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Modality and representation in analogy

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Abstract

Design by analogy is a powerful part of the design process across the wide variety of modalities used by designers such as linguistic descriptions, sketches, and diagrams. We need tools to support people's ability to find and use analogies. A deeper understanding of the cognitive mechanisms underlying design and analogy is a crucial step in developing these tools. This paper presents an experiment that explores the effects of representation within the modality of sketching, the effects of functional models, and the retrieval and use of analogies. We find that the level of abstraction for the representation of prior knowledge and the representation of a current design problem both affect people's ability to retrieve and use analogous solutions. A general semantic description in memory facilitates retrieval of that prior knowledge. The ability to find and use an analogy is also facilitated by having an appropriate functional model of the problem. These studies result in a number of important implications for the development of tools to support design by analogy. Foremost among these implications is the ability to provide multiple representations of design problems by which designers may reason across, where the verb construct in the English language is a preferred mode for these representations.

Keywords: Analogy; Cognitive Models; Idea Generation; Innovation; Psychology of Design

1. INTRODUCTION

The idea generation phase is a crucial part of the design process in which concepts are developed either intuitively or through systematic processes. There are many approaches to idea development, but we focus in this paper on factors that influence the use of analogies. Designers frequently retrieve and use solutions from analogous designs to help them create innovative solutions to new problems (Casakin & Goldschmidt, 1999; Leclercq & Heylighen, 2002; Christensen & Schunn, 2007). Indeed, studies of the evolution of technologies frequently cite analogies as an important force in the development of product classes (Basalla, 1988). One recent example is a retractable mast with sail designed after studying bird and bat wings (BBC, 2000; Fig. 1). This sail is also useful for cargo ships to harness wind power and reduce fuel costs. The sails are easily raised and lowered and are very compact (Reed, 2006).

Although observational studies of designers at work demonstrate the use of analogy (e.g., Christensen & Schunn, 2007), there are many open questions surrounding the factors that promote the retrieval and use of analogies. For the above example, what modalities and representations make this type of innovation more likely? How do different modalities and representations influence a designer's abilities? What will make designers more successful? What tools do designers need to support this process? The paper uses a fundamental experimental approach to explore the effects of representation within the modality of sketching and the effects of coupling the modalities of functional modeling and sketching. We begin by reviewing previous research in cognitive science on analogical reasoning. This review serves as the foundation for the research questions and experimental approach described in the following sections. Then we present an experiment that examined the use of analogies in mechanical engineering design, and we discuss the implications of this work for automated design.

2. MOTIVATION AND PREVIOUS WORK

In this section, we review related research on analogical reasoning and design. In this paper, we focus on design by analogy in the modality of sketches. Much work within design research has investigated the use of sketches (Ullman et al., 1990; Goldschmidt, 1991; Goel, 1995; Suwa & Tversky,

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Fig. 1. The design of the sails of the cargo ship are based on analogies to a bat's wing (left panel, BBC, 2000; middle panel, Reed, 2006; right panel, adapted from *Scientific American*, 1998).

1997; Purcell & Gero, 1998; Stahovich et al., 1998; Shah et al., 2001; Nagai & Noguchi, 2002; Yaner & Goel, 2006*a*, 2006*b*, 2007; Yang & Cham, 2007). There is other research looking at modalities such as the use of physical models in design, and we believe that the work we present here is relevant to these other modalities (e.g., Vidal et al., 2004; Christensen & Schunn, 2007). 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.

2.1. Representation

A representation is a physical or mental construct that stands for some other physical or mental construct. Analyses of the concept of representation suggest that there are four necessary parts to a mental representation: the physical or mental construct serving as the representation, the domain being represented, rules (usually implicit) that map parts of the representation onto the item represented, and a set of processes that makes use of the information in the representation (Markman, 1999). 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.

The study of mental representations makes clear that people represent relationships among items, and that these relationships play an important role in analogical reasoning. Theories of analogy often posit that mental representations have a structure akin to that of predicate–argument structures used in logic, artificial intelligence, and linguistics (Gentner, 1983; Holyoak & Thagard, 1989). Using this representational notation, a predicate is a statement that is asserted of a subject or subjects, and arguments are the subjects of which predicates are asserted. For example, Brown(x) is a predicate capable of representing the property that some object x is brown. The variable x serves as an argument to this predicate and delimits the scope of the predicate. Thus, the proposition Brown(boot) is a statement that has the gloss "The boot is brown."

By convention, a predicate (like Brown[boot]) that takes one argument is called an *attribute*. Attributes are typically used to describe objects in a domain. Predicates that take two or more arguments are called *relations*. For example, Larger_than(x, y) takes two arguments and represents the relation that some object x is larger than some other object y. This distinction is important, because analogies typically involve similarities between two domains in the set of relations that describe them (see Falkenhainer et al., 1989). We discuss analogical reasoning in more detail below.

2.2. Cognitive memory representation

Cognitive models of memory propose that there are many different modalities of representation that play an important role in cognitive processing. One distinction of interest is between perceptual (i.e., nonverbal) representations and verbal representations (Loftus & Kallman, 1979; Barrlett et al., 1980; Paivio, 1986). The distinction between perceptual and verbal representation is supported by findings such as the verbal overshadowing effect in which talking about perceptual information can interfere with the later retrieval of that information from memory (Schooler et al., 1997). One implication of these kinds of verbal overshadowing effects is that verbal idea generation techniques may suppress or interfere with perceptual information in memory that may be the source of important analogies. Thus, sketching techniques may be particularly useful for supporting the retrieval of perceptual information. Finally, although perceptual and verbal representations appear to be psychologically distinct, there is good reason to believe that there are relational structures of the sort described in Section 2.1 in both perceptual and verbal modalities (Barsalou, 1999).

2.3. Cognitive process model for design by analogy

We know that analogies are important in the design process, because designers frequently report using analogies when generating novel solutions to design problems (Basalla, 1988; Dunbar, 1997; Christensen & Schunn, 2007). Thus, it is important to describe what is known about analogical reasoning processes in more detail. The consensus view of analogical reasoning in cognitive science is that analogy involves the mapping of relational knowledge from one situation to another (Gentner, 1983; Falkenhainer et al., 1989; Holyoak & Thagard, 1989; Chiu, 2003). The problem domain is typically called the *target* of the analogy. A domain of prior knowledge that provides a potential solution to the problem is called the *base* of the analogy. Research on analogy suggests that people first find a mapping between the relations in the base and the target. On the basis of this mapping, aspects of the target may be rerepresented to make them more similar to the base. Furthermore, inferences about the target (such as potential solutions) may be made based on the similarity of the target to the base. The potential for creative problem solving is clearest when the two domains being compared are very different on the surface, although the same process of comparison can also be used for domains that share significant surface similarity (Gentner & Markman, 1997).

Research has been carried out in the field of psychology to understand the cognitive processes people use to create and understand analogies (Falkenhainer et al., 1989; Gentner & Markman, 1997; Hummel & Holyoak, 1997; Gentner, Holyoak & Kokinov, 2001; Blanchette & Dunbar, 2001). 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.

Analogy has traditionally been viewed as a comparison between two products in which their relational, or causal structure, but not the superficial attributes, match (Gentner, 1983; Gentner & Markman, 1997). For example, an airplane wing and a hydrofoil can be viewed as analogous because both generate lift using flow over their surfaces. The fact that airplane wings involve air flow and hydrofoils involve water flow does not affect the analogy (nor does other potential surface detail such as the colors that the items are painted).

In the psychology 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 they are difficult to retrieve from memory (Gick & Holyoak, 1980). Conversely, naturalistic research with experts typically finds that analogies are often used (e.g., Dunbar, 1997; Casakin & Goldschmidt, 1999; Leclercq & Heylighen, 2002). This dichotomy may reflect that experts can see the deeper, logical structure of situations, whereas those without domain expertise are mainly aware of only the superficial features (cf. Chi et al., 1981; Gentner & Landers, 1985; Novick, 1988).

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 may also be distracted by superficial features. These characteristics make them an appropriate test bed for determining the role of base representation in analogical reminding. Moreover, it has been suggested that implicit processes could mediate analogical problem solving (Schunn & Dunbar, 1996). That is, problem solving may occur based on analogy even when the problem solver is not aware that the analogy is being used. Therefore, in studies of analogical reasoning, it is important to look separately at when a solution based on a prior analogy is found and when an individual because aware of the analogy between two domains.

2.4. Retrieving analogies

Thus far we have discussed cognitive processes that allow a problem domain to be augmented by analogy to some base domain. A central problem in developing innovative solutions to problems, however, is that domains that are analogous to the problem are difficult to retrieve, particularly before the designer recognizes that the base domain is relevant for solving a problem.

The core principle of human memory retrieval is *encoding specificity* (Tulving & Thompson, 1973). In essence, this principle states that a memory will be retrieved to the extent that the context at retrieval is similar to the context at encoding. The context consists of the representation of information at the time of retrieval as well as other factors like emotional state and physical location. Much research in cognitive psychology suggests that people tend to retrieve information based on attribute similarities between domains (e.g., Holyoak & Koh, 1987; Gentner et al., 1993; Catrambone, 2002). Good analogies are ones that have primarily relational similarities. Paradoxically, then, people find good analogies useful, but they have difficulty retrieving them when they need them. On the encoding specificity view, this difficulty in retrieving analogies occurs, because people are typically focused on the specific situation they are in at the time of encoding. That is, representations of specific situations have a lot of attribute information in them. Consequently, they tend to be reminded of those situations only in new contexts that also share those attributes (see Forbus et al., 1995, for a computational model of analogical retrieval).

What would this view of analogical retrieval suggest if we wanted to improve people's ability to retrieve known situations that could be used to solve a new problem? One clear prediction is that, for any given target domain, a relationally similar base domain is more likely to be retrieved if it has few attributes than if it has many, because those attributes can only interfere with relational retrieval. In addition, this

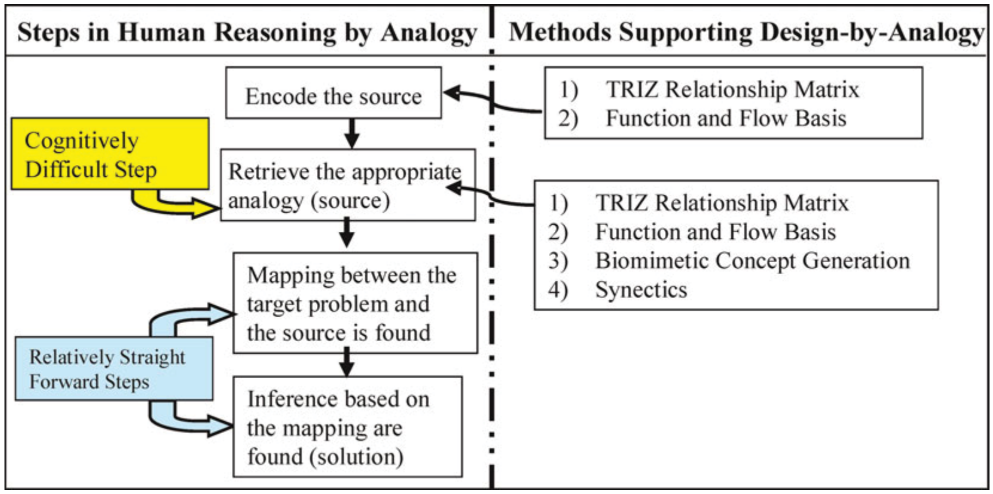

Fig. 2. The steps in human reasoning by analogy and the current methods available to support those processes.

view predicts that a base domain will generally be easier to retrieve when it is represented using general relational terms (e.g., fill or travel) than when it is represented using specific relational terms (e.g., inflate or walk). When a domain is represented using specific relational terms, it will only be similar to other domains that also use related relational terms. In contrast, a domain that is represented using general relational terms, will be similar to problems expressed with a wider variety of more specific relational terms. For example, a domain represented using the relation *walk* will only be similar to domains that use some kind of locomotion, but a domain represented using the more general relation *move* will also be similar to relations like *drive* or *fly*.

It is less clear how design by analogy should be affected by the specificity of the problem representation. On the one hand, a general representation of a problem will minimize the attributes in the description and will create a description focused on relations. On the other hand, a problem domain does not contain any relations that are part of the solution to the problem (otherwise it would not be a problem). Thus, it may actually be better to have a specific representation of the problem being solved, because this representation will contain much of the detail that will be necessary for constraining the solution to the problem. The study we present here will examine the influence of the level of specificity of the base and problems domains on the retrieval and use of analogies.

2.5. 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 (French, 1988, 1996), 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 (Gordon, 1961). Synectics gives little guidance on finding successful analogies. Other methods also base analogies on the natural world. French (1988, 1996), highlights the powerful examples nature provides for design. Biomimetic concept generation provides a systematic tool to index biological phenomena (Hacco & Shu, 2002; Tinsley et al., 2007; Vakili et al., 2007). From the functional requirements of the problem, key words are derived. The key words are then referenced to an introductory college textbook and relevant entries can be further researched.

Analogous concepts can be identified by creating abstracted functional models of concepts and comparing the similarities between their functionalities. Analogous and nonobvious products can be explored using the functional and flow basis (McAdams & Wood, 2000). A case study of a pickup winder for an electric guitar developed using this approach is shown in Figure 3. A guitar pickup is an electromagnetic device with thousands of small-gauge wire windings used to electrically transmit the vibration from the strings. Obvious analogies for the pickup 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 Fig. 3). Developing a systematic approach to search for and evaluating the utility of functionally similar concepts is critical to the successful implementation of design by analogy as is enhancing natural human capability.

Other design by analogy methods have been recently developed, including both electronic tools and sketching-based approaches. A representative example of such recent tools is the work by Chakrabarti et al. (2005*a*, 2005*b*). In this case, an automated tool exists to provide inspiration to designers as part of ideation process. Chakrabarti has tested the

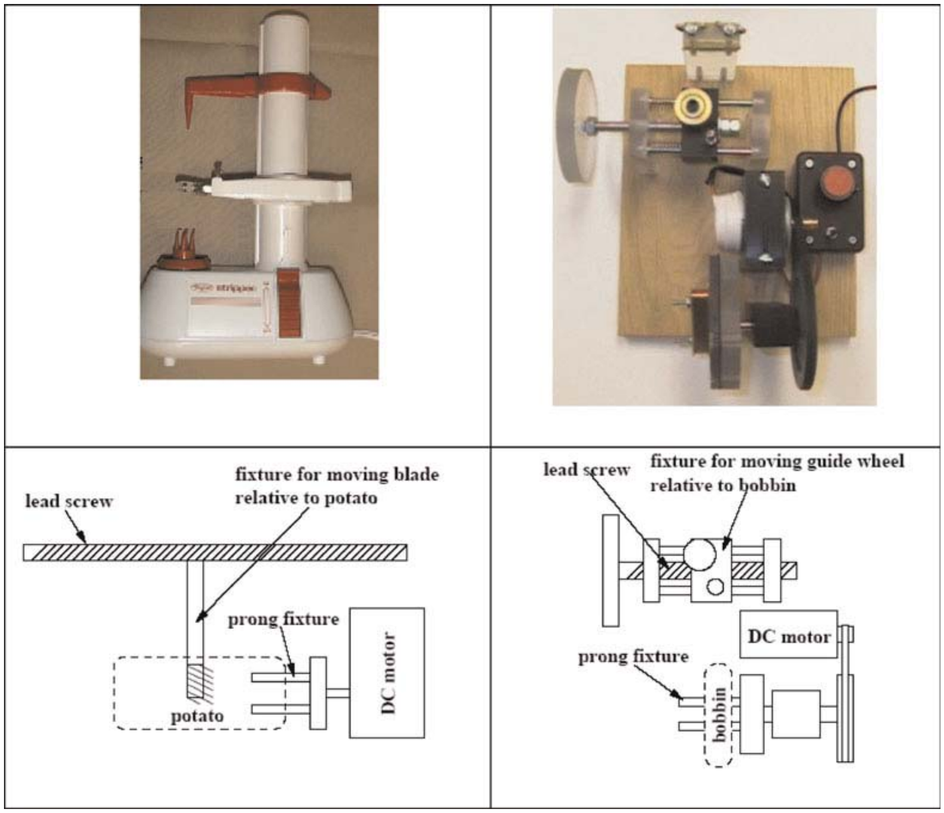

Fig. 3. An innovative analogy that was discovered based on a functional model and using the representation of the function and flow basis.

automation tool and its analogy representations with student participants as part of university design courses.

2.6. Previous research on design by analogy

Human-based design methods require a deep understanding of the processes people use and the areas in which 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 have been done that focus on the role of analogy in design. Important work in this line has been done by Casakin and Goldschmidt (1999), Ball et al. (2004), Kolodner (1997), and Kryssanov et al. (2001). Casakin and Goldschmidt (1999) found that visual analogies can improve design problem solving by both novice and expert architects. Visual analogy had a greater impact for novices compared to experts. Ball et al. (2004) investigated the spontaneous use of analogy with engineers. They found that 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 likely reflects that novices have more difficulty retrieving relevant information when needed and have more difficulty mapping concepts from disparate domains because of a lack of experience (Kolodner, 1997).

A structured design by analogy methodology would be useful for minimizing the effects of experience and for enhancing 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 (Goldschmidt & Weil, 1998; Kryssanov et al., 2001).

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 (Clement, 1994; Clement et al., 1994). 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 only on 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 and modalities 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 predictable methods and supporting automated tools 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 (Linsey et al., 2006). Open questions remain regarding the effects of the design problem representation and the modality of sketching.

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, we ran a study that 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 analogical retrieval to be evaluated. These models, along with additional knowledge gained from experimentation, can be used as the basis for tools and methods development. The experiment uses 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: Designers frequently base their solutions to novel design problems on prior analogous solutions they have stored in memory. 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 within the modality of sketching?
- 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 within the modality of sketching?
- Question 3: Does the additional modality of functional models facilitate solving a novel 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 setup allows the effects of representation in memory and of the design problem to be observed. Throughout the experiment, participants used the modality of sketching and words to both reason and document their ideas. These participants were made up of senior-level mechanical engineering students. These students ranged in age from early 20s to early 30s, and experience level from minimal industrial experience, to internship and coop experiences, to multiple years of experience obtained before returning for a higher education degree.

The choice of participants is appropriate for this study for a number of reasons. A key characteristic of the experiment concerns the use of domain knowledge for multimodal reasoning with different types of representations. The choice of experimental subjects clearly meets this characteristic. In addition, the use of college student participants allowed us to gather a sample of engineers with a range of demographic backgrounds without being affected by the scheduling constraints involved in running engineers from industry. Finally, our chosen participant group provides the opportunity to explore the effect of ideation methods as part of a higher education curriculum.

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 (Thompson et al., 2000). 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 that the experiment evaluated various skills used in the design process. The effects of the design problem and the analogous product representation were evaluated. A 2×2 factorial experiment design was employed which resulted in four different experimental groups (Table 1). For both the analogous product and the

Table 1. *Overview of the factorial experiment design*

		Factor 1: Analogous Product Representation	
		General	Domain Specific
Factor 2: design problem representation	General	Group 1: general, general	Group 2: general, domain
	Domain specific	Group 3: general, domain	Group 4: domain, domain

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 very domain specific wording or in more general terms (Table 2).

3.2. Procedure

For the first task, memorize the analogous products, participants were given five short functional–textual descriptions of products along with a picture (Fig. 4) and were asked to spend 30 min 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 3. 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 15 min to answer a quiz, requiring them to write out the memorized descriptions. Finally, the groups spent up to 10 min to evaluate their results. Two 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. 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 in mechanical engineering in which 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.

Fig. 4. Analogous products and solutions based on the analogies.

In the second task, solve the design problems, participants were given two design problems to solve. Each design problem was staged in 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 (Fig. 5)
phase 6: informed task 1 products are analogous
phase 7: target analogous product is given

Phases 1 and 2 were completed for the two design problems followed by phases 3–6. Throughout all phases participants were given the general idea generation guidelines to generate as many solutions as possible with a high quality and large variety and to write down everything even if it

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

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.

Sentences are general (G) or domain specific (D).

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.

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 were given 11 min to generate ideas for the open-ended design problems and then they given an additional 11 min 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 5-min break.

In phase 3 participants spent 10 min listing any analogies they had used and also using analogies to develop additional solutions. An open question from one of our prior experiments (Linsey et al., 2006) was whether participants would be more likely to find the source analogy from task 1 if they were given more time to use analogies. Therefore, following the initial phase using analogies, participants were given an additional 10 min 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 (Stone & Wood, 2000; Otto & Wood, 2001; Kurfman et al., 2003; Hirtz et al., 2002). They are a particular form of functional representations, where a number of such representations have been studied as part of the design process (Chandrasekaran et al., 1993; Qian & Gero, 1996; Goel, 1997; Umeda & Tomiyama, 1997; Balazs & Brown, 1998, 2002; Kitamura et al., 2002; Gero & Kannengiesser, 2003; Chandrasekaran, 2005; Stone & Chakrabarti, 2005). When function structures are created for novel design problems, process choices must be made. Process choices include using human energy to actuate the device as opposed to a battery and electric motor or a gasoline engine. The process choices for the function structures were made to be 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 whether an appropriate functional representation will assist participants in solving a difficult design problem. This experiment does not address how these particular functional representations with appropriate process choices can be developed by participants.

In phase 6 the participants were told that products from the first task were analogous, and were asked to mark their solutions that used the analogy and to generate additional solutions using analogies. Finally, participants were given the target analogy for each problem, and were asked to place a check where they had used it and to generate more ideas if they had not used the described analogy. These final two phases serve as a control to verify that the analogies being used are sensible, are useful for these particular design problems, and that they facilitate data evaluation. At each phase the participants used a different color of pen, which made it easier for the experimenters to identify the phases of the study at which information was added. A short survey at the conclusion of the experiment evaluated English language skills, 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. This caused a break in the middle of the experiment. The data were reviewed, and little impact was observed. These four participants are included in the results. The entire experiment required about 2 h.

3.3. Metrics for evaluation

Each analogy produces a set of solutions, not a single solution. Participants also created a large number of solutions that were not based on the analogies provided. We were primarily interested in the phase of the study at which participants produced 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 judged the data independently, recording when the analogous solution was found. Initial agreement was approximately 80% across the 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.

4. RESULTS

Figures 6a and 7a show the percentage of participants at each phase who were able to generate the solution to the design problems based on the analogous product. Figures 6b and 7b show when participants both generated the solution and then also explicitly the analogous product from task 1. Both sets of graphs are based on participants' indication of the solution being based on the desired analogous product. Results based on evaluators' judgements of the correct features being mapped from the analogous product to the solution show a very similar pattern of results. Examples of

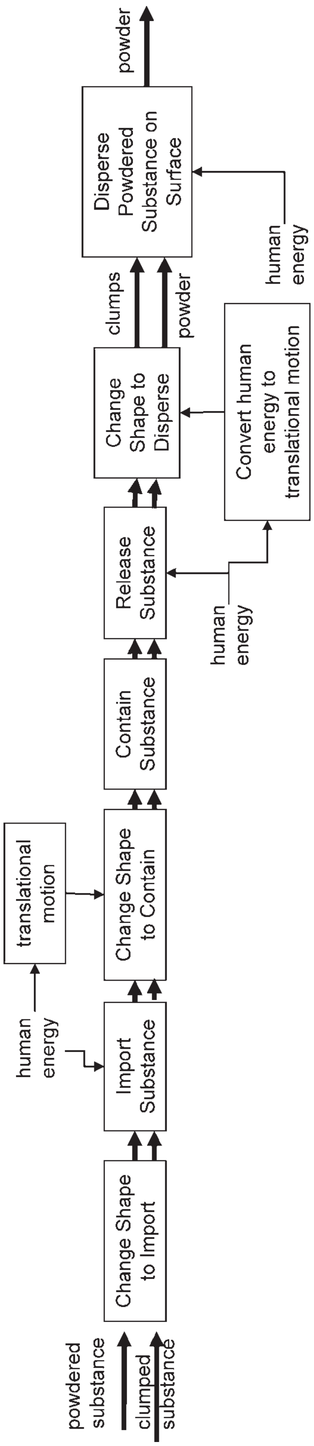

Fig. 5. The functional model for design problem 2: flour sifter.

participants' solutions based on the analogous product are shown in Figure 8. Figure 8 also contains models of the participants' ideas built by the authors for illustration and clarification. 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. Participants who had previously seen the solution to the design problems based on the analogous product were removed from the data set. This included 21 participants for design problem 1 and 3 participants for design problem 2. Participants who only completed one task of the experiment were also not included in the results. Participants who memorized the analogous product in a general form had the highest rate of success. This result is shown by the top (general/domain) line in the figures, where the success rate increased by up to 40%.

A two-predictor logistic model (Kutner et al., 2005) 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 because 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 nonsignificant ($\beta = 1.0$, $p > 0.2$). The sample size is fairly small, because of participants having seen the targeted solution, and therefore, the statistical power to detect difference is low. As the graph clearly shows, the general/domain condition is different from the other three conditions. Using a binomial probably distribution with pairwise comparisons between the conditions, the general/domain condition is statistically significantly different from the other three conditions (all $p < 0.01$; Devore, 1999). Statistical analysis based on evaluators' judgment of an appropriate mapping between the analogous product and the solution instead of the participant evaluation are consistent but with slightly higher probabilities ($p < 0.015$, <0.01, <0.015). 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.

A two-predictor logistic model (Kutner et al., 2005) 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 pairwise comparisons between the conditions, the general/domain condition is statistically significantly different from the domain/general condition ($p < 0.01$; Devore, 1999). Statistical analysis based on evaluators' judgment of an appropriate

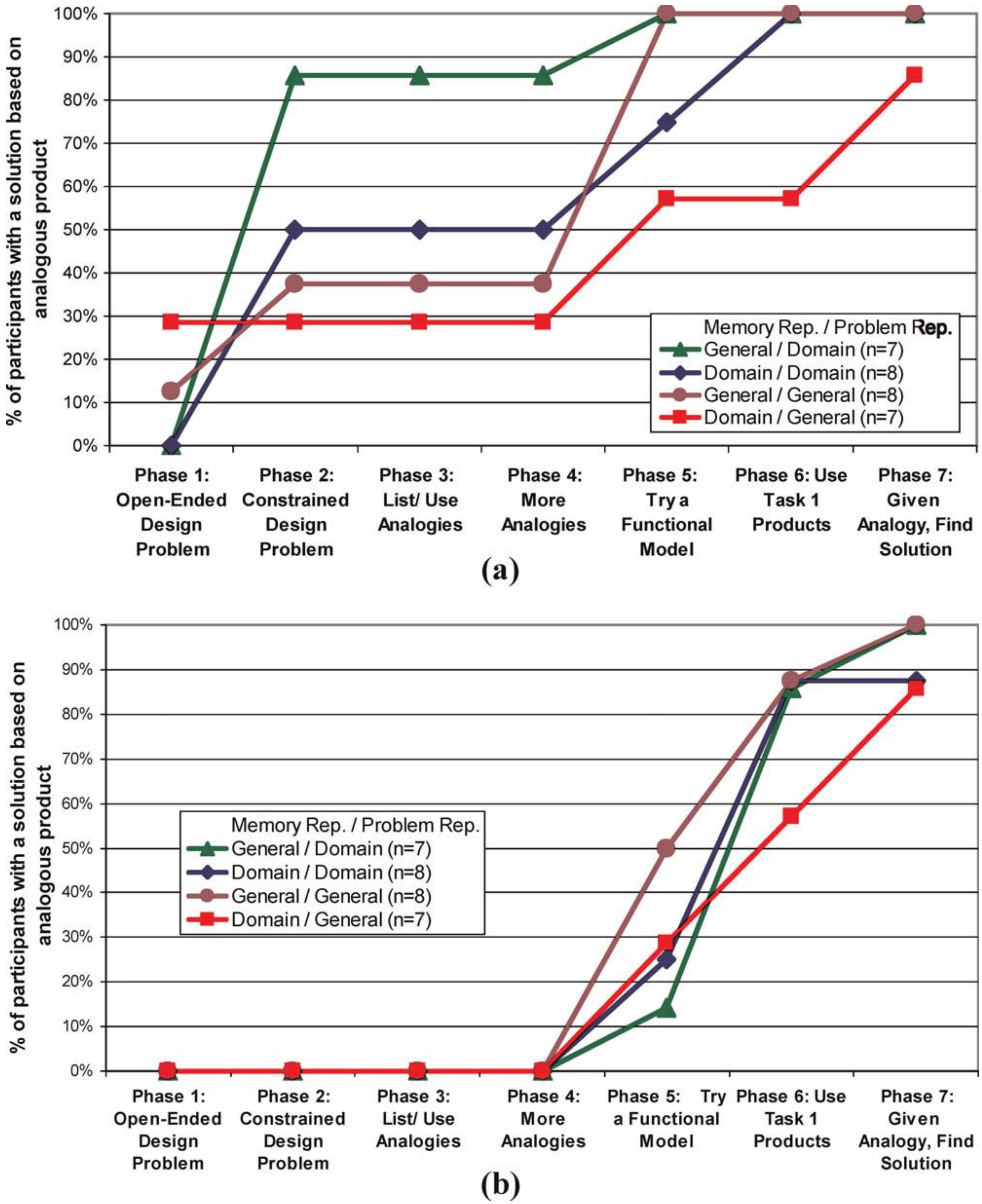

Fig. 6. (a) The percentage of participants with a solution based on the target analogous product at each phase for design problem 1, and (b) the percentage of participants who had a solution based on the target analogous product and also identified the analogy at each phase for design problem 1.

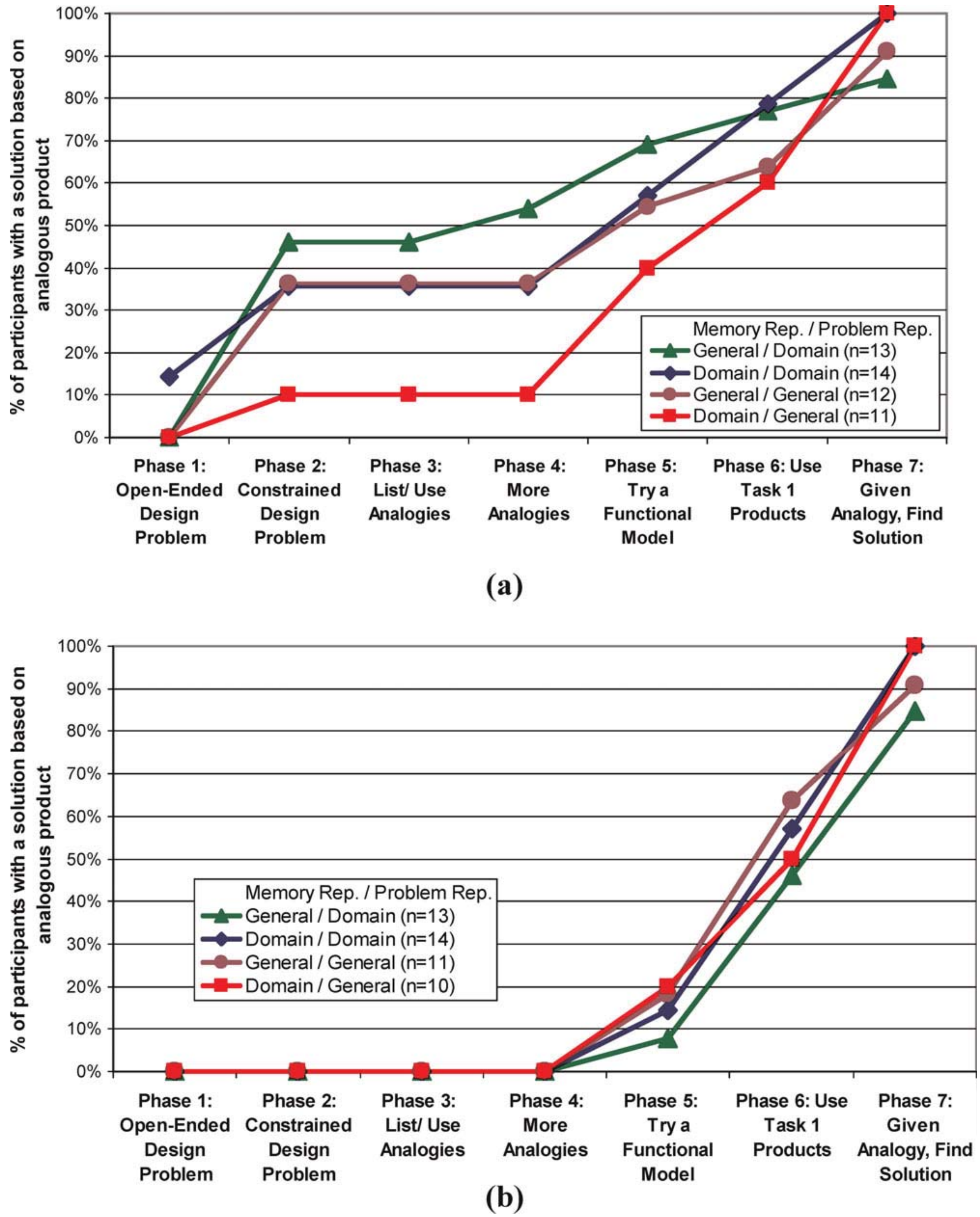

Fig. 7. (a) The percentage of participants with a solution based on the target analogous product at each phase for design problem 2, and (b) the percentage of participants who had a solution based on the target analogous product and also identified the analogy at each phase for design problem 2.

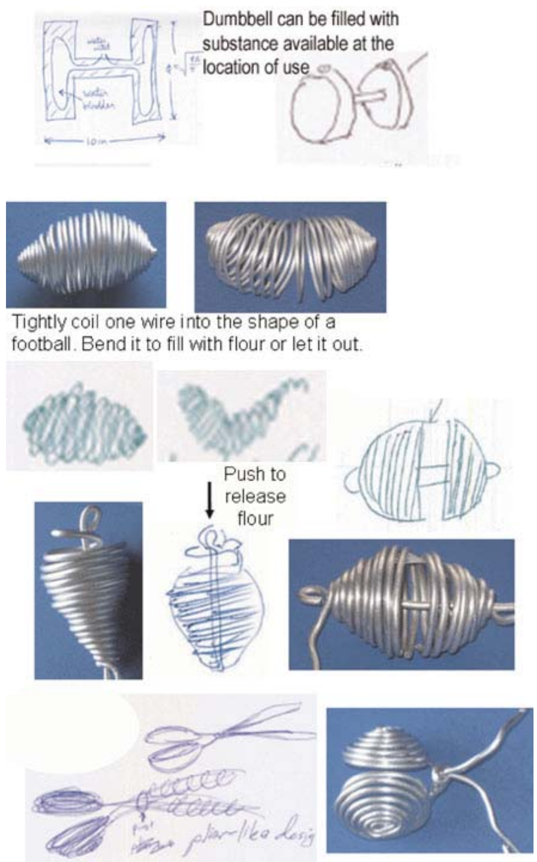

Fig. 8. Example solutions found by the participant and models built by the authors for illustration of the participants' ideas.

mapping between the analogous product and the solution instead of the participant evaluation show the same results.

Figures 6b and 7b show 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 2 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 5, when they were given a functional model. Designers frequently use previous solutions without realizing it. This effect will be discussed in detail in Section 6.

4.1. Effect of the functional models

Figure 9 shows the percentage increase with the addition of the functional models in the number of participants who had found the targeted solution to the design. Figure 9 shows the percentage increase from phase 4 to phase 5, the addition of the functional models. Across the experimental conditions the effect is similar, with the exception of the general analogous product representation with a general problem statement for design problem 1.

5. EVALUATION OF POSSIBLE LIMITATIONS TO THE EXPERIMENT SURVEY RESULTS: DID PARTICIPANTS HAVE ENOUGH TIME?

To evaluate whether the participants felt they had enough time to generate ideas, 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 (Fig. 10).

The length of each of the phases for this experiment is based on the results of a pilot experiment. However, we are interested in whether participants might have generated more analogous solutions if they had been given more time. To address this issue, we gave participants a survey after the study asking them if they had run out of time or ideas first. Overall, 76% of participants stated that they ran out of ideas first, but only 14% felt that they ran out of time before they were able to state all of their ideas (Fig. 10). 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* on the problem. To assess this possibility, the total time for participants to search for solutions through analogies was doubled compared to one of our prior experiments (Linsey et al., 2006) and corresponds to phases 4 and 5. 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. Although the increased time period did not facilitate 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.

6. ADDRESSING THE RESEARCH QUESTIONS

The data illuminates the effects of problem representation and representation of analogous products on design by analogy within the modality of sketching. The following discussion provides further insights based on the results.

6.1. Research question 1

General linguistic representations, which apply both in the analogous product and design problem domain, increase the success rate more than *domain-specific* representations. General linguistic representations are more likely to be retrieved from memory. If a designer retrieves analogous products from memory with more general representations, then they are more likely to later use these analogies to solve

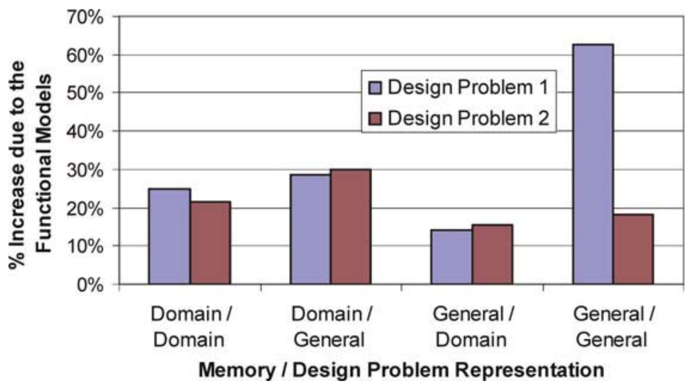

Fig. 9. The functional models assisted the designers who had not been able to find the solution using the problem statement and trying to find analogies.

novel design problems (Figs. 6a and 7a). This result has very important implications for the way we should teach 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. Research question 2

The representation of design problems clearly influences a designer's ability to generate analogous solutions (Figs. 6a and 7a). 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. This experiment evaluated cross-domain analogies; the products and the design problems were not in the same domain. Retrieving solutions to a design problem within a domain is much easier than cross-domain analogies but results in less novel solutions presumably because both the product and design problem are represented in the same domain specific form. For the case of cross-domain analogies, if the analogous product is stored in a general form, then a domain specific representation is the most efficient means to retrieve it. For products that are committed to memory in more domain-specific terms, it is unclear what representation is best. 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 to domain general.

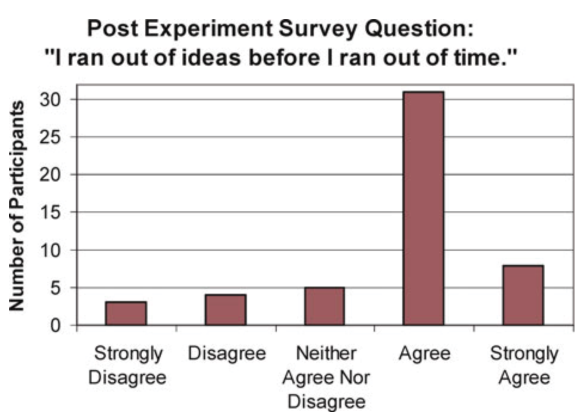

Fig. 10. Almost all participants felt that they had plenty of time and that they ran out of ideas.

6.3. Research question 3

There is a clear increase in the number of participants who found a solution based on the analogy during phase 5, when participants used 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. It is important for us to point out, however, that participants were given function structures with process choices that were consistent with the analogous solutions we hoped that they would find. These function structure also included linguistic functional descriptions that were different from the given problem statements. This experiment does not address the way participants would go about developing these particular function structures on their own. Instead, it suggests that if designers create an appropriate function structure, it will increase the likelihood that they will generate the analogous solution. Further research must explore the kinds of function structures that designers generate spontaneously and the influence of these function structures on the analogies retrieved. However, clear implications from this work is that functional representations are important, and in turn, verb constructs (active functions) from the

English language should be exploited to assist in the retrieval or search for analogies.

7. DISCUSSION OF ADDITIONAL RESULTS

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

7.1. Analogy identification and implications for naturalistic analogy research and evaluation of automated tools that provide analogous solutions

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 (Figs. 6 and 7). Instructing subjects to use analogies and list the analogies they had used caused little effect. Our findings replicate the work of Schunn and Dunbar (1996), except 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 this. One implication of this result is that analogies play an important role in problem solving, but they do so, at least in part, outside of awareness. Another implication is that, in naturalistic observation studies or when evaluating an automatic design tool that facilitates analogies, simply recording how often people say they are basing their solutions on 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.

7.2. Implications for automated or semiautomated design tools

Automatic tools have great potential to support and enhance conceptual design and design by analogy. Designers need more tools that assist in searching and retrieving analogous design solutions, especially far-field solutions. Some tools have been and are currently being developed to assist designers in finding analogies. Chakrabarti et al. (2005*a*, 2005*b*) have created a tool that searches a biological database and retrieves possible solutions. Hacco and Shu (2002) created a tool that cross-references a functional description in engineering terms to the related biological phenomena thereby retrieving possible solutions. Computational tools need to be able to search other representations (shape, form, dynamic motion, etc.) other than linguistic (Yaner & Goel, 2006*a*, 2006*b*, 2007). Computational tools can also support engineering design by creating multiple function structures with different processes choices. It would be useful for automatic tools to a transition from one representation (functional model to problem statement) and to present information in multiple representations.

8. 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 and methods to represent the problem in a multitude of representations. Automated tools need to be developed to support and enhance this process. 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 as they reason within the modality of sketching. This experiment demonstrates, at least foundationally, the impact the right representation within a modality has on the design by analogy process.

The coupling of modalities has significant potential to enhance the design by analogy process and support innovation. This study shows that the addition of a function structure, or more generally functions stated as active verbs, to the sketch-based concept design process improved a designers' ability to find an innovative solution to a novel design problem. Additional representations and modalities are likely to also augment the process and warrant further investigation.

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 and tools to create multiple representations of a design problem will increase the probably a designer will find an analogy for an innovative solution. Automation tools can the assist the designer in finding analogous solutions and automatically creating multiple representations. Representation clearly matters, and seeking improved representations has great potential for significantly enhancing the innovation process.

8.1. Future work

Future work must 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. Additional studies must also explore other influences on the design by analogy process including expertise, physical models, visual information, and a wider variety of design problems. New methodologies will be validated through controlled experiments and with professional, practicing designers.

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