
ELSEVIER
November 2013
34
volume
6
issue
ISSN 0142-694X
The international journal for
design research in engineering,
architecture, products and systems
Design Studies

Using templates and mapping strategies to support analogical transfer in biomimetic design

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While biological phenomena can serve as meaningful analogies to inspire innovative design, previous studies found that designers often use descriptions of biological phenomena in non-analogous ways. Two experiments were conducted with novice designers to investigate how to decrease the non-analogous use of biological phenomena in concept generation. Properly applied, a causal relation template, developed based on Gentner's framework of analogical reasoning, decreased participants' non-analogous concepts. We identified two further interventions that reduce the tendency to develop non-analogous concepts: (1) one-to-one mapping instructions and (2) mapping the source analog to multiple problem-independent scenarios before concept generation. Understanding and reducing non-analogous application of biological phenomena may enable designers to more fully take advantage of biomimetic, or biologically inspired, design.

Keywords: biomimetic/biologically inspired design, conceptual design, design techniques, design method, design cognition

There is increasing consensus that analogies formed between concepts from two distant domains, such as biology and engineering, can stimulate creative ideas (Bonnardel, 2000; Jin & Benami, 2010; Lopez, Linsey, & Smith, 2011; Sartori, Pal, & Chakrabarti, 2010; Tseng, Moss, Cagan, & Kotovsky, 2008). Many studies assume that the use of distant-domain stimuli invokes analogical reasoning, which by Gentner's (1983) definition requires finding structural similarities between two concepts.[1] This however is not always the case, as a designer could develop an idea based on association from superficial characteristics of a distant-domain source.

Previous studies in biomimetic, or biologically inspired, design reported that novice designers frequently develop ideas based on non-analogous association with particular features of biological phenomena (Cheong & Shu, 2009; Helms, Vattam, & Goel, 2009; Mak & Shu, 2004, 2008). However, structural similarities of functions between biological phenomena and design problems

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www.elsevier.com/locate/destud
0142-694X $ - see front matter *Design Studies* **34** (2013) 706–728
http://dx.doi.org/10.1016/j.destud.2013.02.002

are important, as even design solutions that mimic superficial characteristics or forms of biological systems were likely inspired upon recognition of functional similarities between the two domains. For example, while Velcro, the most commonly cited example of biomimetic design, mimics the surface characteristics of a burr, the initial connection was formed after observing how the burr is relevant to the function of attaching.

While biological knowledge is increasingly available in multiple formats, e.g., text, formal models, images, videos, etc., a vast amount of such knowledge still entails text descriptions of processes or mechanisms involved in biological phenomena. Past studies confirm that designers often have difficulty recognizing structural similarities between text descriptions of biological phenomena and design problems, and thus fail to apply such information analogously (Cheong, Hallihan, & Shu, 2012; Helms, Vattam, & Goel, 2010; Mak & Shu, 2004).

Therefore, the current research aims to assist designers analogously apply text descriptions of biological phenomena. We propose a causal relation template, which identifies how one function is enabled by another function in a biological phenomenon, and supports the detection of the relational structure necessary for analogical reasoning. We then conducted two controlled experiments to examine the effectiveness of techniques developed to support mapping of biological analogies and reduce designers' tendency to use non-analogous association when developing concepts.

The following section reviews relevant research in biomimetic design and summarizes challenges observed in using biological analogies for concept generation.

1 Relevant research in biomimetic design

Three approaches to developing generalized methods in biomimetic design are discussed below. Next reviewed are studies conducted to understand cognitive processes of designers practicing biomimetic design.

1.1 BioTRIZ

Vincent and Mann (2002) described how TRIZ, a problem-solving technique in which solution principles are identified for pairs of conflicting goals based on over two million Russian patent certificates, could be adapted to identify how conflicts are solved in biology. Vincent, Bogatyreva, Bogatyreva, Bowyer, and Pahl (2006) created BioTRIZ using the same inductive approach as for TRIZ, but based on over 500 biological phenomena instead of patent certificates. In BioTRIZ, biological knowledge is abstracted and indexed based on conflicting goals, which may be considered a relationship of relationships.

1.2 Database and modeling approach to biomimetic design

A number of researchers have proposed creating databases of biological knowledge indexed by functions to support biomimetic design. Goel, Rugaber, and Vattam (2009) represent causal processes between states using the structure–behavior–function framework. Chakrabarti, Sarkar, Leelavathamma, and Nataraju (2005) identify multiple levels of abstraction to explain how a biological system works to fulfill its goals. Nagel, Nagel, Stone, and McAdams (2010) propose using functional basis terms to model biological systems. Once databases are populated with instances of such models or representation schemes, designers could identify analogous biological phenomena based on functional similarities to engineering systems. However, this approach requires that potentially useful biological information be identified and modeled, which entails significant effort (Goel, Vattam, Wiltgen, & Helms, 2011). In addition, such biological information could be biased by functions that may subjectively appear most relevant. For example, if the burr, which inspired Velcro, is associated only with the function of fastening, potential functions other than fastening that are relevant to burrs may be lost.

1.3 Natural-language approach to biomimetic design

Another approach, taken by our research group for more than a decade, is to enable designers to identify analogies from natural-language text containing biological information (Shu, 2010; Shu, Ueda, Chiu, & Cheong, 2011). This approach involves searching such text with keywords. We developed a process to identify biologically meaningful keywords that often retrieve more useful matches than the corresponding engineering keywords alone (Cheong, Chiu, Shu, Stone, & McAdams, 2011; Chiu & Shu, 2007). However, even with useful matches describing biological phenomena, designers must still evaluate and apply relevant information to design problems.

1.4 Challenges reported from cognitive studies of biomimetic design

Mak and Shu (2004) studied novice designers' ability to apply analogous strategies suggested in descriptions of biological phenomena, and found that participants tend to develop non-analogous concepts because they fail to identify biological strategies and/or abstract biological entities. Mak and Shu (2008) then explicitly identified analogous strategies and asked participants to match corresponding entities between biological phenomena and design problems to develop solutions. Although the intervention helped, some participants still made errors in mapping corresponding entities and produced non-analogous concepts.

Cheong and Shu (2009) observed that novice designers tend to develop non-analogous concepts based on specific entities of biological phenomena, and suggested that identifying causally related functions could help designers transfer functional relations rather than specific entities from descriptions of biological phenomena. Helms et al. (2009) observed students working on semester-long biologically inspired design projects, and described multiple errors, including 'poor problem-solution pairing,' 'misapplied analogy,' and 'improper analogical transfer.'

Following a verbal protocol study, Cheong et al. (2012) reported that readily available associations at lower levels of similarity, i.e., superficial or functional, hinder analogical reasoning, i.e., detecting structural-level similarities. This finding further supports the value of reasoning with abstract, structural-level similarities.

1.5 Other relevant studies in biomimetic design

Vattam, Helms, and Goel (2010) found that biomimetic design often involves compound analogies between decomposed problems and multiple biological phenomena, and that analogies are used in different stages of conceptual design. Helms et al. (2009) contrast the solution-driven approach, where designers seek problems that can be solved using an interesting biological phenomenon, with the more common problem-driven approach. Incorporating these findings and SBF modeling, Goel et al. (2011) developed a knowledge-based CAD system for biologically inspired design.

Chakrabarti et al. (2005) developed SAPPhIRE constructs that represent biological information at different levels of abstraction. Sartori et al. (2010) report that participants who used SAPPhIRE constructs generated more ideas that were feasible and 'biomimetic' than participants who used a generic guideline.

Many cognitive studies in biomimetic design have been descriptive and involve observing the complex processes and challenges involved. Our current work aims to 1) analyze the effectiveness of tools we developed to support analogical reasoning, and 2) further develop systematic methods to support designers during biomimetic design.

2 Developing a causal relation template to support analogical reasoning

To support analogical reasoning, we developed a tool to aid designers in extracting key information from text descriptions of biological phenomena. Similar to Mak and Shu (2008), we use a template-based approach, but rather than the researchers identifying the strategy in advance, we asked designers to identify relevant strategies by completing a template to capture causally related functions in biological phenomena.

The following section reviews relevant work on analogical reasoning, how this work served as the foundation in developing our causal relation template, and a procedure to use the template.

2.1 Definitions in analogical reasoning

The *structure-mapping theory* proposes that in analogies, relations between objects, rather than attributes of objects, are mapped from the source to target (Gentner, 1983). Relevant to our work, *systematicity*, which is formed with higher-order relations (relations between relations), is essential for identifying analogous concepts. Clement and Gentner (1991) empirically demonstrated that people deem more similar, concepts that share a common system of relations, i.e., a higher-order relation, than concepts where similarity only exists between individual relations.

Holyoak and Thagard (1989) assert that finding structural similarities between concepts is only one of three constraints that must be satisfied for analogical mapping, and that semantic and pragmatic constraints also guide the detection of analogies. Markman and Gentner (1993), on the other hand, found that people are more likely to match corresponding objects between analogous concepts based on how they fit in structural alignment, rather than based on semantic similarities between objects. Holyoak and Thagard (1989) and Markman and Gentner (1993) do however agree on the *one-to-one mapping* constraint, i.e., an object from one concept can be mapped to at most one object in another concept.

2.2 Causal relation template

We adopted these concepts, particularly systematicity and one-to-one mapping, to develop our causal relation template, shown in Figure 1, that aims to support designers in identifying relational structures in analogies. Figure 2 shows how information identified using the causal relation template corresponds to the information required for the systematicity framework by Gentner (1983). The template is intended to help designers clarify how an enabling function and its associated subject and object are related to a particular desired function in biological phenomena.

2.3 One-to-one mapping instructions

Once the relevant causal relation is identified, one-to-one mapping instructions are intended to guide designers in mapping objects from a biological

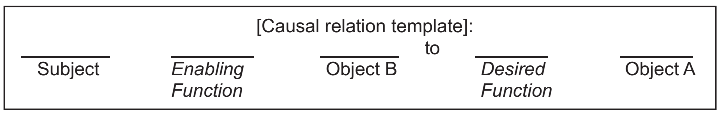

Figure 1 Causal relation template

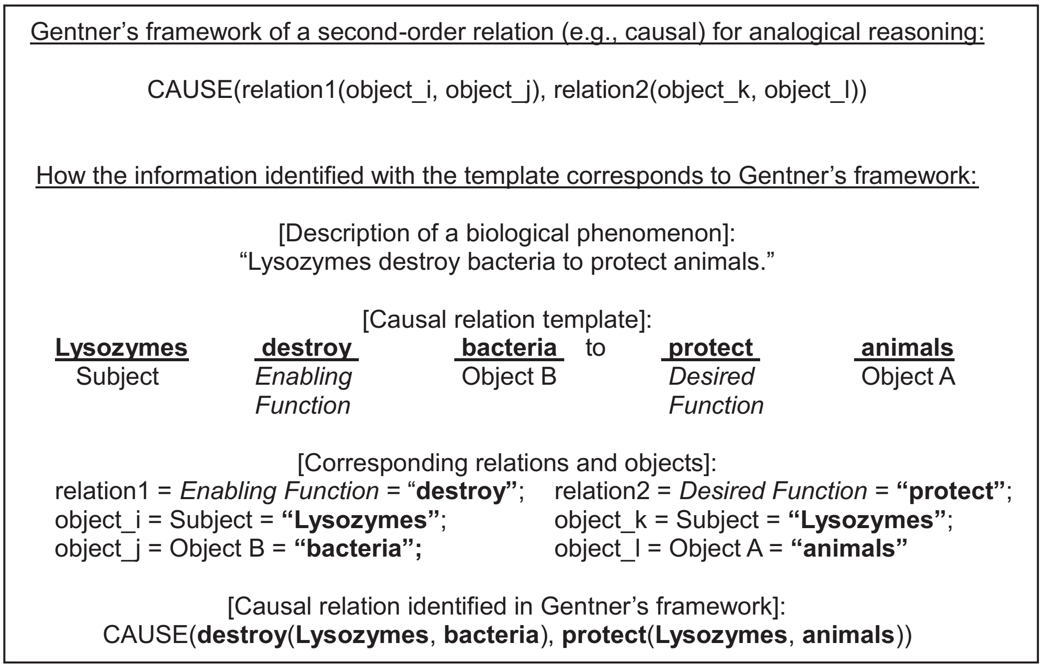

Figure 2 Causal relation template and Gentner's (1983) framework of systematicity

phenomenon to corresponding objects in potential design solutions, shown in Figure 3.

3 *Experiment 1: the effect of the causal relation template and one-to-one mapping instructions on analogical reasoning*

We first investigated the effect of the causal relation template on helping designers detect relevant strategies from biological phenomena. We also examined how one-to-one mapping instructions could support the transfer of relational structures and corresponding entities from biological phenomena to design solutions.

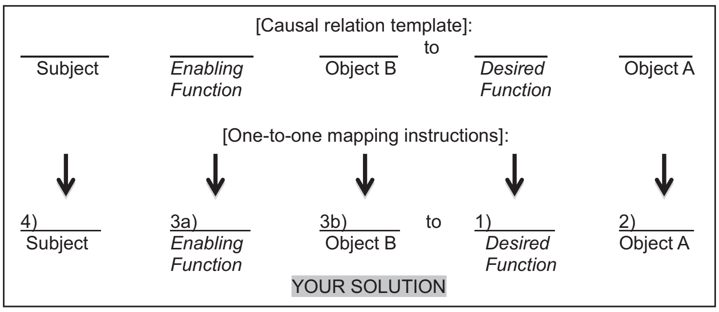

Figure 3 Causal relation template with one-to-one mapping instructions (numbers suggest sequence)

3.1 Participants

Sixty-one fourth-year engineering students in a mechanical design course at the University of Toronto were asked to solve two design problems. The data from three participants were discarded due to the incomplete concepts recorded, reducing the sample size to 58.

3.2 Design problems and biological phenomena

All participants received the same two design problems and corresponding descriptions of biological phenomena as design stimuli, shown in Table 1. The order of the problems was counterbalanced, and the description of a single biological phenomenon was provided for each problem. Both descriptions of biological phenomena were retrieved from *Life, the Science of Biology* (Purves, Sadava, Orians, & Heller, 2001), a reference text for an introductory university-level biology course. Participants worked individually on the design problems.

3.3 Experimental procedure

Participants were randomly assigned to one of two groups, the template-only group ($N = 31$) and the template-plus group ($N = 27$). The two groups received the same design problems, but different sets of aids for concept generation. The template-only group received the causal relation template (Figure 1) and an example problem illustrating how the template could be used to develop an analogous solution. The template-plus group received the causal relation template, one-to-one mapping instructions (Figure 3) and an example problem illustrating how the causal relation template and one-to-one mapping instructions could be used to develop an analogous solution.

Table 1 Design problems and descriptions of biological phenomena used in Experiment 1

Recycling problem: One system used for curbside recycling is 'mixed waste collection,' where all recyclates are collected mixed and the material is then sorted at a sorting facility. One difficult sorting task is separating paper and plastic, which is usually done by hand. Develop concepts that will enable removing paper or plastic from the mixed collection. **Description of a biological phenomenon**: 'Mucus in the nose traps airborne microorganisms, and most of those that get past this filter end up trapped in mucus deeper in the respiratory tract. Mucus and trapped pathogens are removed by rhythmic motion of cilia in the respiratory passageway up toward the nose and mouth.'
LIDAR protection problem:
Lunar dust poses significant problems for space equipment and astronauts during operations on the Moon. Dust particles are very abrasive and tend to stick to each other and other objects because of their rough surfaces. One essential device that must be protected from lunar dust is the LIDAR, an optical device involving a laser and a lens that must be enclosed and protected while not in use. In past lunar operations, dust particles accumulated on the cover joints and lens during and after opening/closing of the lens cover. Develop concepts that effectively achieve protection from lunar dust. Consider also the environment of the Moon, i.e., a low gravitational force, low atmospheric pressure, extreme low and high temperatures, etc. **Description of a biological phenomenon**: 'Lysozyme is an enzyme that protects the animals that produce it by destroying invading bacteria. To destroy the bacteria, it cleaves certain polysaccharide chains in their cell walls.'

Participants were given 30 min for each problem, which included the time to read the problem, follow instructions specific to their experimental condition, and develop solutions. While many design experiments allow 45–60 min per problem (Jansson & Smith, 1991; Linsey et al., 2010; Perttula & Liikkanen, 2006; Tseng et al., 2008), based on our previous experiments, we found 30 min to be adequate for assessing analogical transfer.

3.4 Evaluation of concepts

We used categorical coding to evaluate whether concepts were analogous to the biological phenomena provided. First, we determined the frequency of participant concepts that are highly analogous to the given biological phenomena. We also determined the frequency of non-analogous concepts that were based on either, possibly random association with specific features of biological phenomena, or no clear relation with the biological phenomena. Other studies have used categorical coding as a means to examine fixation effects (Chrysikou & Weisberg, 2005; Jansson & Smith, 1991; Linsey et al., 2010; Perttula & Liikkanen, 2006; Purcell & Gero, 1996; Tseng et al., 2008).

After reviewing all participant concepts, the lead author formed concept categories, shown in Tables 2 and 3. A single concept could consist of multiple ideas inspired from the biological phenomenon; therefore, a single concept could be classified under multiple categories. Table 4 shows how one particular participant's concepts were classified under these categories.

The lead author first classified all the concepts under one or more categories. A second independent rater then classified 30% of the concepts. The two raters agreed on 93% of the category assignments. Perttula and Liikkanen (2006) used a similar approach with an inter-rater agreement of 91% for their category coding.

Table 2 Concept categories identified for the recycling problem

Analogous concepts
Utilize substance that only reacts to either paper or plastic
Partially analogous concepts
Use rhythmic motion, vibration, shaking to separate
Non-analogous concepts (superficial similarity)
Place recyclates in duct, tunnel, or orifice
Use sticks or other stick-like devices
Use sticky substance
Non-analogous concepts (unclear relation)
Use centrifugal force to separate by weight
Use buoyancy to separate by density
Blow/suck air to separate by weight/drag

Table 3 Concept categories identified for the LIDAR protection problem

Analogous concepts	
	Destroy/burn/dissolve/negate dust particles
Non-analogous concepts (based on destroying LIDAR)	
	Use a sacrificial part that attracts dust
Non-analogous concepts (unclear relation)	
	Repel dust particles with charges/field/air
	Wipe/clean/sweep dust off LIDAR
	Cover LIDAR with filter/case/screens
	Use vacuum/suction

3.5 *Evaluation of correct template use*

We also investigated whether participants used the causal relation template correctly. Figure 4 shows the limited number of correct template completions for the biological phenomena of both design problems. Because determining whether the template was completed correctly is much more objective, it involved neither a second evaluator nor inter-rater agreement.

3.6 *Results and discussion*

We examined the template use and types of concept categories by individual participants to give us insight into participant behavior. Other design researchers also assess ratings per participant to observe intervention effects on the outcome of a design process (Linsey et al., 2010; Lopez et al., 2011; Perttula & Liikkanen, 2006; Tseng et al., 2008).

3.6.1 *Correct template use*

We first determined the percentage of participates who used the causal relation templates correctly. For the recycling problem, 52% (16/31) of the template-only group vs. 56% (15/27) of the template-plus group used the template correctly. For the LIDAR protection problem, 68% (21/31) of the template-only group vs. 78% (21/27) of the template-plus group used the template correctly.

Table 4 Example of participant concepts classified under concept categories

Participant concept	*Concept category*
Put mixture in water. The paper would break down and could be pushed through a filter, with plastic trapped and removed	- Utilize substance that only reacts to either paper or plastic
Place mixture on a conveyor belt with vibrating flaps that will catch only lightweight paper	- Use rhythmic motion, vibration, shaking to separate - Use sticks or other stick-like devices
Drop mixture through a tube while blowing air upward. Heavier plastic will fall first	- Place recyclates in duct, tunnel, or orifice - Blow/suck air to separate by weight/drag

RECYCLING PROBLEM:

Subject	Enabling Function	Object B		Desired Function	Object A
Mucus	**traps**	**microorganisms (or pathogens)**	to	**remove**	**microorganisms (or pathogens)**

OR

Subject	Enabling Function	Object B		Desired Function	Object A
Cilia	**moves rhythmically**	**x**	to	**remove**	**microorganisms (or pathogens)**

LIDAR PROTECTION PROBLEM:

Subject	Enabling Function	Object B		Desired Function	Object A
Lysozyme (or Enzyme)	**destroys**	**bacteria**	to	**protect**	**animals**

OR

Subject	Enabling Function	Object B		Desired Function	Object A
Lysozyme (or Enzyme)	**cleaves**	**polysaccharide chains**	to	**destroy (protect)**	**bacteria (animals)**

Figure 4 Cases of correct template use for each design problem

Figures 5 and 6 show the frequency of errors made on each template element. For the recycling problem, most errors occurred in identifying the enabling function and its associated object. These errors may be due to the complexity of the text describing the corresponding biological phenomenon. This phenomenon involved two independent actions, 'trap' and 'move rhythmically' (we considered either as correct), which enable the desired function of 'removing.' In addition, the enabling function of 'moving' was expressed in the noun form 'motion,' possibly causing some participants to overlook it as a functional word. For the LIDAR protection problem, most participants

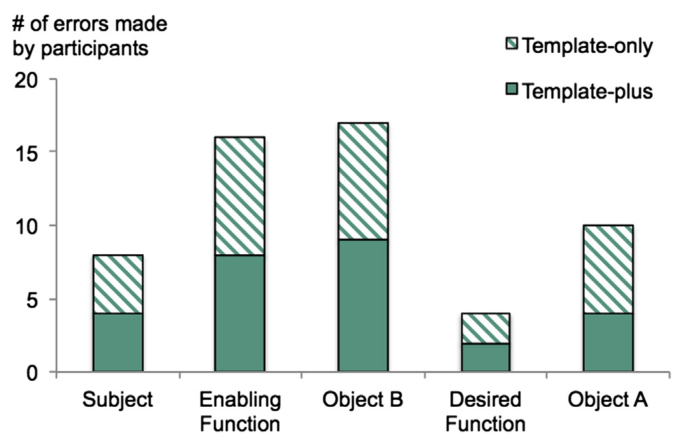

Figure 5 Distribution of errors using causal relation template (recycling problem)

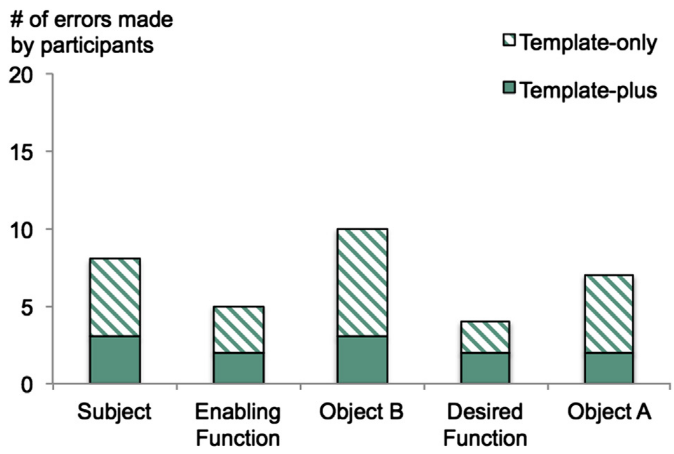

Figure 6 Distribution of errors using causal relation template (LIDAR protection problem)

were able to identify 'destroying' or 'cleaving' as the enabling function of the biological phenomenon. However, some participants identified the associated object incorrectly, most of whom also identified 'cleaving' as the enabling function.

Overall, a considerable number of participants had trouble correctly completing the entire causal relation template, perhaps because they were not trained on template use prior to the experiment. A few errors could be attributed to participants not knowing the difference between a subject and an object in a sentence.

3.6.2 Effect of correct template use on developing analogous concepts

We examined the relationship between correct use of the causal relation template and whether concepts were analogous to the given biological phenomena. Figure 7 shows the relationship between two variables: 1) whether the template was used correctly or incorrectly and 2) whether participants generated an analogous concept or not. The results show that participants were more likely to generate analogous concepts if they used the template correctly, and they were more likely to generate non-analogous concepts if they used the template incorrectly. The effect of correct template use was statistically significant for both experimental groups and both design problems ($p < .05$ for all four cases; Fisher's exact test). The results support our belief that correctly identifying causally related functions from descriptions of biological phenomena supports the detection and application of analogies in design.

3.6.3 Effect of one-to-one mapping instructions on reducing non-analogous association

Comparing the frequency of analogous and non-analogous concepts between groups, the template-only group developed more non-analogous concepts than the template-plus group that received one-to-one mapping instructions.

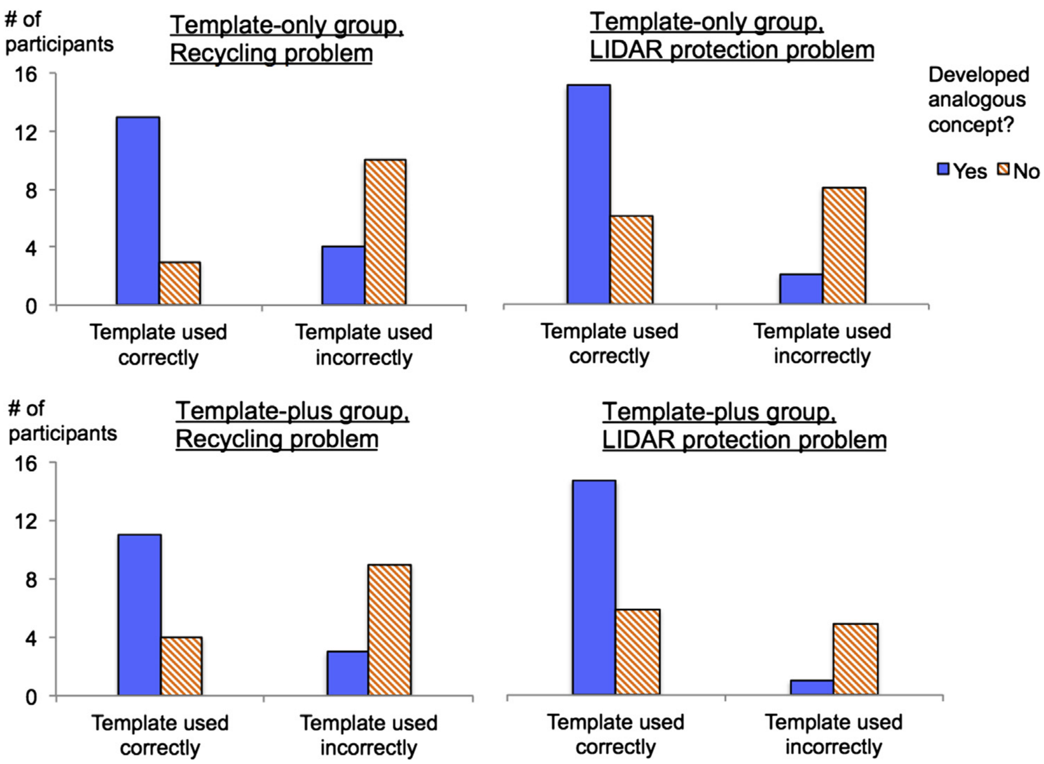

Figure 7 Effects of correct/incorrect template use on development of analogous concepts

For the recycling problem, Figure 8 shows that the template-only group had proportionally more participants who generated concepts based on superficial similarities than the template-plus group (11/31 template-only vs. 5/27 template-plus; $p = .24$; Fisher's exact text). Such concepts featured ducts, cylindrical arms, stickiness, etc. We suspect that these features were based on entities mentioned in the description of the biological phenomenon, e.g., 'respiratory passageway,' 'cilia,' and 'mucus.'

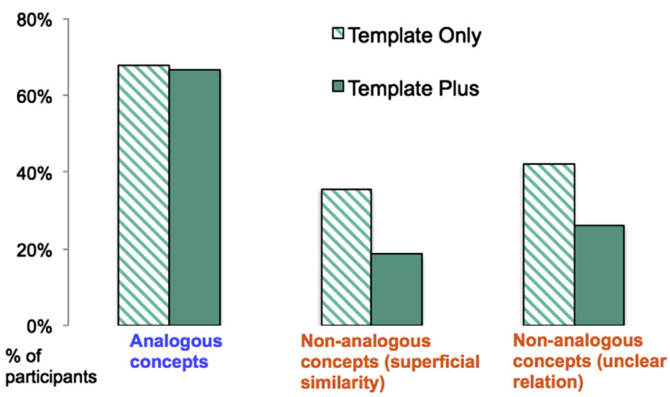

Figure 8 Percentage of participants who generated ideas in concept categories (Recycling problem, Experiment 1)

In addition, proportionally more participants from the template-only group generated concepts based on no apparent relation with the biological phenomenon (13/31 template-only vs. 7/27 template-plus; $p = .27$; Fisher's exact text), e.g., utilize weight/size difference, such as centrifugal force, buoyancy, and air-drag.

Figure 9 shows that for the LIDAR protection problem, the template-only participants were more likely to develop concepts that use sacrificial features on the LIDAR to attract dust away from critical components than the template-plus group (12/31 template-only vs. 3/27 template-plus; $p < .05$; Fisher's exact text). Some template-only participants may have recognized the function of 'destroying' as highly relevant, but incorrectly mapped corresponding entities between the biological phenomenon and the design problem. While likely practical, concepts based on sacrificial features involve intentionally destroying a part of the LIDAR, whereas analogous solutions based on correct one-to-one mapping would involve destroying dust particles.

3.6.4 Effect of one-to-one mapping instructions on the average number of solutions

The one-to-one mapping instructions had a moderate effect on the average number of concepts generated by each participant. For both problems, the template-only participants generated more concepts than the template-plus participants (Recycling problem: $M = 1.97$ vs. 1.59, respectively, $t(56) = 1.77$, $p = .082$; LIDAR protection problem: $M = 2.52$ vs. 2.00, respectively, $t(56) = 1.38$, $p = .17$). However, the average number of analogous concepts between the template-only and template-plus groups did not vary much (Recycling problem: $M = 0.90$ vs. 0.91, respectively, $t(56) = 0.0439$, $p = .97$; LIDAR protection problem: $M = 0.83$ vs. 1.00, respectively, $t(56) = 0.567$, $p = .57$). These results suggest that although the one-to-one mapping requested of the template-plus group reduced the quantity of concepts generated, this group generated a higher proportion of analogous concepts than the template-only group.

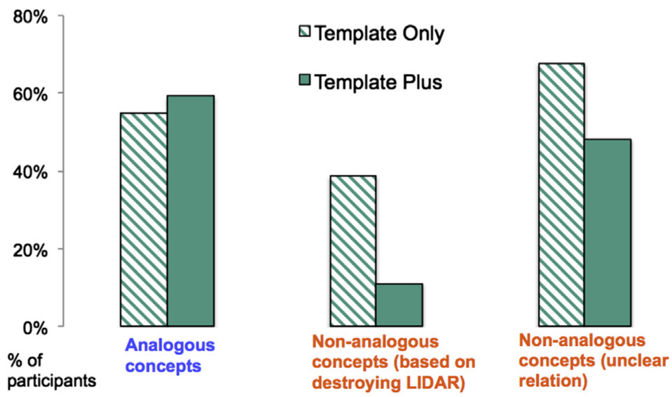

Figure 9 Percentage of participants who generated ideas in concept categories (LIDAR protection problem, Experiment 1)

3.6.5 Summary of Experiment 1

When used correctly by novice designers, causal relation templates increased the proportion of solutions that are analogous to the biological phenomena provided. One-to-one mapping instructions further reduced the proportion of non-analogous concepts developed by novice designers.

4 Alternative method to guide analogical reasoning: problem-independent scenario mapping

While the causal relation template and one-to-one mapping instructions were helpful, the specific format used for this study (Figure 3) may not be applicable to all possible analogies. We therefore wanted to explore a more general method that supports designers in abstracting analogies.

Gentner, Anggoro, and Klibanoff (2011) observed that children are more likely to learn relational concepts, e.g., analogies, if multiple examples of the same relational concept were provided. Gadwal and Linsey (2011) reported that presenting multiple analogs based on the same high-level principle helped designers identify that principle. Multiple examples of the same analogy may not share superficial similarities and therefore help designers focus on the common structural similarity at an abstract level.

Providing multiple examples of the same analogy however, could be difficult in practice, as someone or something must prepare such examples relevant to each design problem. Instead, we decided to ask designers to map a source analog to multiple analogous scenarios from their prior knowledge without considering the given problem. In this process we call 'problem-independent scenario mapping,' designers are encouraged to think about different forms of the relevant analogy and use them as stimulus in concept generation. We hypothesized that this process would have the same positive effect as being presented with multiple examples of the same analogy on increasing use of the high-level strategy. Experiment 2 investigates this hypothesis.

5 Experiment 2: the effect of problem-independent scenario mapping on analogical reasoning

For this experiment, we wanted to investigate whether mapping a source analog to multiple problem-independent scenarios would help designers to subsequently develop more analogous and fewer non-analogous concepts.

5.1 Participants

Fifty-six fourth-year engineering students were recruited from the same course as for Experiment 1, but in the subsequent year. Results from four participants were discarded due to the incomplete concepts recorded, reducing the sample size to 52.

5.2 Design problems and biological phenomena

The design problems and biological phenomena given to each group were the same as in Experiment 1, shown in Table 1. In Experiment 2, since we wanted to investigate the effect of making multiple mappings on the *transfer* of analogies, participants were provided with causal relations already identified using the template, shown in Figure 10. The one-to-one mapping instructions were not provided in Experiment 2.

5.3 Experimental procedure

Participants were randomly assigned to one of two groups, control ($N = 26$) and scenario mapping ($N = 26$). Both groups received the same design problems, biological phenomena, and identified causal relations. The scenario-mapping group was asked to first identify on a worksheet, five scenarios that are analogous to the given causal relation, without considering the problem already provided. For example, based on the causal relation 'destroy to protect,' participants generated scenarios such as 'apply heat to destroy microbes on surgical instruments and protect patients.' They were then asked to use their identified scenarios to generate at least five concepts for the given design problem. The control group, on the other hand, was simply instructed to generate at least five concepts for the design problem using the given causal relation. Both groups were given 30 min for their tasks.

Participants were asked to generate at least five concepts for two reasons. In Experiment 1, we suspected that some participants, who initially generated one or two analogous concepts, may have been satisfied with their solutions and stopped generating additional concepts. In this study, we wanted to observe whether participants could continue to generate multiple analogous concepts, or start relying on non-analogous association. In addition, this requirement led to similar average numbers of concepts between the control and scenario-mapping groups (Recycling problem: $M = 4.85$ vs. 4.55, respectively, $t(50) = 1.45$, $p = .15$; LIDAR protection problem: $M = 4.84$ vs. 4.67, respectively, $t(50) = 1.02$, $p = .31$), allowing us to better compare the average number of analogous concepts generated between the conditions.

Recycling problem:
Mucus **traps** airborne microorganisms to **remove** them from air
(*Enabling Function*) (*Desired Function*)

Lidar protection problem:
Lysozyme **destroys** invading bacteria to **protect** animals
(*Enabling Function*) (*Desired Function*)

Figure 10 Causal relations identified for participants

5.4 Concept evaluation

The same concept evaluation scheme and a second independent rater were used as in Experiment 1. The inter-rater agreement for Experiment 2 data was 88%.

5.5 Results and discussion

5.5.1 Effect of problem-independent scenario mapping on developing analogous concepts

For the recycling problem, the scenario-mapping group generated a slightly greater number of analogous concepts than the control group ($M = 2.16$ vs. 1.62, respectively, $t(50) = 1.57$, $p = .12$). For the LIDAR protection problem, the scenario-mapping group generated more analogous concepts than the control group and this difference was statistically significant ($M = 2.79$ vs. 1.92, respectively, $t(50) = 3.01$, $p < .01$). These results suggest the benefit of identifying multiple problem-independent scenarios for developing analogous concepts.

5.5.2 Effect of problem-independent scenario mapping on reducing non-analogous association

The effect of problem-independent scenario mapping is more apparent when we consider the percentage of participants who generated non-analogous concepts. As in Experiment 1, there is strong evidence that participants used non-analogous association with specific biological features to develop many of their concepts.

Shown in Figure 11 for the recycling problem, participants in the scenario-mapping group were less likely to generate concepts that featured superficial characteristics of the biological phenomenon than the control group (8/26 scenario mapping vs. 19/26 control; $p < .01$; Fisher's exact text). In addition, fewer participants in the scenario-mapping group generated concepts

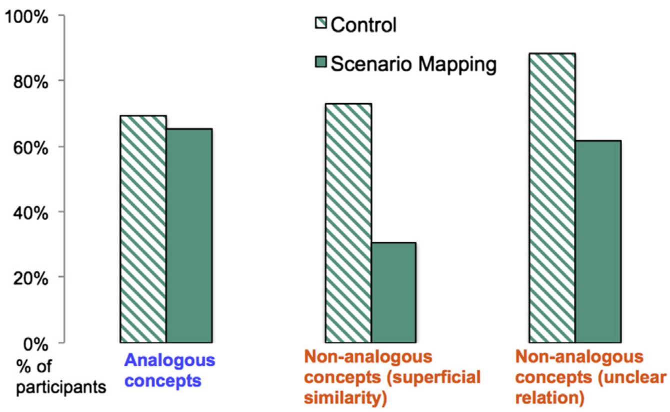

Figure 11 Percentage of participants who generated ideas in concept categories (Recycling problem – Experiment 2)

apparently unrelated to the biological phenomenon than the control group (16/26 scenario mapping vs. 23/26 control; $p = .05$; Fisher's exact text).

Shown in Figure 12 for the LIDAR protection problem, the tendency to develop non-analogous unrelated concepts was significantly reduced in the scenario-mapping group (13/26 scenario mapping vs. 24/26 control; $p < .005$; Fisher's exact text). Such concepts featured conventional solutions of handling dust, e.g., wiping, blowing air, filtering, etc. Also, fewer participants in the scenario-mapping group generated concepts based on using sacrificial features than the control group (10/26 scenario mapping vs. 16/26 control; $p = .17$; Fisher's exact text).

As most participants in the control group were able to develop at least one analogous concept (69% for recycling problem and 85% for LIDAR protection problem), non-analogous concepts were likely generated either before or after developing a few analogous concepts. Combined with the above observations, this suggests that the control group participants were more likely to deviate from using the suggested analogy and may have reverted to conventional domain knowledge. This finding is consistent with Cheong et al.'s (2012) observation that readily available associations with conventional domain knowledge may present a significant obstacle to analogical reasoning.

For the scenario-mapping group, we believe that making multiple mappings from the source analog encouraged participants to abstract and focus on the structural similarity between the biological phenomenon and design problem. This process may have primed participants to a clear 'mental set' (Jansson & Smith, 1991) of which strategy should be used to solve the problem.

6 General discussion and conclusion

This section discusses our findings in the context of other research in biomimetic design.

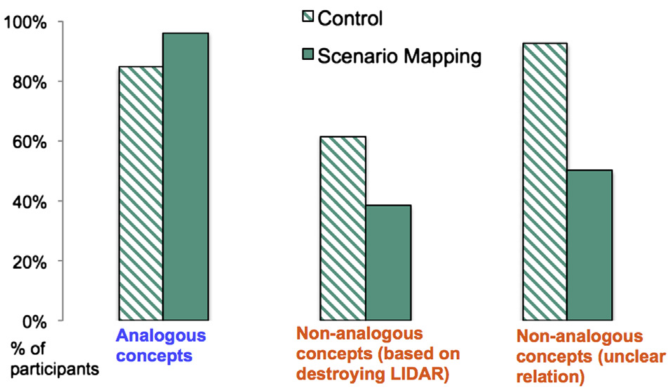

Figure 12 Percentage of participants who generated ideas in concept categories (LIDAR protection problem – Experiment 2)

6.1 Detection of analogies

Experiment 1 revealed that many participants failed to use the causal relation template correctly to detect the relevant analogy. Previous research by Mak and Shu (2004) supports that detecting analogies from descriptions of biological phenomena is challenging, and only after explicitly identifying the analogous strategy were novice designers able to develop analogous concepts (Mak & Shu, 2008).

While correct use of the template appeared helpful, it may be impractical for designers to complete the template for every potential analogy. Therefore, manual use of the template may serve as a training tool for analogical reasoning, but the automatic identification of relevant analogies may be more valuable to designers. Cheong and Shu (2012) have applied statistical parsing to automatically identify in text descriptions of biological phenomena, enabling functions, subjects, and objects of a functional keyword, which as shown in Figure 13, essentially constitute the elements of the causal relation template. Experiment 2 supports that once a relevant causal relation is explicitly identified for designers, they are likely to be able to develop analogous solutions (65–69% for the recycling problem; 85–96% for the LIDAR protection problem).

6.2 Transfer of analogies

In terms of applying the detected strategy, our results suggest that non-analogous association could be reduced by: 1) one-to-one mapping instructions and 2) mapping the strategy to other problem-independent scenarios.

6.2.1 One-to-one mapping instructions

The one-to-one mapping instructions guided participants to construct design concepts in the same functional structure as the causal relation identified (Figure 3), which may have helped participants to accurately map

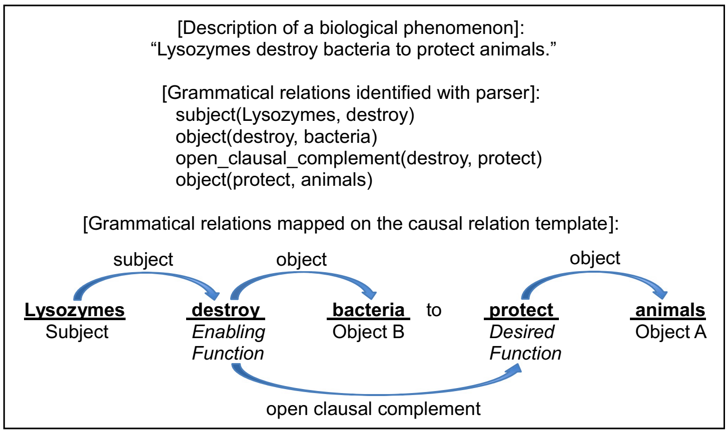

Figure 13 Grammatical relations identified by an automatic parser completes the causal relation template

corresponding entities. This supports the value in facilitating correct analogical transfer of formal representations, e.g., by Chakrabarti et al. (2005), Goel et al. (2009), and Nagel et al. (2010), that express biological systems and engineering solutions in a common representation language. However, modeling biological systems in detail can be time-consuming; Goel et al. (2011) reported that 40−100 h were required to complete an SBF model of a complex biological system. Therefore, during initial exploration of biological analogies, we believe that tools based on linguistic structures, e.g., our causal relation template and one-to-one mapping instructions, can help designers quickly evaluate the relevance of biological phenomena.

6.2.2 Problem-independent scenario mapping

The scenario-mapping process encourages designers to consider multiple forms of the suggested analogous strategy, which may facilitate the use of that strategy in concept generation. This process could therefore have benefits similar to presenting multiple examples of the same analogy to help designers understand the analogy (Gadwal & Linsey, 2011; Gentner et al., 2011).

In practice, designers could first perform the problem-independent mapping process to consider underlying principles in biological phenomena, later transferring the principles to the problem domain. Alternatively, designers could be provided with a number of structurally similar biological phenomena to emphasize the common underlying principle. Formal representations of biological systems would be useful in identifying structural similarities. For biological information described in natural-language text, common semantic relations such as causally related functions (Cheong et al., 2012) could be used to categorize relevant information. The categorization could allow designers to observe multiple biological phenomena that share common underlying principles.

6.3 Supporting analogical transfer over non-analogous solutions

We focus heavily on supporting analogical transfer and avoiding non-analogous association because we believe this will encourage the consideration of biological analogies beyond those that are superficially related or otherwise obvious. Without skills in analogical reasoning, many potentially useful, nonobvious or unfamiliar biological phenomena could be overlooked.

We recognize that solutions based on non-analogous association can be both novel and useful. In fact, the concepts based on sacrificial features for the LIDAR protection problem could be quite practical. One could also argue that making multiple mappings in Experiment 2 reduced the variety of solutions, including non-analogous solutions. However, in this work, we aimed to support designers in overcoming obstacles in developing analogous solutions, such that they can better mimic strategies in addition to forms from biology.

6.4 Limitations of the current research

Evaluating the product of cognitive processes is not trivial. For design research in general, it is difficult to use one standardized evaluation measure to study one of many cognitive processes involved in concept generation. We used categorical coding because we were interested in supporting analogous over non-analogous concepts. We found categorical coding suitable and reliable for this study, but we still had to infer whether certain categories of concepts were based on analogical reasoning or non-analogous association. In addition, it is difficult to fully understand why many participants developed concepts that did not seem to be at all related to the given biological phenomena. To overcome such intrinsic limitations of pen-and-paper studies, observational studies may yield additional insights, but challenges include collecting data, performing quantitative analyses, and validating observations. Different approaches have unique merits and should be used as appropriate for future studies of biomimetic design.

7 Conclusions

Detecting analogies and using them to solve problems are not trivial tasks. We have repeatedly observed that with descriptions of biological phenomena, designers tend to rely on non-analogous associations over analogical reasoning. With such complex design stimuli, performing analogical reasoning is probably not the 'path of least resistance' (Ward, 1994) available to designers.

Novice designers would benefit from extensive training and practice to detect and apply biological analogies. Nelson, Wilson, and Yen (2009) found that students who took a course on biologically inspired design and practiced analogical reasoning were able to develop more novel and diverse design ideas than those who did not take the course. We further believe that developing skills in analogical reasoning would enable designers to detect relevant strategies in phenomena they may otherwise overlook, thereby supporting biomimetic innovation beyond using commonly applied biological analogies. Our work suggests that specific mapping instructions and problem-independent scenario mapping could enable designers to better focus on analogical reasoning.

While our research focused on using text descriptions of biological phenomena as the source of inspiration, other representations such as pictures, diagrams, or formal models for biomimetic design should also be studied (Helms et al., 2010; Sarkar & Chakrabarti, 2008). However, much of the biological information that designers can readily access or come across in practice is likely to be at least in natural-language format. Therefore, we consider natural language to be the foundation upon which other representations of complex biological analogies are built, and strongly believe in the value of both manually and automatically understanding and applying text descriptions of biological phenomena to design solutions.

Acknowledgments

The authors gratefully acknowledge the financial support of the Natural Science and Engineering Research Council of Canada, the contribution of experiment participants, and the helpful comments of anonymous reviewers.

Notes

1. Here, by 'structure' Gentner means relational structure of a concept, not some physical form. This paper also uses 'structure' in this sense.

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