (blood/body fluid/B) can drop the core body temperature, and the amount of heat lost through the (feet/body part /C).
Expected analogous solution: Run exhaust gas and scrubber solution in countercurrent direction to maximize pollutant removal.

3. Results

Fig. 1 shows the effects of experimental conditions for each problem. For the promotional mailing problem, abstraction had the least effect; many participants in the control condition were able to detect/apply the expected analogy. For the authorized disassembly problem, both abstraction conditions somewhat helped participants to detect/apply the relevant analogy, while participants in the control condition had difficulty developing analogous concepts (Fisher's exact test, hypernym: $p = .069$; letter: $p = .155$). For the wet scrubber problem, the letter condition actually made the detection/application of the relevant analogy significantly more difficult (Fisher's exact test, $p < .05$).

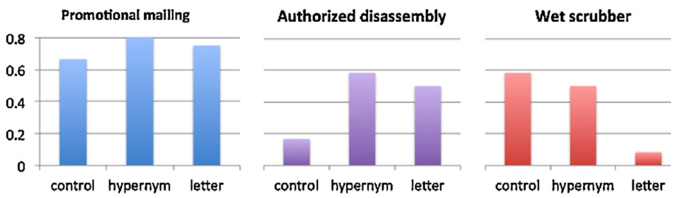

Fig. 1. Proportion of participants who developed an analogous concept for each condition/problem. For each condition/problem, $N = 12$.

4. Discussion

For the two problems affected by abstraction, the effects of the type/level of abstraction are discussed below.

4.1. Authorized disassembly problem

For the authorized disassembly problem, the abstraction conditions may have benefited the participants in two ways. First, replacing the word "enzyme" with a more generic form reduced the non-analogous association with irrelevant, prior knowledge of enzymes.

Second, abstraction may have altered how participants perceive the enzyme phenomenon. Most participants in the control condition developed concepts based on using specific fasteners or interfaces to assemble parts, but did not incorporate shape change to assist in part disassembly. We suspect that the participants found the text describing how enzymes bind to substrates based on specific shape, more salient than the text describing shape change based on environmental factors.

Surprisingly, abstraction may have required participants to pay more attention to the entire description of the biological phenomenon, because it was more difficult to understand the abstracted description. This in turn could have led the participants to incorporate the overall analogy in their solutions.

One participant who did not generate an analogous concept in the hypernym condition provided an interesting insight. The participant stated in the exit interview that despite abstraction, he recognized that the description was about enzyme-substrate interaction and recalled the "lock-and-key" phenomenon. This participant then generated a solution using a specific key to unlock parts, likely inspired from his recall of the "lock-and-key" phenomenon. This insight supports the significant effect of prior knowledge on how the provided analogy is used, and suggests that that prior knowledge may prevail despite abstraction. However, we believe that the likelihood of association with prior knowledge is reduced with the abstraction of biological nouns.

4.2. Wet scrubber problem

For the wet scrubber problem, participants needed to perceive spatial relations correctly to identify the biological strategy of countercurrent flows. In exit interviews, three participants who could not identify the expected analogy in the letter condition specifically stated that they had difficulty visualizing the spatial relations between the entities. For example, with "veins" and "arteries" in the description replaced with the letter "D", one participant could not see that "D" represents a channel. Another letter-condition participant inferred the spatial configuration of the entities, but could not identify the countercurrent flows involved. These difficulties, supported by participants' sketches in Fig. 2, likely prevented participants in the letter condition from identifying countercurrent flow as the key analogy.

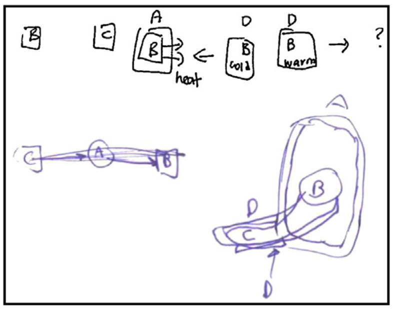

Fig. 2. Sketches of participants in the letter condition attempting to visualize the penguin's circulatory system.

In the hypernym condition, "tubes" replaced "veins" and "arteries", which convey the shape of these entities, and thus participants did not have difficulty visualizing the phenomenon.

4.3. Conclusion

Replacing biological nouns with hypernyms may be the ideal level of abstraction for biomimetic design. Unexpectedly, abstract representation of biological phenomena could force designers to holistically consider text descriptions, thereby increasing application of overall analogies. As expected, abstraction appeared to reduce non-analogous association between biological entities and irrelevant prior knowledge. However, too much abstraction, e.g., replacing biological nouns with letters, prevents understanding and thus detection of analogies in certain biological phenomena.

5. Approach to automate abstraction

Hypernym abstraction could be automatically performed for text-based descriptions. Thus, biomimetic search results could be abstracted before being presented to the designer.

In natural-language text, nouns in general can be identified with a part-of-speech (POS) tagging tool. For example, the Stanford POS tagger is about 97% accurate with trained text [20].

To identify the biological, or biologically meaningful, nouns that require abstraction, one could apply the concept of WordNet "hood". A hood is a group of words that are hyponyms, i.e., more specific words, of a generic hypernym that defines the hood [21]. For example, Fig. 3 shows how "ant" belongs in the hood "living thing, animate thing". Other hoods, e.g., "macromolecule", "body substance", can also be used to identify biological nouns.

Entity -> physical entity -> object, physical object -> whole, unit -> **living thing, animate thing** -> organism, being -> animal, animate being -> invertebrate -> arthropod -> insect -> hymenopterous insect -> **ant**

Fig. 3. How "ant" is classified in the WordNet hierarchy. Words under the hood "living thing, animate thing" are likely to be biological nouns.

One challenge is disambiguating the sense of nouns identified. For example, "seal" used in the sense of the marine mammal should be abstracted, but "seal" used in the sense of excluding should not be abstracted. Word sense disambiguation is an active research topic in computational linguistics, but has not achieved high enough accuracy for practical applications [21].

For a particular biological noun, an appropriate replacement hypernym can be located from the hood that contains the biological noun. In most cases, the top most hypernym or the second hypernym in the hood hierarchy is appropriate, because the meaning of those hypernyms would be general enough to reduce the chance of non-analogous association during concept generation. For example, for "ant," the replacement hypernym could be "living thing" or "organism."

6. Closing remarks

This work investigated how abstraction of biological nouns in descriptions of biological phenomena can help reduce cognitive bias and support analogical transfer in biomimetic design. Besides reducing non-analogous associations between biological nouns and prior knowledge, abstraction may force designers to process the entire description, increasing the likelihood of applying the overall analogy in their solutions. Importantly, the abstraction method can be incorporated into a computational tool to support the natural-language approach to biomimetic design, using part-of-speech tagging and the WordNet hierarchy.

Cognitive biases are ubiquitous in design. The abstraction technique described in this paper can be applied to support design-by-analogy with other types of domain knowledge and design stimuli.

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