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EXTRACTION AND TRANSFER OF BIOLOGICAL ANALOGIES FOR CREATIVE CONCEPT GENERATION

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ABSTRACT

Biomimetic design, which borrows ideas from nature to solve engineering problems, has been identified as a promising method of concept generation. However, there are still many challenges. Previous research has revealed that novice designers have difficulties in extracting the analogical strategy present in biological phenomena and mapping the strategy even if the strategy is provided. This research, therefore, attempts to develop tools that could assist novice designers to execute effective biomimetic design and ultimately generate creative concepts.

In particular, we investigated the use of tools developed by the authors: 1) a *causal relation template* that helps retrieve relevant strategies from biological descriptions and 2) *instructional mapping rules* that aid structural mapping of the strategies to design concepts and abstraction of the enabling functions of the strategies. We found that the participants who used both tools generated concepts with significant correlation between the correctness of analogical transfer and creativity of the concepts. This effect was not observed for the participants who only used the first tool, mainly because of the participants' inability to explore enabling solutions for the applied biological strategy and generate concepts that are wholly developed. To encourage generation of creative ideas in biomimetic design, the tools must be devised to facilitate abstraction of biological strategies, enable effective mapping of strategies from biology to engineering, and discourage design fixation.

1. INTRODUCTION

Many researchers in the past have noted that analogical reasoning plays a key role in creative design (Goel 1997, Gentner et al. 2001, Brown 2008). Biomimetic design involves analogical reasoning, as it borrows ideas from nature to solve engineering problems. Biology has been well recognized as a promising source of analogies (Gordon 1961, Vincent and Mann 2002, Bar-Cohen 2006, Wilson and Rosen 2007) and there are now numerous successful applications of biomimetic design in the literature. Furthermore, an almost infinite amount of potential analogies in biology is yet to be explored, as biological knowledge is quickly expanding (Rebholz-Schuhmann et al. 2005).

Despite its promising prospect and successful case studies in the past (Hacco and Shu 2002, Shu et al. 2006, Davidson et al. 2009), there are obstacles that hinder designers from effectively executing biomimetic design. First, there are issues associated with interdomain information retrieval and finding biological information relevant to design problems (Chiu and Shu 2007, Ke et al. 2009). Other difficulties are also present when designers attempt to make analogical transfer from the relevant biological information to design solutions. This paper focuses on addressing and solving the latter difficulties.

Our previous research at the Biomimetic for Innovation and Design Laboratory (BIDLAB) at the University of Toronto identified that novice designers tend to fixate on irrelevant aspects of biological information; have difficulties in extracting analogical strategies present in biological information; and need support for structural mapping between biological information and target solutions (Mak and Shu 2004, Mak and Shu 2008). In short, novice designers often have difficulty in performing analogical transfer from biological to engineering domains.

Cheong and Shu (2009) have observed that one key reason for novice designers failing to make correct analogical transfer is their inability to recognize relevant causal relations in biological information. A causal relation is when one action causes another action; e.g., in a phrase "X chases Y, and Y flees," the verbs "chase" and "flee" are said to be in a causal relation. Biological strategies usually contain a causal relation where an enabling function allows or enables a desired function. While recognizing relevant causal relations is essential for analogical strategy retrieval, we also believe that abstraction of the retrieved strategy is important as well for effective mapping to the target domain. Goel (1997) pointed out that the use of generic abstractions, which express the structure of relationships between generic types of objects and processes of source analogs, is required for effective analogical transfer. Linsey et al. (2007) found that more general representation of analogous products resulted in a greater chance of being used as a source analogy for a novel design solution later. Because biological information is usually written in domain-specific language, designers must perform a complex analogical transfer process. First, they must recognize the domain-specific strategy in biology, and then they must abstract and transfer this knowledge in order to generate creative ideas.

We aim to further explore the above challenges in this paper. First, we study the effect of aiding designers with a tool that could facilitate causal relation recognition for analogical strategy retrieval. Second, we investigate a means to ensure structural mapping and abstraction of the recognized strategy to design solutions. Ultimately, we attempt to examine how the use of these tools could lead to generation of creative concepts.

2. BACKGROUND

In this section, we discuss interdomain analogical transfer and how it evokes creative design. We then explain analogical reasoning in biomimetic design, which involves interdomain analogical transfer, and discuss difficulties associated with it.

2.1. Interdomain analogical transfer and creativity

Analogy involves transferring of information or ideas from one source to another. Researchers have found that interdomain sources stimulated and inspired designers more than intradomain sources (Bonnardel 2000, Hon and Zeiner 2004). Benami and Jin (2002) found that analogies from different domains stimulated more novel ideas. Tseng et al. (2008) observed that distantly related stimuli are particularly effective when designers had set open goals of a design problem.

Interdomain analogical transfer tends to promote creative ideas because it involves transfer of a deeper level of relations. For example, it requires designers to map relational patterns, e.g., functional similarities, rather than to simply map perceptual similarities (Holoyak and Thagard 1996). In many cases, a higher-order relation, i.e., a relation between relations such as a causal relation, is mapped from source to target. Such analogies with rich, inter-constraining information have been found to be more useful in science and education (Clement and Gentner, 1991).

On the other hand, designers often find it difficult to utilize interdomain analogies because the source analog is seemingly dissimilar to the target problem. Bonnardel et al. (2005) found that novice designers were evoked more by intradomain sources than interdomain sources, while expert designers found both sources to be useful. Linsey et al. (2007) identified that the influence of domain knowledge was apparent in the novel design of a kayak based on an analogy to an airplane. They pointed out the needs for a design methodology that can highlight areas where domain knowledge is lacking and facilitate the recognition of the underlying principles of interdomain sources.

2.2. Analogical reasoning in biomimetic design

Few literature sources have discussed analogical reasoning specifically in biomimetic design from a cognitive perspective. Vattam et al. (2008) observed that a biomimetic design process involves a complex interplay between analogy retrieval and problem decomposition. Helms et al. (2009) identified one error that occurs regularly in a biomimetic design process is focusing on the structure of biological solutions. Their findings support the notion that mapping relational patterns in interdomain analogical transfer is complex and can be difficult for designers.

Another difficulty in biomimetic design is the designer's lack of familiarity in the biological domain. Bar-Cohen (2006) suggested that examining biology from an engineering point of view would help utilizing biological analogies. Tinsley et al. (2007) attempted to solve this issue by using the Functional Basis to functionally model biological systems to facilitate biomimetic design. As both researchers discussed, developing a systematic tool that facilitates biomimetic design independent of the domain knowledge would be useful.

Mak and Shu (2004) reported a number of issues present when novice designers use biological information as stimulus to solve design problems. They initially found that novice designers tended to fixate on certain irrelevant aspects of biological descriptions or specific solution modes from previous problems. Both tendencies led the designers to use undesired strategies to develop concepts. In order to overcome these tendencies, Mak and Shu (2008) provided novice designers with expected strategies from the biological stimulus and asked them to map corresponding entities from biology to a design solution. Although a higher percentage of designers were able to generate relevant concepts, the authors still found that novice designers tend to map entities incorrectly, which again led to unexpected concepts. We suspect that incorrect mappings occurred because participants were focused on recognition of similar entities, rather than similar relations between biology and design problems. Guiding novice designers to extract and transfer functional relations between the two domains would be more effective than asking them to match object or entities.

Cheong and Shu (2009) observed that the presence of causal relations, i.e., one action enabling or causing another action, in biological descriptions plays a key role in designers implementing correct analogies. They found that novice designers have trouble retrieving the correct analogy from a biological description if the description is too complex or written in the passive voice, such that the relevant causal relation cannot be easily recognized. Recognition and utilization of causal descriptions in biological phenomena are also stressed in compiling biomimetic database for idea generation (Chakrabarti et al. 2004).

Our goal in this paper, therefore, is to create systematic tools that help retrieve relevant causal relations from biology and appropriately transfer that knowledge to solutions. In addition, we implemented a structure-directed approach, rather than a purpose-directed approach to facilitate analogical transfer (Kedar-Cabelli, 1985). That is, we want designers to focus on finding relational similarities between biology and engineering problems. We believe this will encourage designers in analogical mapping, an important aspect of biomimetic design.

2.3. Creativity measurement

Various models of creative artifacts, e.g., designs, ideas, and concepts, etc., often include characteristics of novelty and appropriateness (Amabile 1983). While novelty refers to how the idea is original and surprising, appropriateness could be regarded as whether the idea is logical, useful, and valuable (Besemer and Treffinger 1981). This indicates that creative ideas must not just be novel, but also need to solve problems (Ullman 2003). MacKinnon (1975), in addition to these two dimensions, suggested a third criterion: "true creativeness involves a sustaining of the original insight, an evaluation and elaboration of it, a developing of it to the full." Creative Product Analysis Matrix (CPAM) developed by Bessemer (1998) is based on three similar parameters that are further broken down into more detailed measures: Novelty (original, surprising), Resolution (logical, understandable, useful, valuable), and Elaboration & Synthesis (well-crafted, elegant, organic). Chiu (2010) developed a concept rating methodology based on these ideas, by using three component measures of creativity: Novelty, Usefulness, and Cohesiveness. We implemented Chiu's metrics for this research, because it is deemed to be most appropriate for rating a large number of textual concepts. The definitions of the three component measures and how they are scored are provided in the Methods section.

3. METHODS

The focus of the current work is to facilitate the use of biological descriptions as stimuli for biomimetic design. Specifically, we provided designers with a *causal relation template* that can help them to systematically recognize the relevant causal relations as analogical strategies in biological information. We also gave a set of *instructional mapping rules* that guide structural mapping between the recognized strategy and possible design solutions.

Two experimental groups of novice designers were provided with either the first or both of these aids to generate concepts for design problems. We hypothesized that the group who used both aids would generate concepts that are more likely to based on correct analogical transfer. We also hypothesized that correctness of analogical transfer would positively correlate to concept creativity.

3.1. Participants

61 fourth-year engineering students in a mechanical design theory and methodology course at the University of Toronto were asked to solve two design problems. They were given 30 minutes for each problem, which included the time to read the problem, follow the instructions to complete the template and the mapping process, and generate as many concepts as possible. Results from three participants were discarded due to incomplete or improper concepts, reducing the sample size to 58.

3.2. Experimental setup

Participants were randomly divided into two groups, Group A (N=31) and Group B (N=27). Participants in both groups received the same design problems and corresponding biological descriptions as design stimulus, shown below. They received one biological description for each problem. Each participant worked on the problems individually.

Problem 1*: One of different systems used for curbside recycling is "mixed wasted 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 concepts that will enable removing paper or plastic from the mixed collection.*

Design Stimulus:
"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."

Problem 2:
Lunar dust poses significant problems for space equipment and astronauts during operations on the Moon. These dust particles are very abrasive and have a tendency to stick to each other and other objects because of their rough surfaces. One essential device that must be protected from lunar dust is a Lydar. A Lydar is an optical device that produces laser for signaling purposes. It 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. You should also consider the environment of the Moon, i.e.,

a low gravitational force, low atmospheric pressure, extreme low and high temperatures, etc.

Design Stimulus:
"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."

These problems and stimuli were used before in our previous work (Cheong and Shu 2009) where participants were not provided with any aid tools. We used them again for this work in order to observe any unique or surprising results that arise from using the aids that we have provided for this experiment.

We retrieved the descriptions of the design stimuli by using our biomimetic search tool from the corpus, *Life, the Science of Biology*, by Purves et al. (2001), which is a text for an introductory university-level biology course. We used the biologically meaningful keywords corresponding to the functional keywords that best described the desired solutions for each problem as the search query (Cheong and Shu 2009).

Participants in each group were given a different set of aids for concept generation. Group A (N=31) was given the *causal relation template* along with step-by-step instructions on how to complete it. They were also given an example problem with a solution that was developed by using the template.

Group B (N=27) was also given the *causal relation template* along with step-by-step instructions. In addition, they were given the *instructional mapping rules* of how to map each of the subject, two functions, and two objects that are associated in the retrieved causal relation to a possible solution strategy. They were also encouraged to abstract the enabling object and function of the causal relation for a variety of solutions. Similar to Group A, they were given an example problem with a solution that was developed by completing the *causal relation template* and following the *instructional mapping rules*. Figure 1 depicts the difference between the two groups. See Appendix A for the complete experimental materials.

We predicted that Group B would score higher in terms of correct analogical transfer, because the set of *instructional mapping rules* would improve the participants' chance of performing correct structural mapping. We also predicted that increasing the likelihood of making correct analogical transfer would improve the creativity of the concepts generated by Group B.

3.3. Raters and rating system

Two independent raters were recruited to rate the participants' concepts based on correct analogical transfer and creativity. One rater was a senior Ph.D. candidate with engineering research experience in design theory and methodology. Another rater was a senior undergraduate student taking senior level mechanical design courses and completing a design-based undergraduate thesis project.

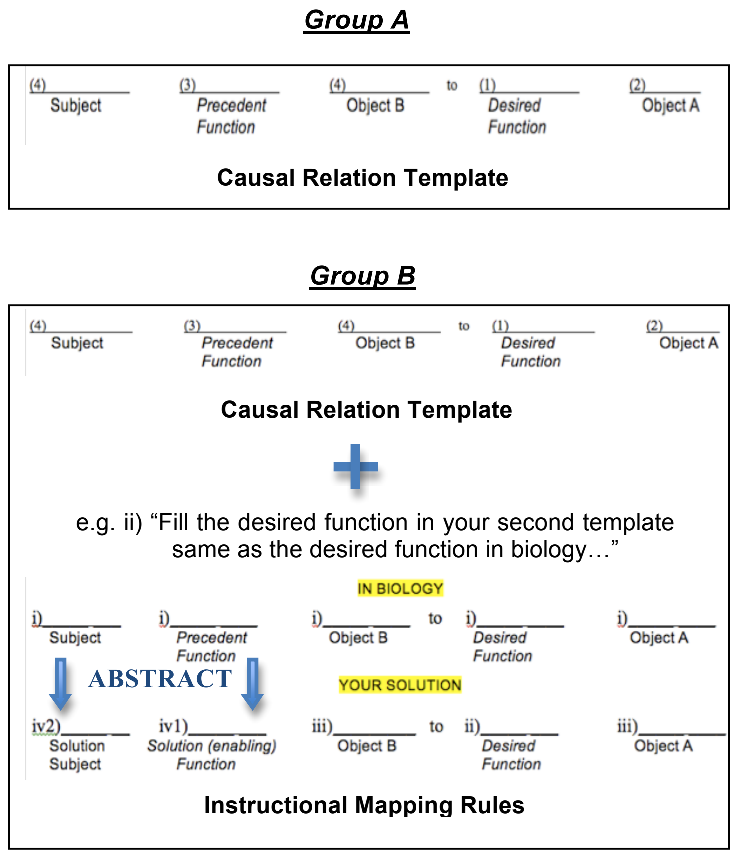


Figure 1: Difference between the two experimental groups. Group B received the *instructional mapping rules* in addition to the *causal relation template* as an aid for structural mapping of a biological strategy to engineering solutions.

In order to measure correct analogical transfer for each concept, the raters were informed of the expected analogy to be used, which was determined by the authors, for each problem. The raters were also given two anchor concepts as examples: 1) one example that properly used the expected analogy and 2) one example that did not use the expected analogy (Appendix B).

There were three component measures for creativity: novelty, usefulness, and cohesiveness. They are defined as the following (Chiu 2010):

Novelty – "Novel concepts are new, original and surprising."

Usefulness – "Useful concepts are valuable, functional, practical and feasible. They solve the problem."

Cohesiveness – "Cohesive concepts appear whole, well developed and are detailed enough to be understandable."

The raters were again provided with anchor concepts associated with a low and high rating for each component measure of creativity. These anchor examples are shown in Appendix B.

Each measure, i.e., correct analogical transfer, novelty, usefulness, and cohesiveness, was rated on an 11-point scale, with 0 being the lowest score and 10 being the highest score. For example, scoring 0 on novelty indicated a not novel concept, while scoring 10 on novelty indicated a very novel concept.

We calculated the inter-rater agreement between the two raters by using the Cohen's kappa for each of the rated measures (Table 1). For correct analogical transfer, the raters showed moderate agreement ($\kappa = 0.52$) according to the scale suggested by Landis and Koch (1977). For novelty, usefulness, and cohesiveness, which are the component measures of creativity, the raters showed fair agreement ($\kappa = 0.312$, $\kappa = 0.352$, and $\kappa = 0.354$, respectively). It should be noted that the scale suggested by Landis and Koch is usually accepted and used for analysis in biometrics, which involves rating more concrete measures. In our case, determining whether concepts are creative or not, is a much more abstract and subjective task. Therefore, although we would have preferred a higher level of agreement, we decided to proceed with analysis using the ratings provided by our raters.

	Correct analogical transfer	Novelty	Useful.	Cohesive.
Cohen's kappa (N = 116)	0.520	0.312	0.352	0.353

Table 1: Cohen's kappa calculated between the two raters for each rated measure. Moderate agreement was observed for "Correct analogical transfer", while fair agreement was observed for creativity component measures.

4. RESULTS AND DISCUSSION

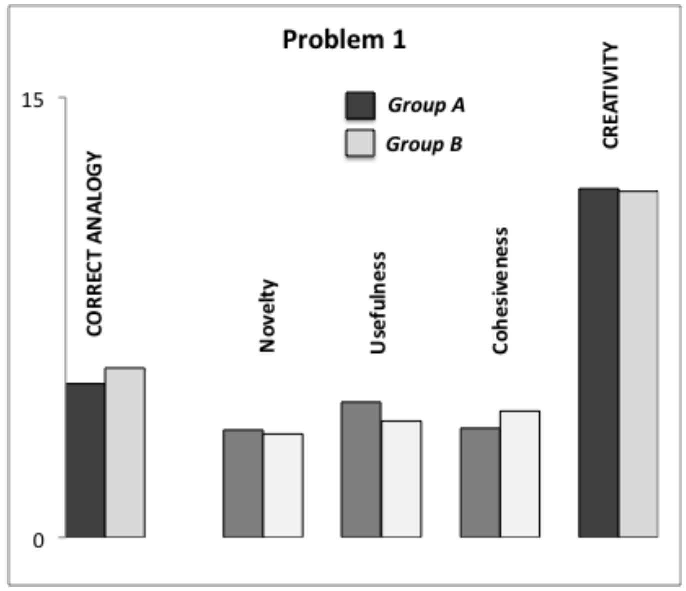
The experimental results were analyzed both quantitatively and qualitatively. First, we performed statistical analyses on the differences of correctness and creativity measures between Groups A and B. We then examined correlations between the correct analogical transfer rating and the creativity measure ratings, i.e., novelty, usefulness, and cohesiveness. In this section, we present the results and discussion of significant effects observed.

4.1. Between-group difference

The mean values for each measure rating and their statistical group differences are presented in Figures 2 and 3. For problem 1, there were no statistically significant differences observed for all ratings between the two groups.

For problem 2, we observed that the correct analogical transfer rating and all the creativity component measures were higher for Group B. The differences of the ratings, however, were not statistically significant. The results therefore suggest that introducing the additional *instructional mapping rules* for structural mapping and abstraction did not seem to improve the concepts for either correct analogical transfer or creativity. In general, we suspect that the recognition of analogical strategies has a larger effect on the correct analogical transfer and concept creativity than the mapping process.

Group Differences of Rating Measures for Problem 1

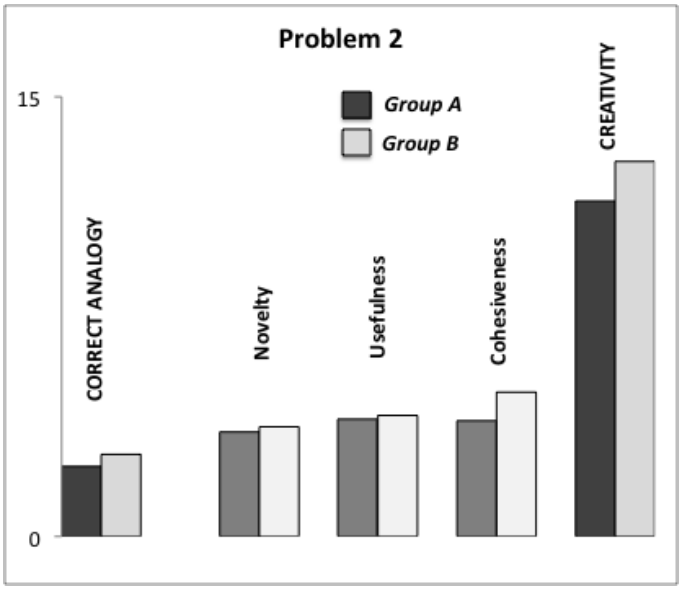


PROBLEM 1	Correct Analogical Transfer (out of 10)	*Novelty (out of 10)*	*Useful. (out of 10)*	*Cohesive. (out of 10)*	Creativity *[N + U + C]* (out of 30)
Group A	5.24	3.66	4.56	3.67	11.89
Group B	5.77	3.53	3.97	4.31	11.80
t(56)	-.639	.282	1.166	-1.381	.069
p(two-tailed)	.525	.779	.249	.173	.945

Figure 2: Average ratings of correctness of analogical transfer (0-10), novelty (0-10), usefulness (0-10), cohesiveness (0-10), and creativity (0-30) for Problem 1. No statistically significant differences between groups were found.

The results might suggest that our *instructional mapping rules* for Group B were not as effective as we hypothesized. One interesting point, however, is that the cohesiveness ratings were noticeably higher for Group B for both the problems. In fact, the p-values for the differences in cohesiveness ratings were lowest among the creativity component measure ratings, indicating that the between-group effect was most significant on the concept cohesiveness. For Problem 2, the difference in the cohesiveness ratings was borderline significant ($t(56)=-1.85$, $p=.07$, $p\sim.05$). Furthermore, when we observed the individual samples more closely, we found an interesting correlation between the correct analogical transfer and creativity that was more statistically significant for Group B than Group A. In the next section, we report on these within-group correlation trends and explain how the between-group effect could have played a role in the difference of creativity ratings.

Group Differences of Rating Measures for Problem 2



PROBLEM 2	Correct Analogical Transfer (out of 10)	*Novelty (out of 10)*	*Useful. (out of 10)*	*Cohesive. (out of 10)*	Creativity *[N + U + C]* (out of 30)
Group A	2.38	3.56	3.95	3.93	11.44
Group B	2.80	3.74	4.13	4.92	12.79
t(56)	-.559	-.308	-.302	-1.847	-.851
p(two-tailed)	.579	.759	.764	.070	.399

Figure 3: Average ratings of correctness of analogical transfer (0-10), novelty (0-10), usefulness (0-10), cohesiveness (0-10), and creativity (0-30) for Problem 2. Although no statistically significant differences between groups were found, Group B generally scored hired on both the correct analogical transfer rating and the creativity measure ratings.

5.2. Within group correlation

As hypothesized, there appears to be a correlation between correctness of analogical transfer and creativity of the solution. Examples of participant concepts that demonstrate this correlation are presented in Figure 4. When we analyzed correlations between the correct analogical transfer rating and the creativity measurements, Group B showed larger and more significant correlations than Group A. Figure 5 shows these results.

For Group B, the ratings of correct analogical transfer had medium or large, statistically significant correlations with all the component measures of creativity: novelty (Problem 1: $r=.52$, $p<.01$; Problem 2: $r=.77$, $p<.001$), usefulness (Problem 1: $r=.54$, $p<.01$; Problem 2: $r=.52$, $p<.01$), and cohesiveness (Problem 1: $r=.42$, $p<.05$; Problem 2: $r=.53$, $p<.01$). For Group A, statistically significant and medium correlations were found only for usefulness in Problem 1 ($r=.45$, $p<.05$) and novelty in Problem 2 ($r=.44$, $p<.05$). These results indicate that the additional *instructional mapping rules* given to Group B had effects on the concepts with correct analogical transfer also scoring high on creativity.

In order to investigate why such effects are present, we looked at participants' concepts that did not have a strong correlation between the correct analogical transfer rating and the creativity rating in Group A. In other words, these participants scored high on the correct analogical transfer rating but low on the creativity ratings. Some examples of such participant's concepts are presented below.

Solution for Problem 1: *Use some substance that only sticks to paper or plastic. Separate utilizing the added substance.*

Solution for Problem 2: *Use something to break the lunar dust apart.*

Interestingly, these concepts adapted the expected strategy from the biological stimulus (Appendix B). However, for both examples, we could observe that the concepts were vague and the level of detail was lacking. Examples of concepts that used the same expected strategy but with more details are shown below.

Solution for Problem 1: *Use water to disintegrate paper. Separate utilizing the disintegrated nature of paper.*

Solution for Problem 2: *Use lasers to incinerate the lunar dust particles, therefore removing their sharp edges.*

In general, we found the former case of vague concepts more from Group A than Group B. Example concepts above from both groups would score high in terms of using correct analogical transfer. Also, novelty scores for both groups would be similar because the concepts are based on the same principles. However, the raters assigned higher ratings of usefulness and cohesiveness for Group B's concepts because the concepts were more wholly developed and cohesive.

We suspect that while the use of the *causal relation template* helped Group A participants to retrieve the appropriate strategy and apply it correctly to solutions, it did not necessarily lead to creative concepts because the solution means were not well specified. In other words, recognizing the analogical strategy alone did not evoke the participants to explore a variety of solution means that could enable the strategy for solution concepts.

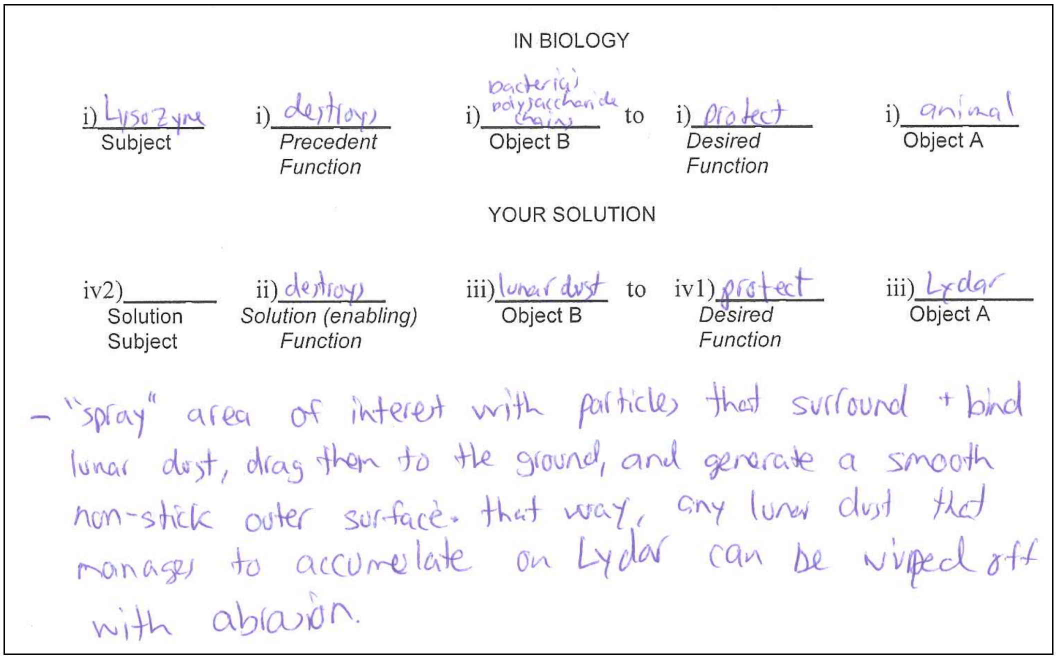


FIGURE 4a: An example of a participant performing correct analogical transfer from a strategy in biology to design solution. The participant in this case was also able to generate a concept that correctly utilized the expected strategy and scored high in creativity ratings.

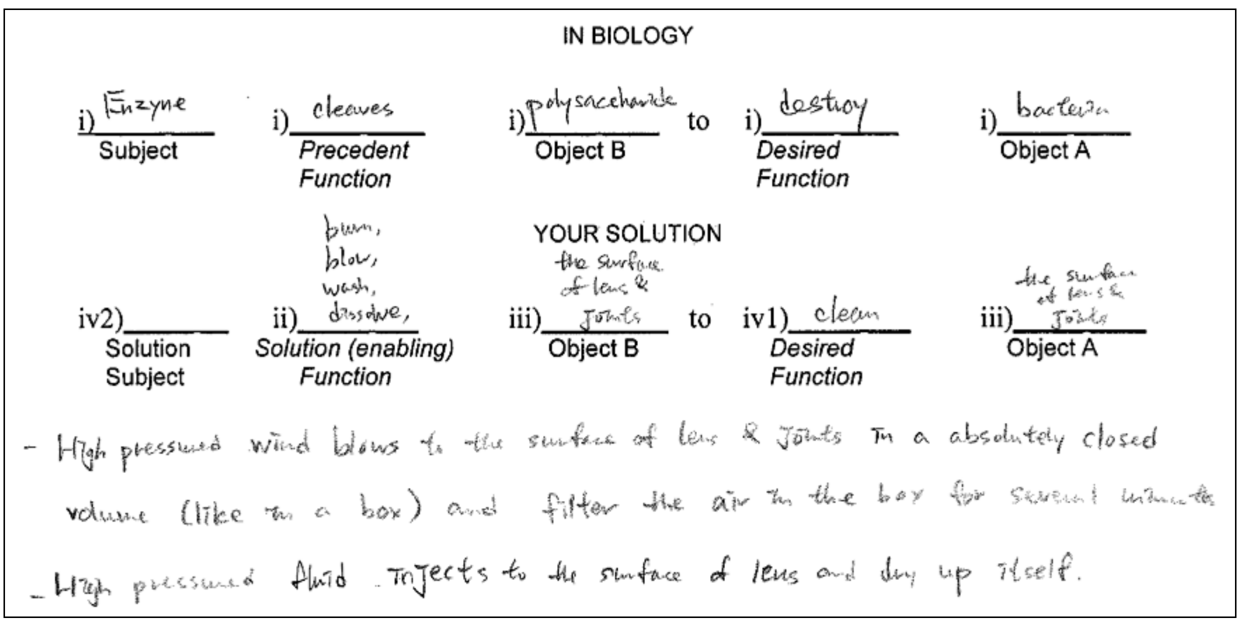


FIGURE 4b: An example of a participant performing incorrect analogical transfer from a strategy in biology to design solution. The participant in this case generated a concept that did not utilize the expected strategy and also scored low in creativity ratings.

Group B participants, on the other hand, were specifically asked by the *instructional mapping rules* to generate ideas that are analogous to the enabling function in the recognized strategy. This forced the participants to not just focus on applying the strategy to solution concepts, but also to think further on how that particular strategy could be enabled. In other words, using the *instructional mapping rules* for solving problems caused the participants to shift their frame of reference. Other researchers have identified that this shift of the frame of reference is beneficial in overcoming routineness in problem solving (Akin and Akin 1996, Chiu and Shu 2008).

The above observations may explain why Group B scored noticeably higher on the cohesiveness ratings than Group A. Because the additional *instructional mapping rules* for Group B ensured that the concepts that utilized correct analogical transfer were well developed, we believe that there was significant correlation between the correct analogical transfer ratings and the creativity ratings only for Group B. The following section examines a specific case of when using the *instructional mapping rules* was beneficial.

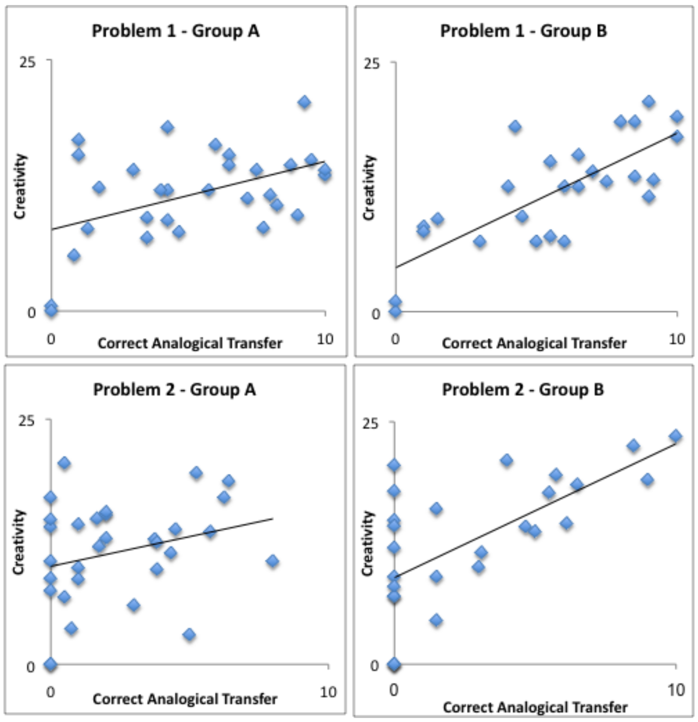


Figure 5a: Stronger correlations between correct analogical transfer and creativity for Group B.

	PROBLEM 1		PROBLEM 2	
	Group A	Group B	Group A	Group B
Correct Analogical Transfer vs. Novelty	r = .280 p = .127	r = .521 p = .005	r = .438 p = .014	r = .769 p = .000
Correct Analogical Transfer vs. Usefulness	r = .452 p = .011	r = .539 p = .004	r = .170 p = .361	r = .519 p = .006
Correct Analogical Transfer vs. Cohesiveness	r = .341 p = .061	r = .416 p = .031	r = .222 p = .229	r = .533 p = .004
Correct Analogical Transfer vs. Creativity	r = .352 p = .052	r = .610 p = .001	r = .265 p = .149	r = .620 p = .001

Figure 5b: Correlations between correct analogical transfer and each creativity measure. Light shading indicates significant correlations with 95% confidence interval. Dark shading indicates significant correlations with 99% confidence interval, i.e., more significant correlations.

5.2.1. Fixation due to domain-specific language

For Problem 2, the expected strategy to be used for the solution was to destroy the roughness of lunar dust particles using certain mechanisms, e.g., microwaves, laser, or other appropriate means to melt the particles' sharp edges or releasing substance that binds with particles to reduce the roughness. We expected that such concepts would be based on the following causal relation retrieved from the stimulus:

Lysozyme *destroys* bacteria to *protect* animals

Some participants from both Groups A and B, however, had completed the *causal relation template* with the following strategies:

Lysozyme *cleaves* polysaccharide chains to *destroy* bacteria
OR
Lysozyme *cleaves* polysaccharide chains to *protect* animals

Most of the participants in Group A, who had retrieved the above strategies, did not generate concepts involving destroying of lunar dust or could not come up with a specific means of destroying lunar dust. On the other hand, many of the participants in Group B, who also had retrieved the above strategies, were able to come up with concepts that destroyed lunar dust with specific mechanisms.

The difference between these two groups was again the *instructional mapping rules* given to facilitate structural mapping between the retrieved strategies and solution concepts. For mapping of the enabling function, e.g., "cleaves," from the strategy to solution concepts, our instructional rule for Group B asked the participants to generate analogous functions to "cleaves" that could enable the desired function of "protect." Because of this specific instruction, we believe that the participants thought of different ways of destroying dust particles, other than the specific "cleaving" action. We suspect that the Group A participants, on the other hand, were fixated on the specific action of "cleave" and were not able to think of different ways of effectively destroying dust particles. When the "cleaving" of dust particles did not seem feasible, they instead turned to other solutions, which did not utilize the retrieved strategy as expected.

We could conclude that the term "cleave," which entails a more specific meaning than "destroy" in the context of the given biological phenomenon, was fixating the participants of Group A. When we compared the creativity rating score between the groups of participants that recognized "cleave" as the enabling function of the causal relation, Group B scored significantly higher than Group A (Group B = 14.93, Group A = 10.62, $t(24)=-2.145$, $p<.05$).

In this work, enabling functions that are found as a part of the analogical strategy will usually be described in domain-specific language (Cheong et al. 2008). Such domain-specific terms are useful when searching the biological domain for relevant information; however, this research has revealed that developing concepts from the domain specific terms can be difficult for novice designers. Therefore, novice designers may need support to consider more domain-neutral functional terms when performing analogical transfer.

5.3. Effect of the *causal relation template* on concept creativity

Although we believe that using the *causal relation template* helps designers to recognize the relevant strategy from biological information, it could also constrict designers' solution space. For Problem 1, most participants extracted the following causal relations:

Mucus *traps* microorganisms to *remove* pathogens
OR
Cilia *creates* rhythmic motion to *remove* trapped pathogens

The concepts generated from the two strategies were distinctively different. For example, most of the concepts that were based on the first strategy involved using substances or design features that react with only paper or plastic, and sort the reacted or non-reacted material. When the participants identified the second strategy in the template, they mostly developed concepts that are based on mechanical movements such as vibration or rhythmic motion.

Many biological phenomena are complex and could therefore consist of a series of sequential functions that are part of a causal relation. For the stimulus given for Problem 1, we could construct the following relation hierarchy:

Design Stimulus:
"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."*

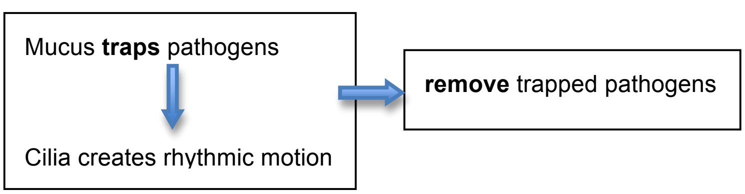


Figure 6: A combination of sequential functions as the enabling function for a causal relation. The vertical arrow represents a sequential order and the horizontal arrow represents the causal relation.

In using the *causal relation template*, designers therefore should be allowed to retrieve as many relevant causal relations as are present in the biological information. This would help designers explore all the possible solutions that can be generated from multiple strategies of the given biological phenomenon.

6. SUMMARY AND CONCLUSIONS

In this study, we explored how to facilitate effective biomimetic design for novice designers. While we believe that providing the *causal relation template* to help retrieve analogical strategies from biological descriptions is important, there is also a need to guide the designers to abstract and correctly map the retrieved strategy to solution concepts. The additional set of *instructional mapping rules* given to Group B participants led to stronger correlations between the correctness of analogical transfer and the creativity of concepts, compared to Group A participants who were only provided with the *causal relation template*. We suspect that this effect was observed because the *instructional mapping rules* for Group B encouraged the participants to abstract the enabling function of the analogical strategy and helped them to generate whole and well-developed concepts. For Group A participants, even in cases when they recognized and tried to apply the retrieved strategy, they could not develop concepts that were as cohesive, and creative in general.

The above observation highlights a significant issue in systematic biomimetic design. Designers first decompose the problem at hand and identify desired functions that must be achieved. Then they must specify these functions into biology domain-specific language in order to effectively search and retrieve analogical strategies. The problem arises when mapping the retrieved strategies to concepts. Because the strategies will usually be written in biology domain-specific language, designers could fixate on specific concepts and not explore all the possible solutions utilizing the strategies. Abstraction of biological strategies is therefore necessary to encourage creativity in the concepts generated. There have been efforts in functionally modeling natural systems so that the similarity and analogy between biological systems and engineering solutions could be identified (Tinsley et al., 2007). However, there is perhaps a need to create systematic methods or approaches that can enable abstraction of identified biological strategies for the specific use of concept generation.

We also conclude that tools and instructional rules for facilitating biomimetic design, such as the ones presented in this paper, have various limitations. While they could help novice designers in applying correct analogical transfer, they could also constrict ideas and cause designers to fixate on the analogical strategy, and not explore enabling functions of the strategy. Our *causal relation template* was designed to identify only a single causal relation at a time, which was not sufficient to capture strategies that consist of complex series of functions. More importantly, once designers identify a certain strategy from biological phenomena, they are very likely to fixate on that particular strategy and fail to explore a wide range of solutions. These tools must then be carefully designed, so that while facilitating effective analogical transfer, they also ensure that creative concepts can be generated. More research on analogical reasoning in biomimetic design could reveal other essential information that could be used to develop more systematic and effective tools for biomimetic design.

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APPENDIX A

EXPERIMENT MATERIALS – PROBLEMS, STIMULI, AND INSTRUCTIONS

Please generate as many concept solutions as possible for the following design problems using the biological phenomenon given as design stimulus. It is retrieved from the textbook, *Life – The Science of Biology*, by searching with keywords related to the design problem. Following the given instruction carefully, complete the template provided to make correct analogical transfer from the biological phenomena to your engineering solution. You have 60 minutes to work on two problems. Please record all ideas.

Problem 1*:*
One of different systems used for curbside recycling is "mixed wasted 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 concepts that will enable removing paper or plastic from the mixed collection.

Design Stimulus:
"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."

Problem 2:
Lunar dust poses significant problems for space equipment and astronauts during operations on the Moon. These dust particles are very abrasive and have a tendency to stick to each other and other objects because of its rough surface. One essential device that must be protected from lunar dust is a Lydar. A Lydar is an optical device that produces laser for signaling purposes. It 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. You should also consider the environment of the Moon, i.e., a low gravitational force, low atmospheric pressure, extreme low and high temperatures, etc.

Design Stimulus:
"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."

Instructions:

GROUP A

1) What is the desired function that needs to be achieved in your problem? Identify the corresponding function in biology.

			to	(1)__________	
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

2) Which object in biology is acted on by the desired function?

			to	(1)__________	(2)________
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

3) In biology, there should be a precedent function that allows or enables the desired function. What is this precedent function?

	(3)__________		to	(1)__________	(2)________
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

4) In biology, identify the subject and object (label this as Object B, it may be the same as Object A) of the precedent function that you have identified above.

(4)__________	(3)__________	(4)__________	to	(1)__________	(2)________
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

5) The completed template should identify the causal relation found in biology that can be applied to your engineering solution. Generate as many concepts as possible, using the causal relation to make correct analogical transfer.

GROUP B

1) What is the desired function that needs to be achieved in your problem? Identify the corresponding function in biology.

______	______	______	to	(1)______	______
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

2) Which object in biology is acted on by the desired function?

______	______	______	to	(1)______	(2)______
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

3) In biology, there should be a precedent function that allows or enables the desired function. What is this precedent function?

______	(3)______	______	to	(1)______	(2)______
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

4) In biology, identify the subject and object (label this as Object B, it may be the same as Object A) of the precedent function that you have identified above.

(4)______	(3)______	(4)______	to	(1)______	(2)______
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

5) The completed template identifies the causal relation found in biology that can be applied to your engineering solution. Another template used to map the causal relation from biology to engineering solution is provided below. Follow the following instructions for correct analogical mapping:

   i) Fill the first line of template (in biology) with the terms identified from steps 1) to 4)

IN BIOLOGY

i)______	i)______	i)______	to	i)______	i)______
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

YOUR SOLUTION

______	______	______	to	______	______
Solution Subject	*Solution (enabling) Function*	Object B		*Desired Function*	Object A

ii) Fill the desired function in your second line of template (your solution) same as the desired function in biology.

IN BIOLOGY

i)________	i)________	i)________	to	i)________	i)________
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

YOUR SOLUTION

________	________	________	to	ii)________	________
Solution Subject	*Solution (enabling) Function*	Object B		*Desired Function*	Object A

iii) Identify objects from your <u>problem statement</u> that correspond to the objects (A and B) associated in the causal relation found from biology. Objects A and B in your solution may be the same object.

IN BIOLOGY

i)________	i)________	i)________	to	i)________	i)________
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

YOUR SOLUTION

________	________	iii)________	to	ii)________	iii)________
Solution Subject	*Solution (enabling) Function*	Object B		*Desired Function*	Object A

iv) Using the completed template, create as many concepts as possible based on following ideas:

iv1) Generate ideas for a solution function that can enable the desired function. This solution function must be similar to the precedent function identified in biology.

iv2) Generate ideas for a solution subject that is associated with your solution function.

IN BIOLOGY

i)________	i)________	i)________	to	i)________	i)________
Subject	*Precedent Function*	Object B		*Desired Function*	Object A

YOUR SOLUTION

iv2)________	iv1)________	iii)________	to	ii)________	iii)________
Solution Subject	*Solution (enabling) Function*	Object B		*Desired Function*	Object A

APPENDIX B

CONCEPT RATING INSTRUCTIONS

<u>Problem 1</u>
Expected analogy to be used:
Mucus traps airborne microorganisms to remove them
-> Use substance or design features that react with only paper or plastic, and sort the reacted or non-reacted material. For your information, in biology mucus reacts only with pathogens, not air, in the respiratory tract.

<u>Problem</u> <u>2</u>
Expected analogy to be used:
Lysozyme destroys invading bacteria to protect animals
-> Use methods that can destroy the dust particles or eliminate their rough surface characteristic to protect the Lydar.

<u>Examples – High Anchors</u>
Below are examples of concepts with HIGH correctness, HIGH novelty, HIGH usefulness and HIGH cohesiveness. It will be up to you to decide the exact numerical score within the "high" categories. You may find concepts that you think will score lower or higher than the examples shown below.

	Problem 1: Sorting mixed recyclates	Problem 2: Space lydar protection
High Correctness	Fill the recyclates with water. Only paper will disintegrate. Filter out the plastic.	Use laser to destroy lunar dust particles.
High Novelty	Apply heat to the recyclates. Paper will incinerate first. Collect plastics.	Spray particles that will bind to and surround the lunar dust. It adds weight to drag them to the ground and also eliminates the rough surface of dust particles.
High Usefulness*	Fill the recyclates with water. Only paper will disintegrate. Filter out the plastic.	Use laser to destroy lunar dust particles.
High Cohesiveness	Fill the recyclates with water. Only paper will disintegrate. Filter out the plastic.	Spray particles that will bind to and surround the lunar dust. It adds weight to drag them to the ground and also eliminates the rough surface of dust particles.

*Although the examples for both high correctness and high usefulness are the same, concepts that score low on correctness may score high on usefulness, as long as they solve the problem well (or vice-versa).

<u>Examples – Low Anchors</u>
Below are examples of concepts with LOW correctness, LOW novelty, LOW usefulness and LOW cohesiveness. It will be up to you to decide the exact numerical score within the "low" categories. You may find concepts that you think will score lower or higher than the examples shown below.

	Problem 1: Sorting mixed recyclates	Problem 2: Space lydar protection
Low Correctness	Use vibrating mechanism to separate plastic from paper.	Use a sacrificial part that attracts dust away from the lydar.
Low Novelty	Fill the recyclates with water. Paper will absorb water and sink, while plastics float.	Use a fan to blow dust away.
Low Usefulness	Use vibrating mechanism to separate plastic from paper. (Does not indicate how the vibration results in separation)	Use a fan to blow dust away. (not feasible in space)
Low Cohesiveness	Identify and filter out paper and plastic through several processes.	Destroy lunar dust particles.