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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.