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EFFECTS OF ANALOGOUS PRODUCT REPRESENTATION ON DESIGN-BY-ANALOGY

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ABSTRACT

Design-by-analogy is well-recognized for its power in innovation processes. Understanding the cognitive processes involved in the formation of analogies is important for understanding the concept generation process. This paper takes a distinctive interdisciplinary route to combine research in cognitive psychology and design to develop a more complete understanding design-by-analogy and to provide the basis for formal method development.

Designers use numerous external representations in the design processes including, but not limited to, linguistic descriptions of the problems, diagrams and sketches. Information and prior solutions the designer has seen are examples of internal representation. Representation has significant impact on the design-by-analogy process. This paper presents experimental results showing that the representation of a product in a person's memory and the representation of the design problem influence the person's ability to solve the design problem based on an analogous product. This experiment shows that appropriate representations facilitate design-by-analogy. A more general semantic description of a product allows for a greater higher likelihood of using a previously experienced product as a source analogy. These results are significant findings, especially regarding their implications on innovation processes, design-by-analogy methods, and design-by-analogy tools. Future work includes experiments to gain a broader knowledge of useful representations, the development of design methods and experimental evaluation of the design-by-analogy methods.

Keywords: conceptual design, creative design, creativity in design, design cognition, innovation, psychology of design, analogy, idea generation

1. INTRODUCTION

Innovation is a central aspect of the design process. We create design methods and teach them to designers with the intent of improving their abilities to develop new ideas. A central aspect of the ability to develop innovative ideas is the use of analogies, in which ideas from one domain are re-used in another area to solve a new problem [1,2,3,4,5]. The analogies may be visual or functional or some combination of the two. Figures 1-3 illustrate three innovative designs based on analogies: a fuel cell bipolar plate, a set of goggles that remove mud from a dirt bike racer's field of view and a beach chair capable of rotating as the sun changes position. A plant or tree leaf provides a useful analogy for a bipolar plate of a fuel cell, because of its similarity in functionality. The capacity of a fuel cell to generate current is affected by the function chain 'distribute fluid: guide fluid: disperse fluid.' This function chain also appears in a plant leaf. The leaf analogy is appropriate and powerful, the veins and lamina perform the functions 'distribute fluid: guide fluid' and 'disperse fluid' respectively. In Figure 1, an actual bipolar plate flow field makes use of this analogy and has been designed to mimic the structure of the leaf. Two other examples, with similar functional similarity, are shown in Figures 2 and 3 [6].

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. 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.

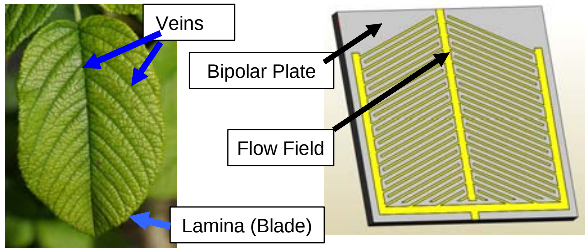

Figure 1: Fuel cell bipolar plate design generated from an analogy to a leaf.

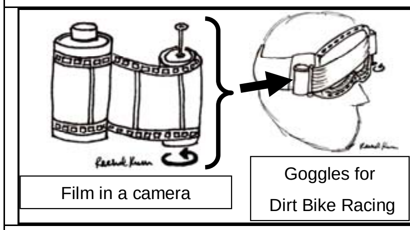

Figure 2: The spooling of film provides a solution to removing mud from a set of goggles [6].

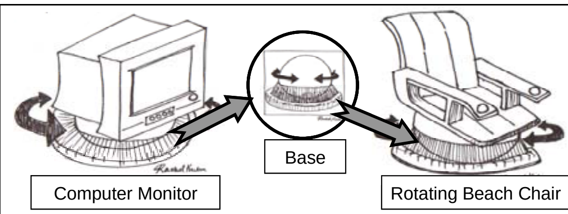

Figure 3: Solution allows a beach chair to rotate as the suns changes position, analogous to a monitor base [6].

2.1. Formal Design-by-Analogy Methods

A few formal methods have been developed to support design-by-analogy such as Synectics, French's work on inspiration from nature [3,4], Biomimetic concept generation and analogous design through the usage of the Function and Flow Basis. 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 [7]. Synectics gives little guidance on finding successful analogies. Other methods also base analogies on the natural world. French [3,4], highlights the powerful examples nature provides for design. Biomimetic concept generation provides a systematic tool to index biological phenomena [8]. 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 further researched.

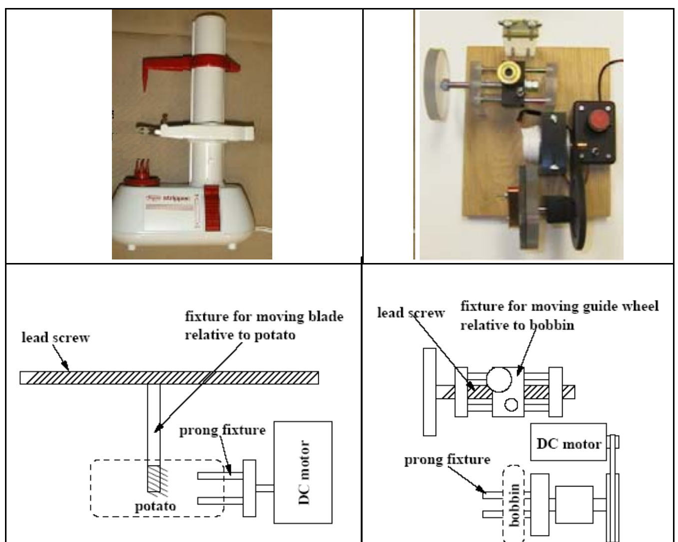

Figure 4: An innovative analogy discovered based on the function and flow basis.

Analogous concepts can 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 bases [9]. A case study, using this approach, of a pick-up winder for an electric guitar is shown in Figure 4 [9]. A guitar pick-up is an electro-magnetic device with thousands of small-gauge wire windings used to electrically transmit the vibration from the strings. Obvious analogies for the pick-up winder include a fishing reel and a bobbin winder on a sewing machine. In addition to the obvious analogies, the abstracted functional model for the pickup winder identifies the similarity to the vegetable peeler. The analogy to a vegetable peeler leads to an innovative design (prototype shown in Figure 4).

2.2. 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 [10,11,12]. 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 [13].

Research has been carried out in the field of psychology to understand the cognitive processes people use for creating and understanding analogies [12,13,14,15,16]. Figure 5 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.

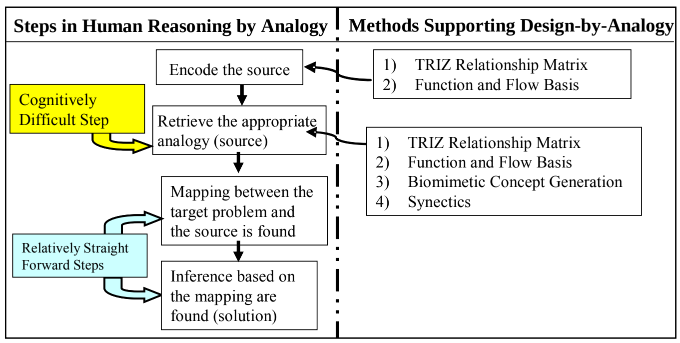

Figure 5: Steps in human reasoning by analogy and the current methods available to support those processes.

In the psychological literature, there has been a great deal of interest in the roles of analogy and expertise in problem solving. A classical laboratory finding with undergraduate students who have no specialized domain knowledge is that analogies are helpful in solving insight problems, but are difficult to retrieve from memory [17]. Conversely, naturalistic research with experts typically finds that analogies are often used [e.g.,18,19]. This dichotomy may be because experts can see the deeper, logical structure of situations while undergraduate students with no domain expertise are primarily aware of only the superficial features [cf. 20, 21, 22].

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 [23]. That is, problem solving can occur without being aware of the analogous solution in memory. Therefore, it is important to assess "finding the solution" and "recognizing the analogy" separately as part of the innovation process.

2.3. 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. This is contrasted with the storage of personal experiences or skills. In the psychological literature, the structure of human semantic memory is often conceived as a network of features that are associated with each other. For example, in Figure 6, the concept of a bed is represented by a node in a somewhat chaotic web of associations with all manner of other things. When one thinks about beds, that node becomes active, and activation can spread out along its associations to other connected ideas. Another idea is remembered when it becomes sufficiently active. However, as the activation spreads out, the further it goes, the weaker it gets. The probability that something will be remembered increases as the path distance (i.e. number of links traversed) shortens, or if multiple paths converge on it. Nodes that stand for 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 should facilitate shorter path distances and higher probabilities of retrieval. On the other hand, trying to search memory for something specific and starting from such a node, means that activation will be widely dispersed, decreasing the probability that the correct node will be retrieved [24,25,26,27].

2.4. Prior Analogy in Design Experiments

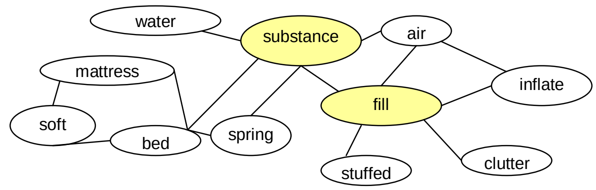

Figure 6: Example Semantic Network

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 research. Even though design-by-analogy is a well-recognized method for design, few human experiments exist focusing on analogy in design. Notable results from these experiments, however, include the work of Casakin and Goldschmidt, Ball, et al., Kolodner, and Kryssanov, et al. Casakin and Goldschmidt found that visual analogies can improve design problem solving by both novice and expert architects [28]. Visual analogy had a greater impact for novices as compared to experts. Ball, Ormerod, and Morley investigated the spontaneous use of analogy with engineers [29]. 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 when needed and have more difficulty mapping concepts from different domains due to a lack of experience [30].

A structured design-by-analogy methodology would be useful for minimizing the effects of the experiential gap between novices and experts. 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 [31,32].

Prior research in analogical reasoning found the encoded representation of a source analogy (the analogous product) can ease retrieval if it is remembered such that the key relationships apply in both the source and target problem domains [33,34]. 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.

3. EXPERIMENTAL APPROACH AND RESEARCH QUESTIONS

Designers need a predictable method for developing innovative solutions to difficult design problems. Prior work has shown that general representations of analogous products in a designer’s internal memory increase the chances the product will be used to solve a novel design problem [35]. Open questions remain regarding the effects of the design problem representation. To further explore the effects of representation on analogy use for real-world problems and to expand the knowledge base from which a design-by-analogy method will be created, an experiment is implemented. The experiment uses a combination of visual and semantic information to represent the source for the design analogy.

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

- Question 1: As designers learn about and store products in memory with either a general sentential representation that applies across multiple domains or in more domain-specific terms, how does the linguistic representation affect their ability to later use the analogous product to solve a novel design problem?
- 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?

3.1. Overview of the Experiment

This experiment controls the way in which a designer learns about an analogous product (represents it in memory) and also how a design problem is stated. This set-up allows the effects of representation in memory and of the design problem to be observed. The experiment consists 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 period for the experiment because any analogies retrieved will clearly be taken from long-term memory. This time frame has been used in previous experiments [36]. Results from the first task were matched to the second task. Participants were senior mechanical engineers with instruction in design methodology including idea generation. Multiple solutions were encouraged for all phases. Participants were told the experiment evaluated various skills used in the design process. The effects of the design problem and the analogous product representation were evaluated. 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. In each task, participants received linguistic representations using either domain specific wording or more general terms, Table 2.

Table 1: Overview of the Factorial Experiment Design

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

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**	The	device	is filled with	a substance	at the location	where it will be	used.	
	D	The	air bed	is inflated with	air	in the home	where it will be	slept on.	
2	**G**	The	substance	required	to cause	the device	to function	is available	at the location
	D	The	air	required	to cause	the air bed	to inflate	is available	in the home

3.2. Procedure

For the first task, *Memorize the Analogous Products*, participants were given five short functional descriptions of products along with a picture (Figure 7) and asked to spend thirty minutes memorizing the descriptions. 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. Two of the products acted as source analogies for the design problems in the last task, *Solve the Design Problems*, and three were distracter products that shared surface similarities with the design problems. 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 air mattress 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 this experiment was on the linguistic representations of the devices, but visual information was also present.

All time limitations throughout this experiment were based on a pilot experiment with graduate students where they were given 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 for the participants 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 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: Correct analogous product is given

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.

Phases one and two were completed for the two design problems followed by phases three through six. 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.

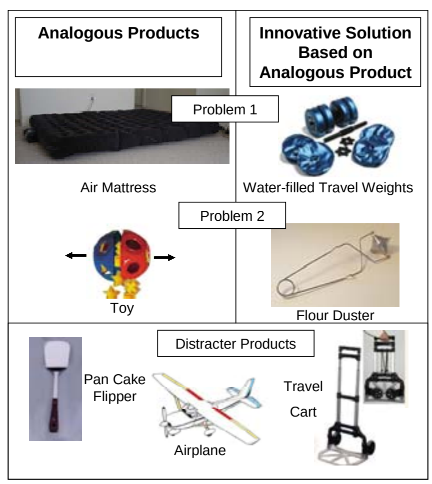

Figure 7: Analogous products and solutions based on the analogies

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

In phase 3, participants spent ten minutes listing any analogies they had used and also using analogies to develop additional solutions. An open question from one of our prior experiments [35] 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.

Next participants were shown a series of six function structures and asked to develop more solutions to the constrained design problem. 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 4 and 9 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. This phase of the experiment addresses the issue if given an appropriate functional representation will it assist in solving a difficult design problem? This experiment does not address how these particular functional representations with appropriate process choices can be developed.

In phase 6, 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 analogies. Finally, participants were given the correct analogy for each problem, asked to place a check where they had used it and asked to see if they could solve the design problem using the correct analogue 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 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. During one of session of task 2, 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. The entire experiment required about two hours.

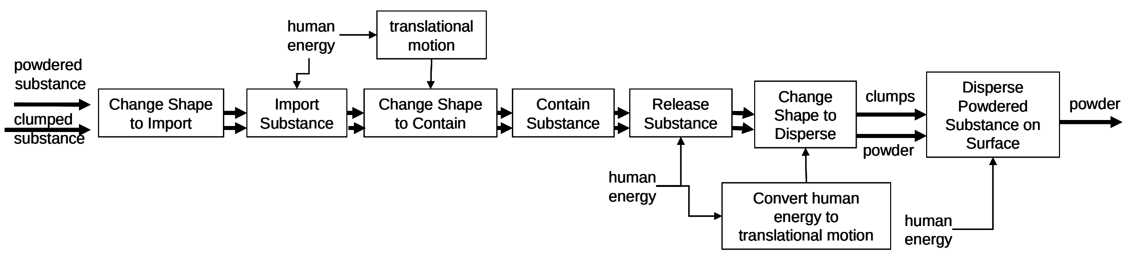

Figure 8: Functional model for design problem 2: flour sifter

3.3. Metrics

Each analogy produces a set of solutions not a single solution. The main metric used for this experiment was when the participants produce a solution to the constrained design problem based on the analogy and when they then identify the correct analogy. 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. Two evaluators rated the data independently. Initial agreement was approximately 80% and disagreements were readily resolved through discussion. The most common reason for the initial small differences in scoring was resolving the participant references to solutions that appeared on different pages of the generated design solutions.

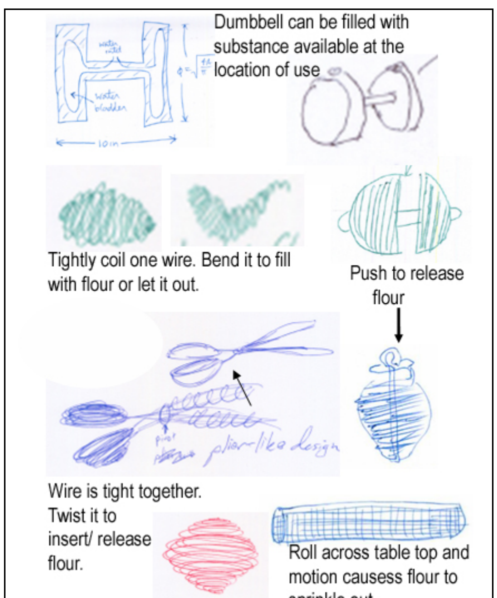

Figure 9: Example solutions found by the participant to the design problems.

4. RESULTS

Our study has a number of interesting results that address and further illuminate the research questions. Example results are shown in Figure 9. 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. Figures 10a-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. This included twenty participants for design problem 1 and three participants for design problem 2. Participants who memorized the analogous product in a general form and were given a domain-specific description of the design problem 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 [37] 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 a fairly large number 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 probably distribution with pair wise comparisons between the conditions, the general/domain condition is statistically significantly different from the other three conditions ($p<0.008$, $p<0.002$, $p<0.001$) [38]. 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.

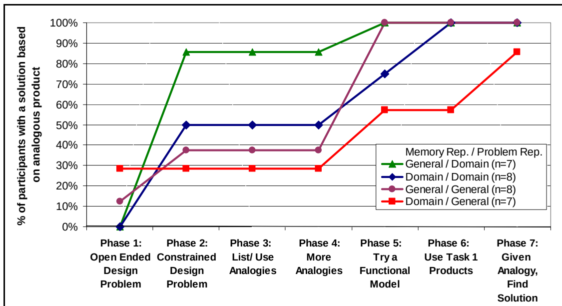

Figure 10a: Percentage of participants with a solution based on the correct analogous product at each phase, Design Problem 1.

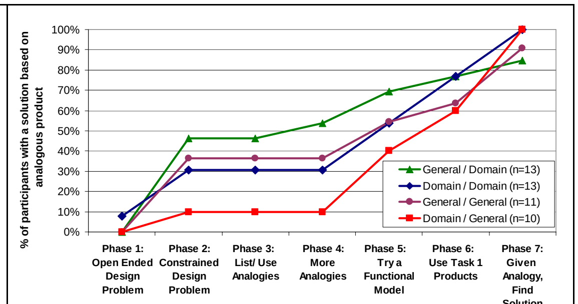

Figure 10b: Percentage of participants with a solution based on the correct analogous product at each phase, Design Problem 2.

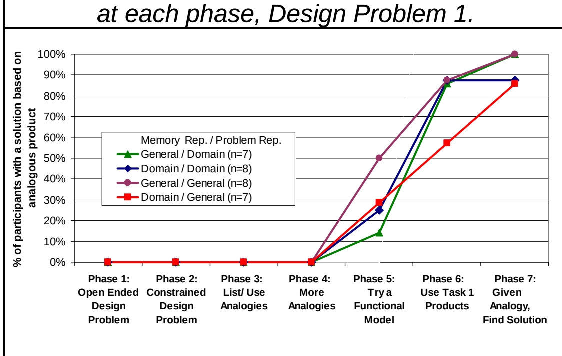

Figure 10c: Percentage of participants who had a solution based on the correct analogous product and also identified the analogy at each phase, Design Problem 1.

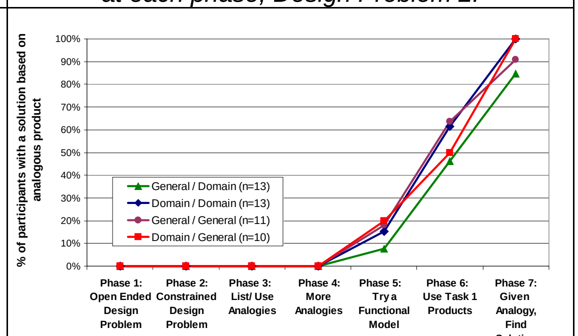

Figure 10d: Percentage of participants who had a solution based on the correct analogous product and also identified the analogy at each phase, Design Problem 2.

A two-predictor logistic model [37] 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. Clearly from the plots, the general/domain condition is different from the other three conditions. Using a binomial probably distribution with pair wise comparisons between the conditions, the general/domain condition is statistically significantly different from the domain/general condition ($p<0.0001$) [38]. Due to the sample size, the power to detect differences using a logistic model is low.

Figures 10a-c show when participants found a solution based on the analogy and also explicitly referenced which product from task 1 was analogous. Participants could have labelled the analogy as early as phase two 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.

4.1. Survey Results- Did participants feel like they had enough time?

To evaluate if the participants felt they had enough time, two Likert scale questions were asked. The questions asked participants to agree or disagree with the statements, "I ran out of time before I ran out of ideas," and "I ran out of ideas before I ran out of time." Over 75% of the participants felt they had plenty of time, and they ran out of ideas before they ran out of time (Figure 11).

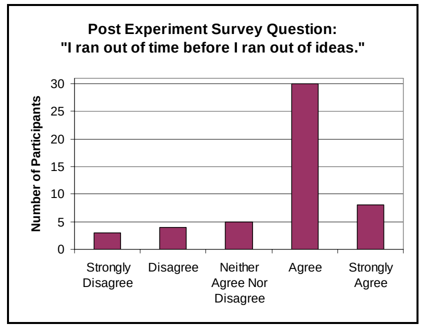

Figure 11: Almost all participants felt they had plenty of time and that they ran out of ideas.

5. ADDRESSING THE RESEARCH QUESTIONS

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

5.1. Question 1: How does the linguistic representation of a product stored in memory affect a designer's ability to later use it to solve a novel design problem?

General linguistic representations, which apply both in the analogous product and design problem domain, increase the success rate relative to the ***domain specific*** representations. If a designer remembers 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 (Figures 10a-d). This result has very important implications for how designers are taught 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.

5.2. 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 the design problem clearly influences a designer's ability to generate analogous solutions (Figure 10a-d). The representation which 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. This study did not evaluate the case where both the source product and the problem statement are in the same domain. This study evaluated only cross-domain analogies. For products that are committed to memory in more domain specific terms, it is unclear what representation is best since this study did not evaluate the case where both the problem statement and the source product were in the same domain. Based on the results, for cross domain analogies, a domain specific problem description is more likely to retrieve a relevant analogy. 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 structure 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 five 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 modelling 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. DISCUSSION OF ADDITIONAL RESULTS

This experiment addresses the research questions and also provides additional interesting results which are further discussed in this section.

6.1. Analogy identification and implications for naturalistic analogy research

Designers frequently use analogies to solve design problems 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 (Figures 10a-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 [23], 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.

6.2. Participants had enough time

The time periods for this experiment were based on a pilot experiment, but open questions from prior work were posed as: would the participants have a much greater chance of generating analogous solutions if they were given more time, and are the time periods adequate? To address these questions, participants received a survey at the end of the experiment asking them if they had run out of time or ideas first. An overwhelming majority of the participants, 76%, agreed that they ran out of ideas first, whereas a mere 14% disagreed. Clearly the vast majority of participants felt they had enough time (Figure 11). It is possible that even though participants felt they had enough time that they would actually have a greater likelihood of generating the analogous solutions if they spent more time ***engaged*** with the problem. To further explore this issue, the time period for searching for solutions through analogies was doubled compared to one of our prior experiments [35] and split into two periods (phase four and five). During this second time period, only one additional participant found the solution for either of the two design problems. Simply spending more time attempting to use analogies has very little effect, at least within our experimental setup, process and conditions. The time periods were long enough for these basic, yet novel, problems. While the increased time period did not facilitate the retrieval of the analogous product from the first task, participants did continue to find additional analogies and solutions. Methods that help designers to spend more time searching for analogies by preventing designers from feeling they have run out of ideas will also enhance the process.

7. CONCLUSIONS

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 ways. 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. The linguistic representation profoundly impacts a designer's ability to find an appropriate analogy in memory. This experiment demonstrates, at least foundationally, the impact the right representation has on the design by analogy process.

Design-by-analogy is a common occurrence in the design process. Designers frequently use analogous products without recognizing where 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 a common place 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. Methods to create multiple representations of a design problem will increase the probably a designer will find an analogy for an innovative solution. Representation clearly matters and seeking improved representations has great potential for significantly enhancing the innovation process.

7.1. Future Work

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

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