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INCREASING INNOVATION: A TRILOGY OF EXPERIMENTS TOWARDS A DESIGN-BY-ANALOGY METHOD

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ABSTRACT

Design by analogy is a noted approach for conceptual design. This paper seeks to develop a robust design-by-analogy method. This endeavor is sought through a series of three experiments focusing on understanding the influence of representation on the design-by-analogy process. The first two experiments evaluate the effects of analogous product description--presented in either domain-general or domain-specific language--on a designer's ability to later use the product to solve a novel design problem. Six different design problems with corresponding analogous products are evaluated. The third experiment in the series uses a factorial design to explore the effects of the representation (domain specific or general sentinel descriptions) for both the design problem and the analogous product on the designer's ability to develop solutions to novel design problems. Results show that a more general representation of the analogous products facilitates later use for a novel design problem. The highest rates of success occur when design problems are presented in domain specific representations and the analogous product is in a domain general representation. Other insights for the development of design by analogy methods and tools are also discussed.

1. INTRODUCTION

Design-by-analogy is a powerful tool for developing ideas. Designers frequently base their designs on products they have seen before. Professional designers often use analogies [1,2,3]. Numerous examples of innovative products based on analogies may be found in technology magazines and related literature. A recent example is a retractable mast with sail designed after studying bird and bat wings [4]. This sail is also useful for cargo ships to harness wind power, reducing fuel costs [5].

Design-by-analogy is clearly a powerful tool in the design process but numerous questions surround its use. What will make the designers more successful? What do designers not do well? What are typical wrong turns or places designers have difficulties? What makes a good analogy? What tools do designers need to support this process?

To more fully understand the use of analogy in design and to serve as a basis for the development of a robust design-by-analogy method, we have performed a series of controlled experiments. This paper begins with a description of the motivation for this work and then describes research and theory on innovation and the underlying cognitive processes that support it. Next we present a series of experiments

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exploring the way the representations of prior knowledge and new design tasks affects the use of analogy. Finally we discuss the implications of these results for a robust theory of design-by-analogy and for the development of tools to support innovation processes.

Figure 1: The sails of this cargo ship are designed based on an analogy to a bat's wing [4,5].

2. MOTIVATION AND PREVIOUS WORK

Prior work in the design research field has focused on the development of formal design-by-analogy methods and understanding relevant cognitive processes.

2.1. Formal Design-by-Analogy Methods

A few formal methods have been developed to support design-by-analogy such as Synectics [6], French's work on inspiration from nature [7], Biomimetic concept generation [8] and analogous design through the usage of the Function and Flow Basis [9]. Synectics is a group idea generation method that uses four types of analogies to solve problems: personal (be the problem), direct (functional or natural), symbolic and fantasy [6]. Synectics gives little guidance to designers about how to find successful analogies. Other methods also base analogies on the natural world. French [7,10], highlights the powerful examples nature provides for design. Biomimetic concept generation provides a systematic tool to index biological phenomena [8,11]. From the functional requirements of the problem, keywords are derived. The keywords are then referenced to an introductory college textbook and relevant entries can be found.

Analogous concepts can also be identified by creating abstracted functional models of concepts and comparing the similarities between their functionality. Analogous and non-obvious products can be explored using the functional and flow basis [9]. This approach requires a database of products represented in the function and flow basis.

2.2. Representation

A representation is a physical or mental item that stands for another thing. Hence, there are four necessary parts to a mental representation: the physical or mental item serving as the representation, the domain being represented, rules (usually implicit) that map parts of the first to parts of the second, and a process (also usually unstated) that is capable of performing the mapping and using the information [12]. Understanding the design process requires understanding both the internal mental representations of designers as well as the external representations (e.g., sketches, function and flow basis diagrams) that are used during the design process.

2.3. Prior Analogy in Design Experiments

Human-based design methods require a deep understanding of the processes people use and the areas where guidance or assistance could improve the process. This knowledge is gained largely through experimental work. Even though design-by-analogy is a well-recognized method for design, few human experiments exist. Notable results from these experiments include the work of Casakin and Goldschmidt, Ball et al., Kolodner, and Kryssanov et al. Casakin and Goldschmidt. Casakin and Goldschmidt found that visual analogies can improve design problem solving by both novice and expert architects [3]. Visual analogy had a greater impact for novices as compared to experts. Ball, Ormerod, and Morley investigated the spontaneous use of analogy with engineers [13]. They found experts use significantly more analogies than novices do. The type of analogies used by experts was significantly different from the type used by novices. Novices tended to use more case-driven analogies (analogies where a specific concrete example was used to develop a new solution) rather than schema-driven analogies (more general design solution derived from a number of examples). This difference can be explained because novices have more difficulty retrieving relevant information and have more difficulty mapping concepts from disparate domains due to a lack of experience [14].

A structured design-by-analogy methodology would be useful for minimizing the effects of the experiential gap between novices and experts and to further enhance experts' abilities. The cognitive analogical process is based on the representation and processing of information, and therefore can be implemented systematically given appropriate conceptual representations and information processing tools [15,16].

Prior research in analogical reasoning found the encoded representation of a source analogy (the analogous product) can ease retrieval if it is entered into memory in such a way that the key relationships apply in both the source and target problem domains [17,18]. This work shows that the internal representations in memory play a key role in retrieval. The analogies and problems used in these experiments were not specific to any domain of expertise and used fantasy problems relying on strictly linguistic descriptions. Little work has been carried out based on a strong psychological understanding of analogical reasoning combined with the design knowledge of analogies for high-quality designs. This paper takes a distinctive interdisciplinary route to combine these threads of research to develop a more complete understanding of the use of analogy in engineering design and to provide the basis for formal method development. Designers rely on both internal mental representations and numerous external representations ranging from sketches to specialized diagrams such as black box models. The use of various representations in the design process warrants further understanding. The following experiments further investigate visual and semantic representation effects on design-by-analogy and lead to a deeper understanding of how to enhance the design-by-analogy process.

2.4. Cognitive Processes: Design-by-Analogy

Understanding the cognitive process involved in the formation of analogies is important for understanding the concept generation process. Analogy can be viewed as a mapping of knowledge from one situation to another enabled by a supporting system of relations or representations between situations [19,20,21]. This process of comparison fosters new inferences and promotes construing problems in new insightful ways. The potential for creative problem solving is clearest when the two domains being compared are very different on the surface [22].

Research has been carried out in the field of psychology to understand the cognitive processes people use to create and understand analogies [21,22,23,24,25]. Figure 2 shows the basic process steps involved in reasoning by analogy, the most cognitively challenging step, and the design methods that are available to support each step.

Understanding the cognitive process involved in the formation of analogies is important for understanding the concept generation process. These processes are best understood by referring to a predicate-argument representation like that used in logic, artificial intelligence, or linguistics. Within this framework, a predicate is a statement that is asserted of a subject or subjects, and arguments are the subjects of which predicates are asserted. These predicates are partitioned into attributes (defined as taking single arguments) and relations (which take two or more arguments). For example, in the statement ‘the boot is brown’, brown is an attribute, and can be written using the one argument predicate Brown(boot). In the form ‘Brown(boot)’, ‘Brown’ is a predicate and ‘boot’ is its argument. In the statement ‘the boot is larger than the shoe’, larger-than is a relation, which would be written with the two argument predicate Larger_than(boot, shoe). Relations can connect other relations as well as objects. The most common example of this is the relation cause, as in ‘Bob is taller than Sam, causing Bob to jump higher than Sam’, written Cause (Taller_than (Bob, Sam), Can_jump_higher_than (Bob, Sam)). Such a relation is known as a higher order relation (for a fuller account, see [21]).

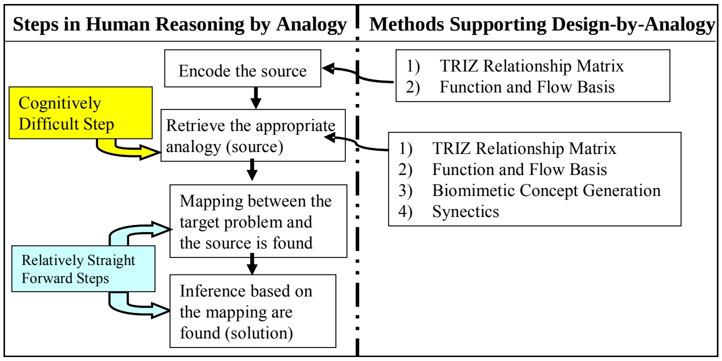


Figure 2: Steps in human reasoning by analogy and the current methods available to support those processes.

Analogy has traditionally been viewed as a comparison between two products in which their relational, or causal structure, but not the superficial attributes match [20,22]. For example, an airplane wing and a hydrofoil can be viewed as analogous because of how they work; the colors they are painted is irrelevant. This process of comparison fosters new inferences and promotes construing problems in new, insightful ways. The potential for creative problem solving is most noticeable when the situation domains are very different.

In the psychological literature, there has been a great deal of interest in the roles of analogy and expertise in problem solving. When working with undergraduate students who have no specialized domain knowledge, a classical finding is that analogies are helpful in solving insight problems, but are difficult to retrieve from memory [26]. Conversely, naturalistic research with experts typically finds that analogies are often used [e.g., 27, 2, 3]. This dichotomy may reflect that experts can see the deeper, logical structure of situations while those without domain expertise are mainly aware of only the superficial features [cf. 28, 29, 30].

To clarify and more fundamentally understand these issues, laboratory research, which affords good experimental control, needs to be conducted with burgeoning domain experts. Such individuals are capable of recognizing the causal structure of products, but could also be distracted by superficial features. These characteristics make them the appropriate test bed for determining the role of source representation in analogical reminding. Moreover, it has been suggested that implicit processes could mediate analogical problem solving [31]. That is, problem solving can occur without being aware of the analogous solution in memory. Therefore, it is important to assess when participants find the solution and recognizing the analogy, separately.

2.5. Semantic Memory Retrieval

Designers frequently base their concepts on ideas they have seen and experienced previously. These designs are retrieved directly from their long-term memory, specifically semantic memory. Semantic memory refers to the storage of meaningful, factual information. Semantic memory is contrasted with the storage of personal experiences (episodic memory) or skills (procedural memory). In the psychological literature, the structure of human semantic memory is often conceptualized as a network of concepts that are associated with each other. For example, in Figure 3, the concept of a bed is represented by a node in a somewhat chaotic web of associations. When one thinks about beds, the node representing that concept becomes active, and this activation can spread out along its associative links to other connected ideas. Another concept is remembered when it becomes sufficiently activatived. However, nodes pass along only a fraction of their activation to neighboring nodes, and so the activation weakens as it gets more distant from the source of activation. The probability that a concept will be remembered increases as the path distance (i.e. number of links traversed) shortens, or if multiple active paths converge on it. Nodes that are more general concepts, such as "substance", tend to be connected to a much greater number of other nodes, becoming hubs in the network. Thus, linking new concepts through them shortens path distances, increasing the probability of retrieval [12,32,33,34].

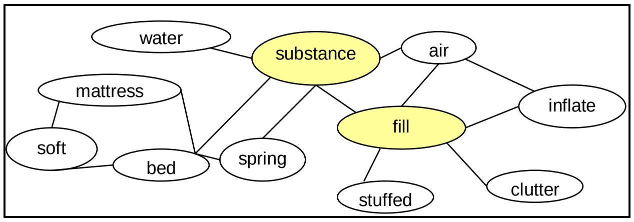


Figure 3: Example Semantic Network

3. EXPERIMENTAL APPROACH AND RESEARCH QUESTIONS

Designers need a predictable method for developing innovative solutions to difficult design problems. Thus, it is crucial that we understand the relationship between the representation of the design problem and the representation of analogous product descriptions in memory Our goal is to explore the factors that make previously seen analogous products easier to retrieve and use in solving the problem. The problems used in these experiments have many viable solutions. The goal of the experiment is not to determine if the participant can find solutions to the design problem but to explore the factors that affect the use of analogous solutions. The solutions of interest for this experiment are the ones based on products presented in the first part of the experiment. These analogous products represent a useful source for finding solution to the design problems. The experiments use a combination of visual and semantic information to represent the source design analogy.

In this context, we seek to answer the following research questions:

- Question 1: Is prior product knowledge more likely to be retrieved and used in innovative design when it is described using domain-general or domain-specific language? Prior psychological literature [17,18] implies that the domain-general descriptions should be more likely to be retrieved but this needs to be validated and explored in a more realistic situation.
- Question 2: How does the representation of the problem statement affect the ability of a designer to retrieve and use a relevant analogous product to expose a solution to a new design problem?
- Question 3: Usually, when a designer is solving a novel problem, the representation of appropriate analogous products is not known to the designer. What is the best way to represent a design problem in this situation and what implications does this have for a design-by-analogy method?

4. EXPERIMENTAL APPROACH

To further explore the effects of representation on analogy use for real-world problems and to further understand how supporting methodologies should be created, a series of three experiments was implemented. This series of experiments controlled how participants learned about a series of products and therefore also controlled how the products were represented in their memories. This allowed the predictions from psychological models of analogical reasoning and semantic memory to be evaluated. These models, along with additional knowledge gained from experimentation, will be used as the basis for methods development. These experiments were conducted over three semesters with senior mechanical engineers with instruction in design methodology including idea generation and from two professors' classes. Each experiment contained a unique set of participants.

The first and second experiment explored the effects of the analogous product representation on a designer's ability to later use the product to solve a novel problem. A total of six design problems with corresponding analogous products were explored to more fully understand the influence of semantic representation and other factors in analogical design. The analogous solutions were semantically described using either domain specific or more general terms that applied across both the problem and the analogous product domains.

The third experiment evaluated the representation effects for both the analogous product and design problem. A 2 X 2 factorial experiment design was employed which resulted in four different experimental groups, Table 1. For both the analogous product and the problem description, two levels of participants were compared, a *"Domain Specific Description"* Group and a *"General Description"* Group, Table 2. All experiments used a combination of visual and semantic information to represent the source design analogy.

5. OVERVIEW OF THE ANALOGOUS PRODUCT REPRESENTATION EXPERIMENTS 1 & 2

The experiments consisted of two tasks: *Memorize the Analogous Products and Solve the Design Problems* with a week in between for most participants. Normally when faced with a design problem, a useful analogous product has not been seen immediately beforehand, but the analogous product is stored in a person's long term memory. A week was chosen as a relevant time because any analogies retrieved will be taken from long-term memory and this time frame has been used previously [35]. Multiple solutions were encouraged for all parts of the experiment. Participants were told the experiment evaluated various skills in the design process.

The two analogous product representation experiments were virtually identical with the exception of the design problems and analogous products being evaluated. Results from Analogy Experiment 1 left many unanswered questions and showed some short-comings in the analogies that were chosen [36]. To further understand design-by-analogy, a second set of analogies were evaluated in Experiment 2. For Experiment 1, the football to the raft analogy required the mapping of visual rather than semantic information and the sketches of the flour sifter device were difficult to interpret. For Experiment 2, two innovative products found in the literature were used. The first, a kayak with a hydrofoil could have been based on an analogy to an airplane wing [37]. The second, a set of dirt bike racer goggles was based an analogy to film in a camera [38].

5.1. Procedure for Experiments 1 & 2

For the first task, *Memorize the Analogous Products*, participants were given five short functional descriptions of products along with a picture (example in Table 2 and see appendix for complete descriptions) and asked to spend thirty minutes memorizing the descriptions. The products were functionally described in a few short sentences either with a more general description that applied in both the source analogy and target design problem domains, or with a domain-specific description. An example of the descriptions used for the film in a camera is shown in Table 2. The product descriptions and the design problems included meaningful pictures. The semantic descriptions of the devices were varied but the pictures were identical for both conditions. The focus of these experiments was on the linguistic representations of the devices, but visual information was also present.

Both groups were then given up to fifteen minutes to answer a quiz, requiring them to write out the memorized descriptions. Finally the groups spent up to ten minutes to evaluate their results. Three of the products acted as source analogies for the design problems in the second task, *Solve the Design Problems*, and three were distracter products that shared surface similarities with the design problems (Figure 4 and Figure 5).

Table 1: Overview of the Factorial Design for Experiment 3

		Factor 1: Analogous Product Representation	
Factor 2: Design Problem Representation		**General**	**Domain Specific**
	General	Group 1: General, General	Group 2: General, Domain
	Domain Specific	Group 3:Domain, General	Group 4: Domain, Domain

Time limitations were based on a pilot experiment with graduate students with no time limits. Time limits were set to be longer than the amount of time required by most participants in the pilot experiment. For certain tasks and phases, it was clear participants were not spending enough time on the task, so the time limits were actually extended well beyond the time required in the pilot experiment.

In the second task, *Solve the Design Problems*, participants were given three design problems to solve in a series of the following five phases:

Phase 1: Open-ended design problems, few constraints
Phase 2: Highly constrained design problems
Phase 3: Identify analogies and try using analogies
Phase 4: Informed task 1 products are analogous
Phase 5: Target analogous product from task 1 is given and participants need to find the solution

Phases one and two were completed for the three problems followed by phases three through five. Throughout all phases participants were given the general idea generation guidelines to (1) generate as many solutions as possible with a high quality and large variety, and (2) to write down everything even if it did not meet the constraints of the problem including technically infeasible and radical ideas. Participants were also instructed to use words and / or sketches to describe their ideas. They were asked not to discuss the experiments with their classmates until all the experiments were completed.

In phase 1, the problems were initially presented with few constraints. Participants received eleven minutes to generate ideas for the open-ended design problems and then eleven additional minutes to create more solutions to the same problem with additional constraints. The additional constraints limited the design space increasing the chance the participants would retrieve the desired source analogy. Next they had a five minute break.

In phase 3, participants spent fifteen minutes listing any analogies they had used and also used analogies to develop

Table 2: An example of the domain specific and general device descriptions given to participants for task 1.

Sentence / **General (G) or Domain (D) Specific**							
1	**G**	Two reels	move	a surface	in the path of	incoming substance.	
	D	Two reels	feed	the film	in front of	the stream of light.	
2	**G**	The surface	collects	the substance	and then a new	unchanged surface	is moved into place.
	D	The film	captures	the image	and then a new	unexposed section of film	is moved into place.

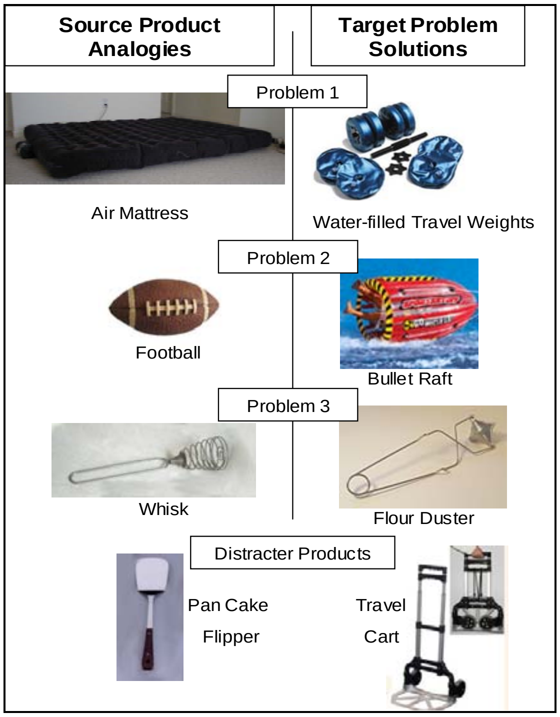


Figure 4: Source products analogies, corresponding target problem solution and the distracter products for experiment 1.

additional solutions. In phase 4, the participants were told that products from the first task were analogous, to mark their solutions that used the analogy and to generate additional solutions using the products from the first task (*Memorize the Products*). Finally, participants were given the target analogy for each problem, asked to place a check where they had used it and asked to generate more ideas if they had not used the described analogy. This final phase serves as a control to verify that the analogies being used are sensible, are useful for these particular design problems and to facilitate data evaluation. At each phase, participants used a different color of pen, thus identifying the phase. A short survey at the conclusion of the experiment evaluated English language experience, work experience, if the participant had heard about the experiment ahead of time, functional modeling experience, if they felt they had enough time and prior exposure to the design problem solutions. For Experiment 2, the survey also included a question asking the participants to write down a list of features they used from the targeted analogous product from task 1 to find their solution to the design problem. For the sketches that were difficult to interpret, the additional survey questions assisted in evaluating if the appropriate features from the analogous product had been used to solve the design problem. Results from the first task were matched to the second task. The entire experiment required about three hours.

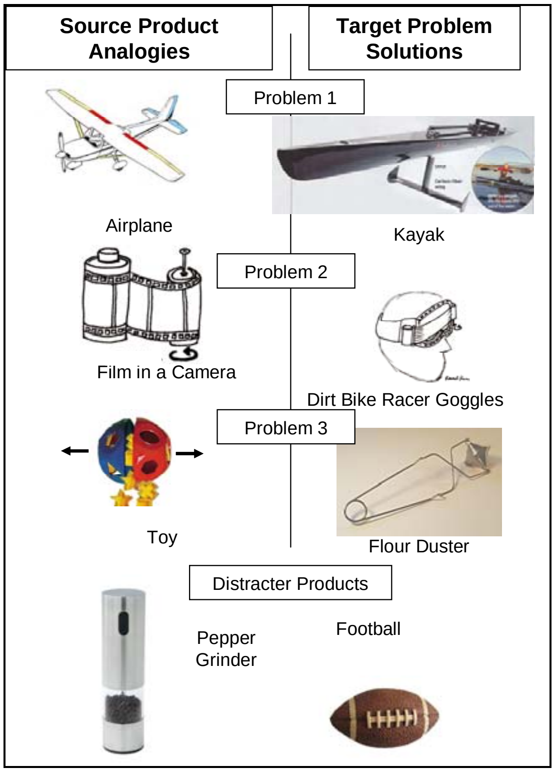


Figure 5: Source products analogies, corresponding target problem solution and the distracter products for experiment 2.

5.2. Metrics

Each analogy produces a set of solutions, not a single solution. Participants also created a large number of solutions which were not based on the analogies provided. We were primarily interested in the phase of the study at which participants produce a solution to the constrained design problem based on the targeted analogy and also the phase at which they identified the analogy that they used. As we will see, people often show evidence of being influenced by an analogous product without explicitly recognizing where the idea came from. Two evaluators coded the data independently, recording when the analogous solution was found. Initial agreement was approximately 80% across the three experiments and disagreements were readily resolved through discussion. The most common reason for the initial differences was the participant referenced solutions that appeared on different pages of the results.

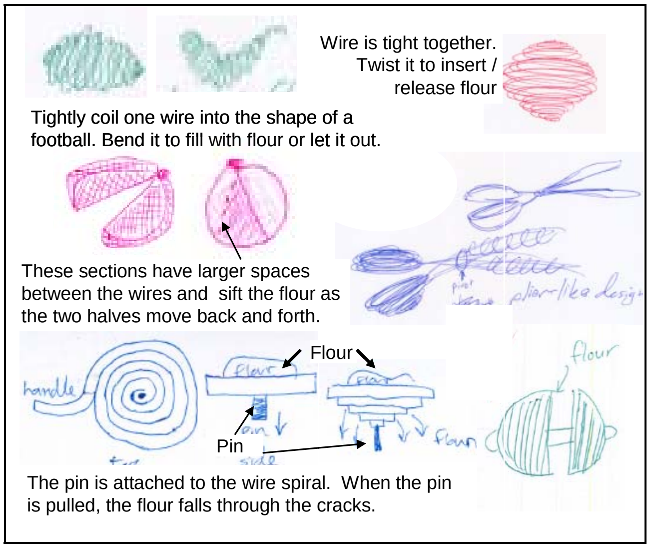
5.3. Results and Discussion: Analogous Product Representation Experiments 1 & 2

Example solutions are shown in Figure 6. Figures 8-13 show the cumulative percentage of participants who found a valid solution to the constrained design problems based on the appropriate analogous product. The analyses excluded participants who remembered seeing the expected solution prior to the experiment. The expected solutions are actual products so it is possible for the participants to have seen the products prior to the experiment. In addition, a verbal description without a picture of the water weight example is given in the textbook used in the participants' design methods class but the section is in the optional readings for the class. It is unlikely that any of the students read this section of the book prior to the experiment.

The representation of the analogies in the participants' long-term memory affected the probability the analogous product would be used to solve an appropriate design problem for certain problems (Figure 7 and Figure 12). Appropriate representations can improve the success rate in design-by-analogy. For two of the design problems, participants who received general descriptions of the analogous products had statistically higher probabilities of success. The results for phase 4, are statistically significant for design problem 1 Experiment 1 and design problem 3 Experiment 2 (Figure 7 and Figure 12). Using a binomial probability distribution [39], the probability that the domain specific description group is from the same distribution as the general description group is almost zero.

We should note that we reported the data from Experiment 1 in a prior paper [36], though it was analyzed differently there. In the previous paper, we did not distinguish between when participants used the analogous solution and when they explicitly mentioned the analogy they had used. Looking more carefully at our data, however, participants frequently find the analogous solution without realizing the source of the idea. This issue is discussed in detail in Section 5.5.

The semantic representation has an impact on analogy retrieval but other factors also influence the process. The key features to be mapped in Experiment 1, problems 2 and 3 were visual information, the shape of the football and the varying spacing of the wires in the whisk. The semantic representation may only influence the analogical reasoning process when the information that must be accessed and mapped is stored verbally instead of visually. This proposal is consistent with our observation that nearly all prior studies of analogical reasoning involve semantic materials (typically written stories) [17,18]. Visual and verbal information are two distinct types of knowledge stored in long-term memory [40].


Wire is tight together. Twist it to insert / release flour

Tightly coil one wire into the shape of a football. Bend it to fill with flour or let it out.

These sections have larger spaces between the wires and sift the flour as the two halves move back and forth.

The pin is attached to the wire spiral. When the pin is pulled, the flour falls through the cracks.

Figure 6: Examples of flour sifter solutions found by the participant based on the analogy to the toy, Experiment 2.

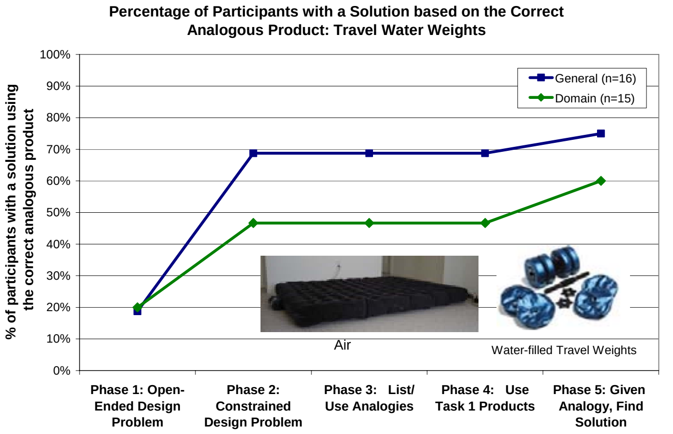

Percentage of Participants with a Solution based on the Correct Analogous Product: Travel Water Weights

Figure 7: Design Problem 1, Experiment 1. A general description facilitated retrieval and use of the analogous product to solve a novel design problem.

For Experiment 1 design problems 2 and 3, it was also much more difficult to evaluate the appropriateness of the solution and to isolate the features that had been mapped. This would lead to more inaccurately mapped solutions being counted and erroneous results. This issue was corrected in Experiment 2. For more details of the Analogous Product Representation Experiments 1 see Linsey et al. [36].

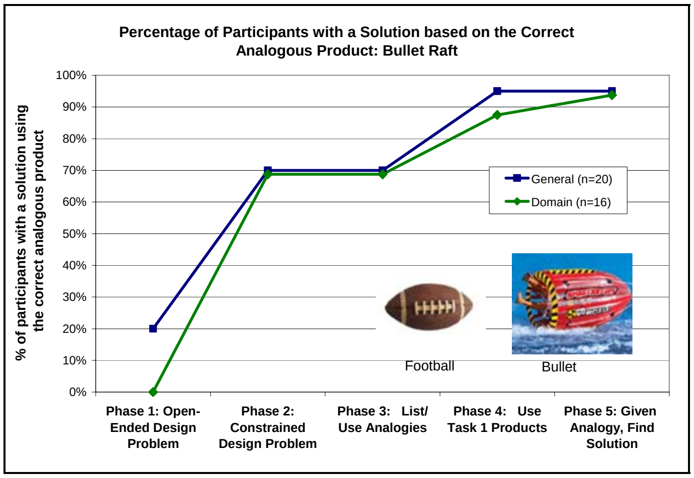


Figure 8: Design Problem 2, Experiment 1. A more general semantic representation does not ease retrieval and use when visual information must be mapped from the analogous solution.

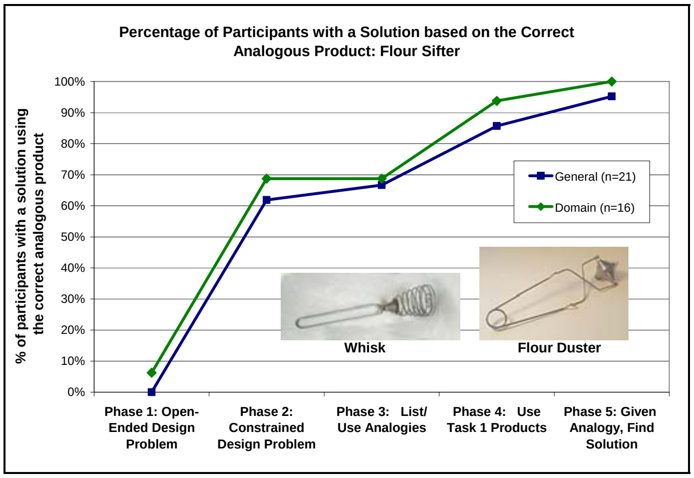


Figure 9: Design Problem 3, Experiment 1. The semantic representation did not influence analogy use for this problem.

Again in Experiment 2 more additional factors which influence the design-by-analogy process were observed. In Figure 10, the participants who received the domain specific descriptions had a higher success rate in solving the design problems. This was not the hypothesized results. The kayak problem, design problem 2, required domain knowledge of fluid mechanics to select and map the appropriate characteristics of the airplane onto the kayak. All participate were expected to have the required domain knowledge but it is clear that some did not. The domain knowledge influence dominated this design problem. It also appears it was easier for participants to retrieve the required domain knowledge when the analogous product was described in domain specific terms (for example airplane) than when it was described generally (Figure 10).

For the dirt bike racer design problem, a retrospective evaluation of the domain description and the problem revealed that the word “film” is readily retrieved for the design problem. This likely caused there to be no influence for the analogous product description (Figure 11). It was as easy for participants in the domain condition to remember the appropriate analogy as it was for participants in the general condition.

Experiments 1 and 2 highlight the effects of sentential representations on the design-by-analogy process. Other factors that influence the design-by-analogy process are also alluded to by these experiments.

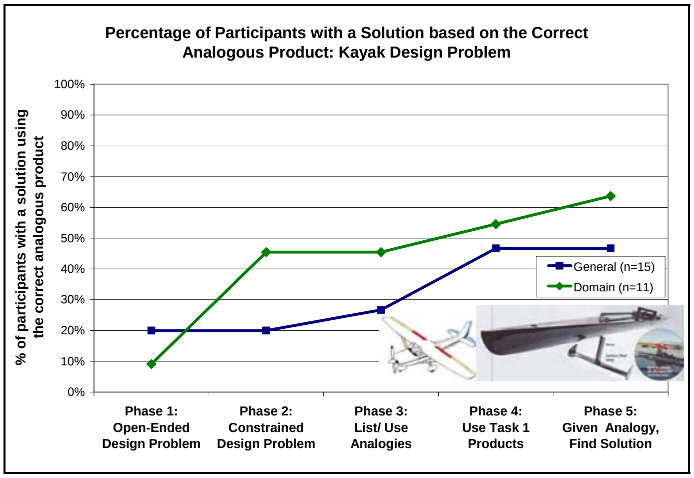


Figure 10: Design Problem 1, Experiment 2. This problem required participants to use their knowledge of fluid dynamics to appropriately choose the right characteristics from the analogy.

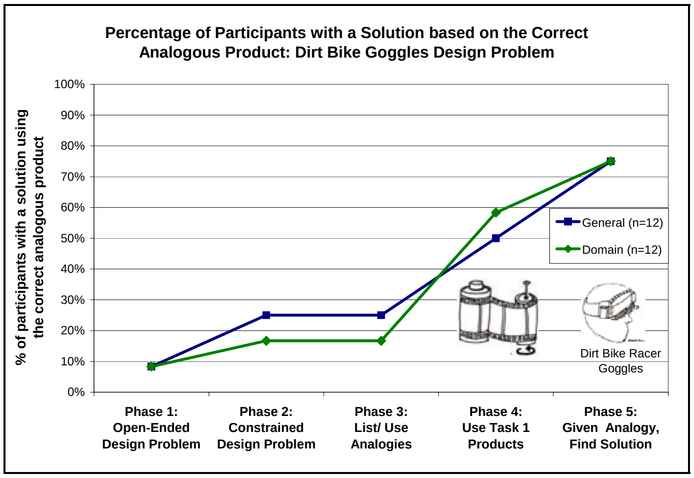


Figure 11: Design Problem 2, Experiment 2. The word “film” in the domain specific description also mapped well for the design problem.

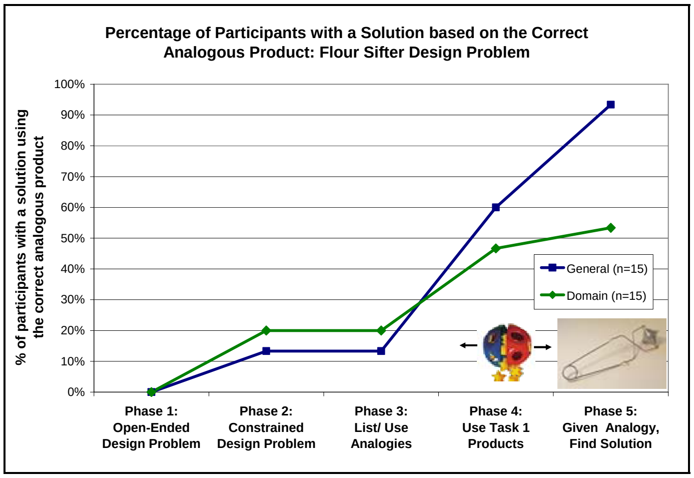


Figure 12: Design Problem 3, Experiment 2. A general description facilitated retrieval and use of the analogous product to solve a novel design problem.

5.4. Method for Effects of the Design Problem Representation Experiment 3

The third experiment evaluated representation effects for both the analogous product and design problem. A 2 X 2 factorial experiment design was employed which resulted in four experimental groups, Table 1. For both the analogous product and the problem description, two levels of participants were compared, a *"Domain Specific Description"* Group and a *"General Description"* Group, Tables 2-3. In addition only the travel water weight and flour duster design problems along were used (Figure 13). The focus of this series of experiments was on understanding how general and domain specific descriptions influenced a designer's ability to use an analogy to solve a problem. Only two of the analogies from Experiments 1 and 2 (water weights and flour sifter) isolated the sentential representation from other factors that influence design-by-analogy. Therefore only these two analogies were used for Experiment 3 which focused on further exploring the influence of sentential representation. .

The third experiment used the same procedure as the first two with the following exceptions. In the second task, *Solve the Design Problems*, participants were given two design problems to solve in a series of the following seven phases:

Phase 1: Open-ended design problems, few constraints
Phase 2: Highly constrained design problems
Phase 3: Identify analogies and try using analogies
Phase 4: Continue using analogies
Phase 5: Try to use a function structure to help you find a solution
Phase 6: Informed task 1 products are analogous
Phase 7: Target analogous product from task 1 is given

Phase 3, list any analogies used and try using analogies, was 10 minutes long instead of 15 as in experiments 1 & 2 since the experiment 3 contained two design problems instead of three. An open question from one of our prior experiments [36] was if the participants were given more time to use analogies, would they be more likely to find the source analogy from task 1? Therefore, following the initial phase using analogies, participants were given ten additional minutes to continue to use analogies to create solutions.

Table 3: Domain Specific and General Problem Statements

	Problem Statement for Design Problem 2
Domain Specific	Design a kitchen utensil to sprinkle flour over a counter.
General	Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

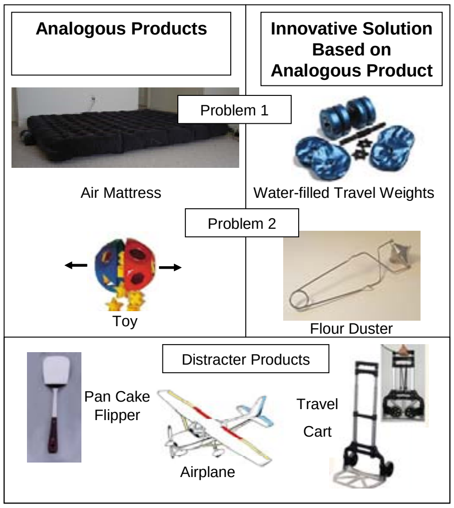


Figure 13: Analogous products and solutions based on the analogies, Experiment 3.

Next, participants were shown a set of six function structures (three per design problem) and asked to develop more solutions to the constrained design problem (Figure 14). This phase provided a foundation for evaluating the effectiveness of function structures for generating novel design solutions. Function structures are representations used in engineering design (see 9 and 41 for more detail). When function structures are created for novel design problems, process choices must be made. The process choices for the function structures were made so that they are consistent with the solution based on the analogous product and were expected to improve participants' ability to generate a solution. Process choices include using human energy to actuate the device as opposed to a battery and electric motor or a gasoline engine. The purpose of implementing the function structures was to evaluate if this representation has potential. This experiment does not address how these functional representations with appropriate process choices are developed.

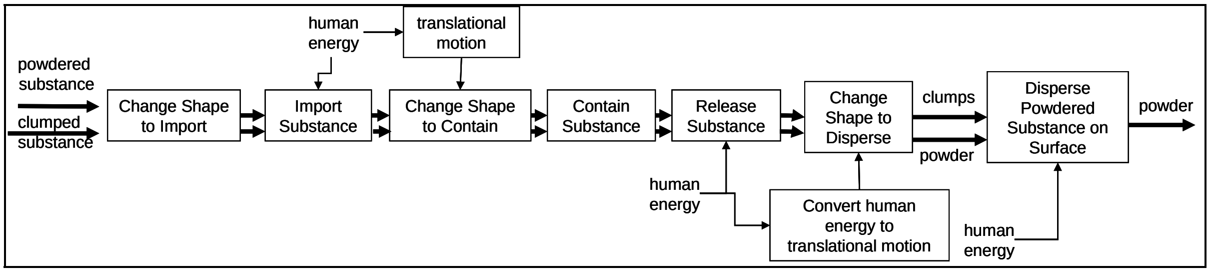


Figure 14: One of the functional model for design problem 2: flour sifter

During one of session experiment 3, a fire alarm occurred during phase 2. The data was reviewed and little impact was observed. These four participants were spread across the conditions and are included in the results.

5.5. Results and Discussion for Effects of the Design Problem Representation Experiment 3

The analogous product representation and the problem representation had a clear influence on the designers' ability to use the analogy to generate a solution to the design problems. The trends are similar across the two design problems and similar to the first two experiments. A summary of the results for experiment 3 which are relevant to the research questions are presented in this paper. More detailed results are presented in [42]. Figure 15a-b show the percentage of participants at each phase who were able to generate a solution to the design problems based on the analogous product. Participants who had previously seen the solution to the design problems based on the analogous product were removed from the data set (twenty participants for design problem 1 and three participants for design problem 2). Participants who memorized the analogous product in a general form had the highest rate of success. This result is shown by the green line in the figures, where success rate increased by up to 40%.

A two-predictor logistic model [43] was fit to the data for problem 1 at phase 4 to evaluate the statistical significance of the effects. A multivariate approach could not be used because too many of the participants had scores for only one of the design problems since many had previous experience with the solution for design problem 1. The logistic model for problem 1 at stage 4 shows no significant interaction between the two predictors and therefore the interaction was removed from the model ($p>0.4$). The remaining predictors show the design problem representation to be a statistically significant predictor ($\beta=-1.6$, $p<0.06$) and the analogous product representation to be non-significant ($\beta=1.0$, $p>0.2$). Clearly from the results plots, the general/domain condition is different from the other three conditions. Using a binomial probability distribution with pairwise comparisons between the conditions, the general/domain condition is statistically significantly different from the other three conditions ($p<0.008$, $p<0.002$, $p<0.001$) [43]. The representation of the design problem has a large effect on the analogies designers retrieve to assist in developing a solution. The representation of the design problem and the representation in memory significantly impact the designers' abilities. Most of the time, the form of representation in memory is not known so multiple design problem representations should be used to retrieve more analogies.

A two-predictor logistic model [43] was also fit to the data for problem 2 at phase 4 to evaluate the statistical significance of the effects. None of the predictors were statistically significant. This is likely caused by the low power, due to limited sample size, of the experiments. Clearly from the plots, the general/domain condition is different from the other three conditions. Using a binomial probability distribution with pair wise comparisons between the conditions, the general/domain condition is statistically significantly different from the domain/general condition ($p<0.0001$) [43].

Figure 15a-d shows when participants found a solution based on the analogy and also explicitly referenced which product from task 1 was analogous. Participants could have labeled the analogy as early as phase three when they were told to try using design-by-analogy to try to solve the design problem, but none of the participants explicitly identified the analogous product until phase five when they were given a functional model.

6. ADDRESSING THE RESEARCH QUESTIONS

The data provide important insight into the effects the representation of the problem and representation of analogous products have on design-by-analogy. The following discussion provides further elaborates on some of these insights.

6.1. Question 1: How does the linguistic representation affect a designer's ability to later use the analogous product to solve a novel design problem?

General linguistic representations, which apply both in the analogous product and design problem domain, increase the success rate more than ***domain specific*** representations. If a designer stores analogous products in memory in more general representations, they are more likely to be able to later use these analogies to solve novel design problems (Figure 15a-d).

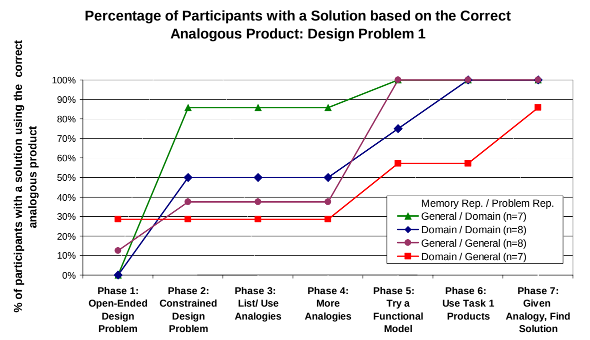


Figure 15a: Percentage of participants with a solution based on the target analogous product at each phase, Design Problem 1.

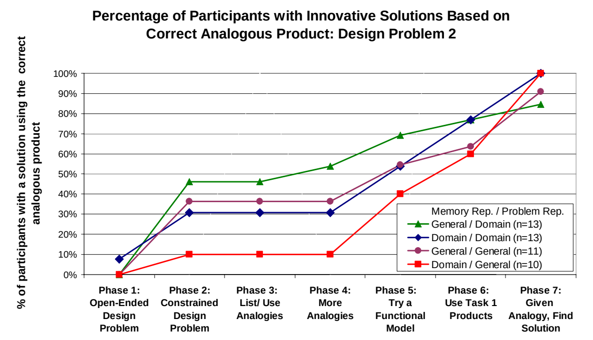


Figure 15b: Percentage of participants with a solution based on the target analogous product at each phase, Design Problem 2.

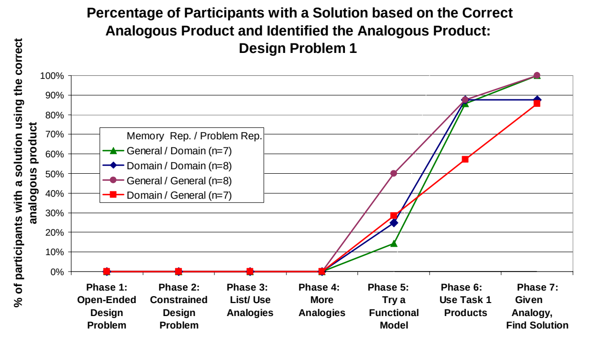


Figure 15c: Percentage of participants who had a solution based on the target analogous product and also identified the analogy at each phase, Design Problem 1.

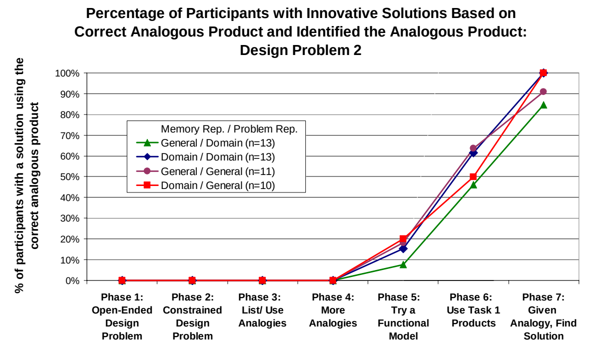


Figure 15d: Percentage of participants who had a solution based on the target analogous product and also identified the analogy at each phase, Design Problem 2

This result has important implications for teaching designers to think about and remember design solutions they encounter. If they seek representations that apply across more domains and in more general forms, they will be much more likely to be able to use the design in the future. For example, framing an air mattress as "a device that uses a substance from the environment it is used in", rather than "a device that is filled with air" makes it much more likely to be used in future design problems that seek innovative solutions.

6.2. Question 2: How does the representation of the problem statement affect the ability of a designer to retrieve and use a relevant analogous product to find a solution to a new design problem?

The representation of design problems clearly influences a designer's ability to generate analogous solutions (Figure 15a-d). The representation that will give the designer the highest probability of exposing or generating an analogous solution depends on how the analogous solution is stored in memory. If the analogous product is stored in a general form, then a domain specific representation is the most efficient means to retrieve it. Generally, it is not known in advance what representation is most likely to retrieve the desired information. This means that the best approach for seeking analogous solutions is to use multiple representations that vary across the range of domain specific or domain general.

This experiment also provided a basic study of the potential for function structures (functional models) to enhance the design-by-analogy process. Participants were given function structures with process choices which are consistent with the analogous solutions. These function structures also included linguistic functional descriptions that were different from the given problem statements. This experiment does not address how the participants would go about developing these particular function structures. This experiment addresses the question that if given an appropriate function structure, does it increase the likelihood of generating an analogous solution? From the results, there is a clear increase in phase six when participant use the function structures to assist in generating solutions. This result is exciting and a validation of anecdotal claims about an important role of functional modeling in design. Function structures are another potential representation that will enhance the design process and should be included in the search for analogous solutions. Diagrammatic representations merit further investigation.

6.3. Question 3: What is the best way to represent a design problem when the representation in memory

is not known and what implication does this have for a design-by-analogy method?

For any design task, a number of representations should be created with a varying semantics. Typically it is not known how relevant analogies are represented in memory and which retrieval cues are required. Therefore a number of representations and therefore retrieval cues should be created to maximize the probability a useful analogy will be found.

7. DISCUSSION OF ADDITIONAL RESULTS AND OTHER IMPLICATIONS

The series of experiments provide results and implications beyond the research questions.

Analogy identification and implications for naturalistic analogy research

Designers frequently use analogies to solve design problem without realizing the source of the idea. The participants used analogies to solve the design problems, but did not mention that they were using analogies and/or did not realize that their solutions were analogous to previously experienced products until a later phase (Figure 15a-d). If the designers had realized the source of the idea, they would have listed the analogy at a much earlier phase (Figure 15c-d). Instructing subjects to use analogies and list the analogies they had used caused little effect.

Our findings replicate the work of Schunn and Dunbar [31], but for an independent data set and in the engineering domain. Schunn and Dunbar found that participants often used analogies to solve difficult insight problems, but the subjects did not realize they were doing so. One implication of this result is that analogies play an important role in problem solving, but do so, at least in part, outside of awareness. Another implication is that, in naturalistic observation studies, simply recording how often people say they are using analogies is likely to underestimate their true frequency. For example, imagine an investigator who seeks to determine how important analogies are in generating new designs. This researcher decides to observe expert designers at their workplace generating novel designs and counts the number of times the experts say “this is just like [some other product]”. Intuitively, this procedure seems reasonable, but our data suggest that it will underestimate the role of analogies. These results also indicate that designers frequently use analogy without recognizing it. This implies that design by analogy has an even greater impact on the design process than what is currently indicated by the anecdotal evidence.

7.1. Design constraints guide move designers to search particular areas of the design space.

We hypothesize the application of design constraints can lead designers to search particular regions of the design space. Systematically adding and removing constraints may assist the designer in thoroughly searching portions of the design space. This approach has potential as part of a design method. The experiments presented in this paper intentionally constrained the design space to areas where it was known that good solutions existed. The constraints required participants to search particular regions of the design space.

8. CONCLUSIONS AND FUTURE WORK

Design-by-analogy is a powerful tool in a designer’s toolbox, but few designers have the methods to harness its full capacity. Simply recognizing its potential and attempting to search mentally for analogies is not enough. Designers need methods and tools to support this process. They need approaches for when they feel they have run out of ideas. They need methods to represent the problem in a multitude of representations. The right representations have the potential to increase a designers’ probability of success by up to 40%. These methods need to be built on a solid understanding of human capacity combined with scientific design knowledge. This experiment demonstrates, at least foundationally, the impact the right representation has on the design by analogy process.

This paper explores a limited set of influences on the design-by-analogy process and highlights only a few of the potential levers that a design methodology may take advantage of. The analogy between the airplane and the novel kayak design illustrate the influence of domain knowledge in this process. This warrants further experimental exploration. A design methodology will needs tools to highlight areas where domain knowledge is lacking and approaches to facilitate the recognition of the underlying principles.

Design-by-analogy is a common occurrence in the design process. Designers frequently use analogous products without recognizing the origin of the idea. Participants who have been exposed to the technique of design-by-analogy will spontaneously use it when asked to generate design solutions. Design-by-analogy is not limited to an elite few designers who learn to harness its power but it is a commonplace approach.

A deeper understanding of the mechanism behind analogical reasoning and their implications within design will guide the development of drastically improved design-by-analogy methods and tools for design innovation. Representation clearly matters and seeking improved representations has great potential for significantly enhancing the innovation process.

8.1. Future Work

Future work will focus on developing new design approaches and methods to increase the quantity, quality, novelty and variety of innovative solutions based on the knowledge gained from the experiments presented and other relevant literature. Greater exploration of the use of functional models and other representations for assisting in the design process will also be investigated. New methodologies will be validated through controlled experiments and with professional designers.

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APPENDIX A: SOURCE ANALOGY AND DESIGN PROBLEM DESCRIPTIONS FOR EXPERIMENT 2

(see [37] for Experiment 1 descriptions)

Design Problem 1

Design a fast kayak.

Design Problem 1- Additional Constraints

Design a fast kayak.

- A person is the only available power source.
- It must have a top speed of greater than 14 mph. Currently, typical human-powered boats have a top speed of less than 6 mph even for top athletes.
- The top speed is limited by drag, the faster a boat goes the greater the drag.
- Your design must reduce the drag.

Design Problem 2

Design a set of goggles that remove dirt and mud from a dirt bike racer's goggles.

Design Problem 2- Additional Constraints

Design a set of goggles that remove dirt and mud from a dirt bike racer's goggles.

- Forcing the dirt and mud across the goggle's surface creates scratches. The goggle system must not scratch the surface of the goggles.
- The dirt and mud can not be forced across the surface of the goggles.
- The dirt bike racer's hands cannot leave the handle bars of the bike.
- A section of the goggles at least 1" by 2" must be completely clean.

Design Problem 3

Design a kitchen utensil to sprinkle flour over a counter.

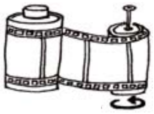
Design Problem 3- Additional Constraints

Design a kitchen utensil to sprinkle flour over a counter.

- The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.
- The entire kitchen utensil must be made from only **one** thickness of wire.
- The kitchen utensil must be **manufactured by bending** and cutting the wire only.
- The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.

Pepper Mill
A small motor inside the pepper mill spins and grinds the peppercorns into ground pepper. A person presses a button to actuate a small dc motor.

Device to create a fine powder
A small motor inside the device turns and breaks down the substance into a fine powder. A force presses a switch to turn on a small actuator.



Film in a camera
Two reels feed the film in front of the stream of light. The film captures the image and then a new unexposed section of film is moved into place.

Film in a camera
Two reels move a surface in the path of the incoming substance. The surface collects the substance and then a new unchanged surface is moved into place.

Football
A person throws the American football. As it flies through the air it spirals. This spiraling reduces air friction allowing the ball to travel farther.

Moving Device
Another object gives energy to this device. As it moves through a substance it turns about. This motion changes the forces allowing the device to move more.

Section view of a Wing

Airplane
An airplane flies through the air allowing rapid flights. The airfoil shape of the airplane's wings causes a lift force as the plane flies through the air. As the plane increase altitude there is less drag due to the air being less dense.

Device for Rapid Travel
This device moves through a fluid allowing rapid travel. The shape of the device’s extensions causes a net force as the device moves through the fluid. As the device changes position there is less resistance due to the fluid being less dense.

Shape-o-toy
This toy serves a number of purposes. The two halves contain the blocks allowing them to be carried. A child pulls the two halves apart and the blocks fall out.

Device to hold and release substances
This device serves a number of functions. The two sections hold the substances allowing them to be moved. A force separates the sections and the substance is released.

APPENDIX A: DESIGN PROBLEM DESCRIPTIONS FOR EXPERIMENTS 3

Source analogies are the same as Experiments 1 & 2

General: Design Problem 1
Design an exercise device that can be carried for long distances in a 3 ft^3 container

General: Design Problem 1- Additional Constraints
Design an exercise device that can be carried for long distances in a 3 ft^3 container. Here are the additional requirements:

- Provides at least 15 lbs of resistance
- Adds less than 4 lbs to the 3 ft^3 container.
- Maximum volume is 120 in^3 (~750 cm^3).
- It must be capable of being used for movements normally done with hand weights
- It cannot use strips or cords of elastomer (rubber) for resistance.

Domain: Design Problem 1
Design a piece of exercise equipment that can be carried in a suitcase.

Domain: Design Problem 1- Additional Constraints
Design a piece of exercise equipment that can be carried in a suitcase. Here are the additional requirements:

- Provides at least 15 lbs of resistance
- Adds less than 4 lbs to the suitcase
- Maximum volume is 120 in^3 (~750 cm^3) or about half the size of a briefcase.
- It must be capable of being used for exercises normally done with hand weights

It cannot use strips or cords of elastomer (rubber) for resistance

General: Design Problem 2
Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

General: Design Problem 2- Additional Constraints
Design a device to disperse a light coating of a powdered substance that forms clumps over a surface.

- The only material that is available to build the device from is various thicknesses of stainless steel wire.
- The entire device must be made from only one thickness of wire.
- The device must be manufactured by bending and cutting the wire only.
- The device must be capable of containing the powdered substance and carrying the powdered substance 1 meter without losing the powdered substance.

Domain: Design Problem 2
Design a kitchen utensil to sprinkle flour over a counter.

Domain: Design Problem 2- Additional Constraints
Design a kitchen utensil to sprinkle flour over a counter.

- The only material that is available to build the kitchen utensil from is various thicknesses of stainless steel wire.
- The entire kitchen utensil must be made from only one thickness of wire.
- The kitchen utensil must be manufactured by bending and cutting the wire only.
- The kitchen utensil must be capable of containing the flour and carrying the flour 1 meter without losing the flour.