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DESIGN IDEAS AND IMPASSES: THE ROLE OF OPEN GOALS

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ABSTRACT
Understanding the source of creative or innovative design ideas has the potential to provide a number of insights into design problem solving as well as practical benefits. The work presented here is a first step at generalizing some findings from the psychological laboratory to a design task. Open goals have been shown to influence cognition so that information about open goals, or unsolved problems, is likely to be incorporated into future problem solving attempts even when that information is presented in a second task unrelated to the original problem. The results of a study on design problem solving are presented, and these results show that open design problem solving goals direct the acquisition of information relevant to the unsolved design problem. Participants read a series of text passages during a break in problem solving with one of those passages containing information that was a distant analogy to the design problem. This information influenced problem solving including how likely participants were to change their representation of the problem. Some of the implications of these results for our understanding of design problem solving are discussed.

Keywords: Cognition, Problem Solving, Creativity, Open Goals, Insight

1 INTRODUCTION
Where do innovative design ideas come from? This question is hard to answer from a scientific perspective. Often times, people can not explain how they come up with an idea, and in those cases where they do have an explanation it is often too vague to be an indication of the mental mechanisms that produced the idea. A theory which explained the source of innovative ideas and the cognitive mechanisms involved in their generation has the potential to further our understanding of cognition and design, and such a theory could lead to the development of design tools that enhance the innovativeness of designers.

Basic psychological research is necessary to understand the mechanisms that produce ideas and how they become incorporated into the design process. Recent work in psychology has shown that open goals, or goals which have not been completed such as unsolved problems, play an important role in problem solving especially in situations where an impasse in problem solving has been reached [1-3]. In this work, participants were allowed to work on simple insight-like problems some of which they did not solve. They were then given a second task which had hints to the solution of some unsolved problems embedded within it. When given another opportunity to work on previously unsolved problems, participants solved more of the problems for which they had seen hints. In addition, the hint was most effective when the participant had an open goal for that problem as the hint was not as effective if shown before the problem had been attempted for the first time.

Following up on these basic results, we found that people were more likely to benefit from exposure to relevant information depending on their representation of the problem and the progress they had made in solving it [2]. People were more likely to make use of relevant information in a task unrelated to the original problem when they were right at the point of impasse. An impasse in problem solving occurs after some amount of work on the problem when the problem solver does not know how to proceed. This initial work is important as it establishes an initial problem representation in the problem solver's mind. However, continuing to work past an impasse results in repetition of prior unsuccessful ideas which actually makes new ideas harder to generate. When participants in our studies suspended work on the problem at the point of impasse they were more likely to make use of the implicit hint provided in another task even though they were unaware they had seen problem relevant information. These results imply that there may be an optimal point at which to suspend work on a difficult problem which is at the point of impasse where the problem solver is most susceptible to relevant information.

The fact that open goals influence cognitive processes in a way that biases the problem solver to acquire information about unsolved problems even when those problems are not being worked on means that creative or innovative solution ideas can come about even while not engaged in work on that particular problem. For instance, information related to an unsolved design problem that is encountered in the environment is likely to be incorporated into the design problem solving process even if the designer is not working on the design problem at the time. Some theories of creativity posit that creative ideas come about through the combination of distant concepts that normally would not be considered [4, 5]. Open goals may be the cognitive mechanism that enables this process to take place.

Previous work on design problem solving shows that designers are sensitive to information in the environment that is relevant to unsolved problems [6-8]. Designers in these studies took advantage of new information as it was encountered and opportunistically switched to the aspect of the problem most relevant to this new information. This recognition and opportunistic behavior in design problem solving is interesting and even surprising given that traditional laboratory studies in psychology find that people fail to recognize the relevance of analogically related information [9, 10]. However, people have been shown to be more likely to notice problem related information after problem solving has begun and the problem solver has an open goal to solve that problem [1-3, 11].

Design problem solvers have been shown to suffer from fixation on prior ideas which may inhibit their ability to generate new and innovative ideas [12-16]. Fixation on prior ideas has also been shown to affect the likelihood that people notice information related to open goals, and this work has shown that there may be an optimal time for the presentation of new information related to open problem solving goals [2]. The time course of fixation and impasses in problem solving is important to understand, and may have important implications for generative problem solving tasks like design.

For example, it is important to understand how the representation of a design problem changes throughout problem solving as this representation guides which information becomes incorporated into problem solving. There are potential applications of these findings to computational aids that seek to encourage the generation of new ideas as well as help designers to overcome impasses. The first step toward the realization of these kinds of applications is to understand how this cognitive mechanism operated in more complex problems.

The purpose of the studies presented here was to start to determine whether the results found with simple problems in the psychological lab would generalize to more complex design problems. The first study was also designed to examine the effect of open goals at various points in the design process. Designers develop a representation of a problem as they continue to work on it, and the likelihood of information from the environment entering the design process is likely to depend on the representation of the open goal at the time the information is encountered. In addition, fixation on prior unsuccessful design ideas is likely to inhibit the acquisition and generation of new information and ideas. The second study presented here shows that fixation can be a significant difficulty even in what was intended to be a simple design problem.

2 EXPERIMENT 1

In this study, participants were given a design task to complete. Participants were interrupted at various points in their problem solving to complete a second task which contained information that was analogically related to the solution of the design problem. One hypothesis was that the analogy was more likely to be used in problem solving when it was presented after work on the problem had begun rather than before problem solving as participants would have an open goal to solve the problem in the former case but not in the latter. A second hypothesis was that presenting the information later in problem solving would have a greater impact as participants would have had more of an opportunity to develop a good representation of the problem and therefore would be more likely to notice the relevance of the analogy.

2.1 Method

2.1.1 Participants

There were 42 participants in this study who were recruited from a senior design course in the mechanical engineering program at Carnegie Mellon University.

2.1.2 Design and Procedure

Participants were randomly assigned to one of four hint conditions. The hint was either not presented, presented before the city design task, presented after 5 minutes of work on the city design task, or presented after 20 minutes of work on the city design task.

The city design task was a task where participants had to design a city that would survive after 50 years of simulated time. There were three types of city areas that had to be laid out on a grid: residential, commercial, and park areas. A screenshot of the task interface is presented in Figure 1. After the design was completed, the computer would show the participant how the city developed over time. The city changed according to deterministic rules. The participants were not given the exact rules, but they were given a few simple principles which captured the basic gist of the rules. This situation meant that participants understood the basic principles of the task, and they could work out further details of the system through experimentation if they wanted to. Participants continued to iterate through the processes of design and simulation until they achieved a solution or until 45 minutes had passed. A solution to the task was defined as a city with at least 2500 residents at the end of the simulated 50 years. Each residential square was equivalent to 100 residents.

The rules in the city design task were structured such that large contiguous cities were not likely to survive with the required number of residents. The main force behind this constraint was that commercial squares expanded or reproduced at a faster rate than residential squares, and residential squares died off when overwhelmed with commercial neighbors. One class of solutions to the city design task involved a small residential area surrounded by parks and a small number of commercial squares. The parks served to insulate the residential area and constrain the growth of commercial areas. These small cities could then be replicated across the grid as non-interacting entities. This class of solutions was used because participants were not likely to construct a solution of this type given their knowledge of cities as large contiguous entities.

Participants were told that at some point they would be presented with a second task where they would have to read three brief text passages that they should remember so that they could answer questions about them later. They were not told that the two tasks were related or given any indication that they would receive a hint. One of these passages was intended to be an implicit hint to help in designing a successful city. The hint passage described cells including how cell membranes served to protect the cell and regulate interactions with extra-cellular entities. The passage also discussed how multiple cells made up tissues. This hint was designed to be analogous to the class of solutions discussed above.

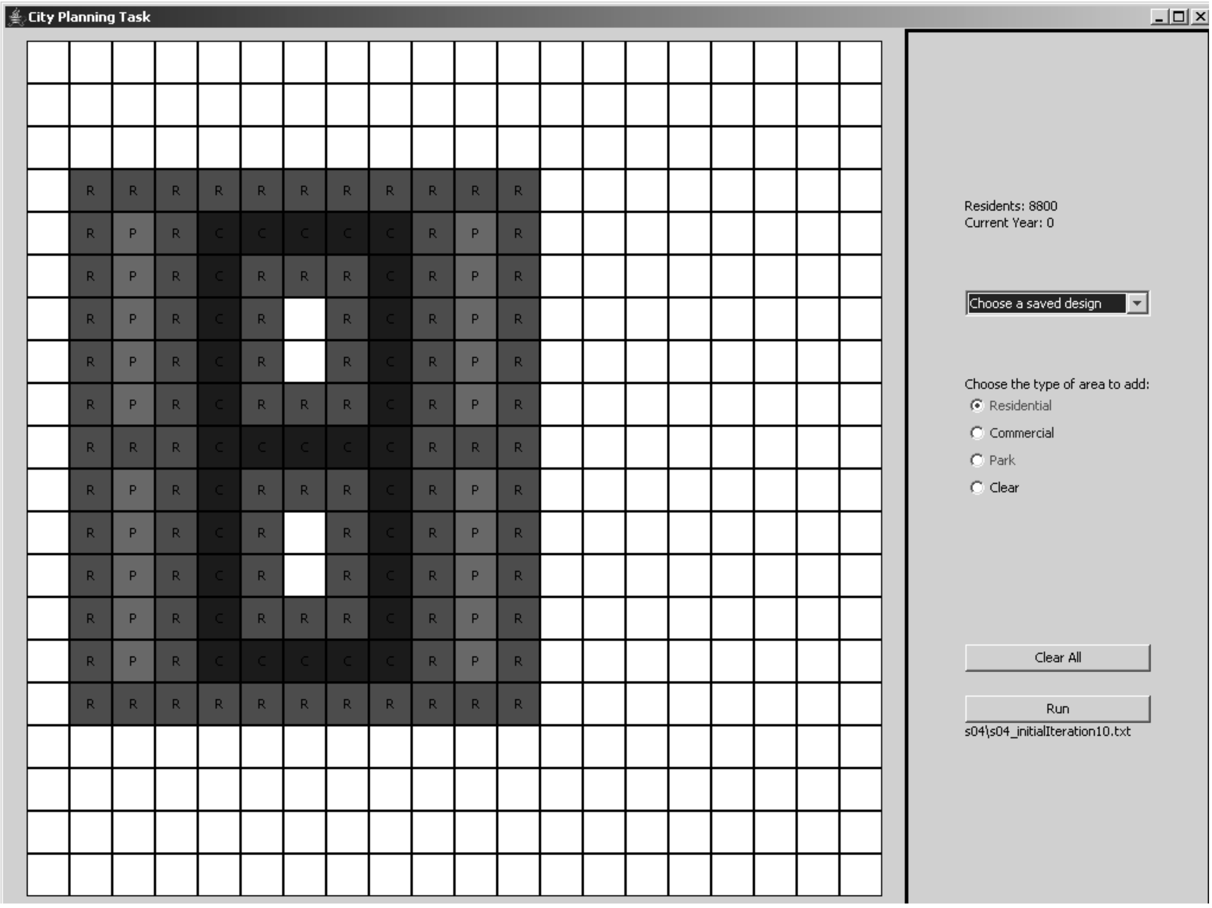

Figure 1. Screenshot of the city design interface

2.2 Results

Due to the fact that this study is exploratory in nature, and the power of the study was limited by the number of students in the class from which participants were recruited from, the level of statistical significance was set at $\alpha = .10$.

Only one participant explicitly indicated that they noticed the analogy. In our previous work with simpler problems it was also the case that few participants noticed the hints even though they clearly benefited from the information contained in the hint. This result means that it is important to assess the impact of the hint from behavioral data rather than through questioning the participants.

2.2.1 Representation Change

A classification scheme was devised so that each candidate design produced by each participant could be classified according to the organizational properties of the candidate city design. There were eight categories as well as one additional “Other” category. The “Other” category included a small number of designs that did not share an underlying organization or any other apparent similarities with any of the other design types. Examining the types of designs produced by a participant over time provided a way of tracking how the participant’s mental representation of the city design problem changed over time. Designs from the same category could be assumed to be produced from similar representations of the task and its constraints. Understanding the representation of the problem is important as this representation determines how the problem is solved. The hint is likely to change the representation of the problem if it is incorporated into problem solving, and this representation change may lead participants to overcome previous difficulties or impasses.

One method of assessing representation change is by looking at how often participants switched design categories from one design iteration to the next. This data is presented in Figure 2 where it can be seen that participants in the control condition switched design categories 47% of the time. There was a regular increasing trend where the hint seemed to spur more representation change the later in the problem it was presented. This trend approached statistical significance, $p = .13$.

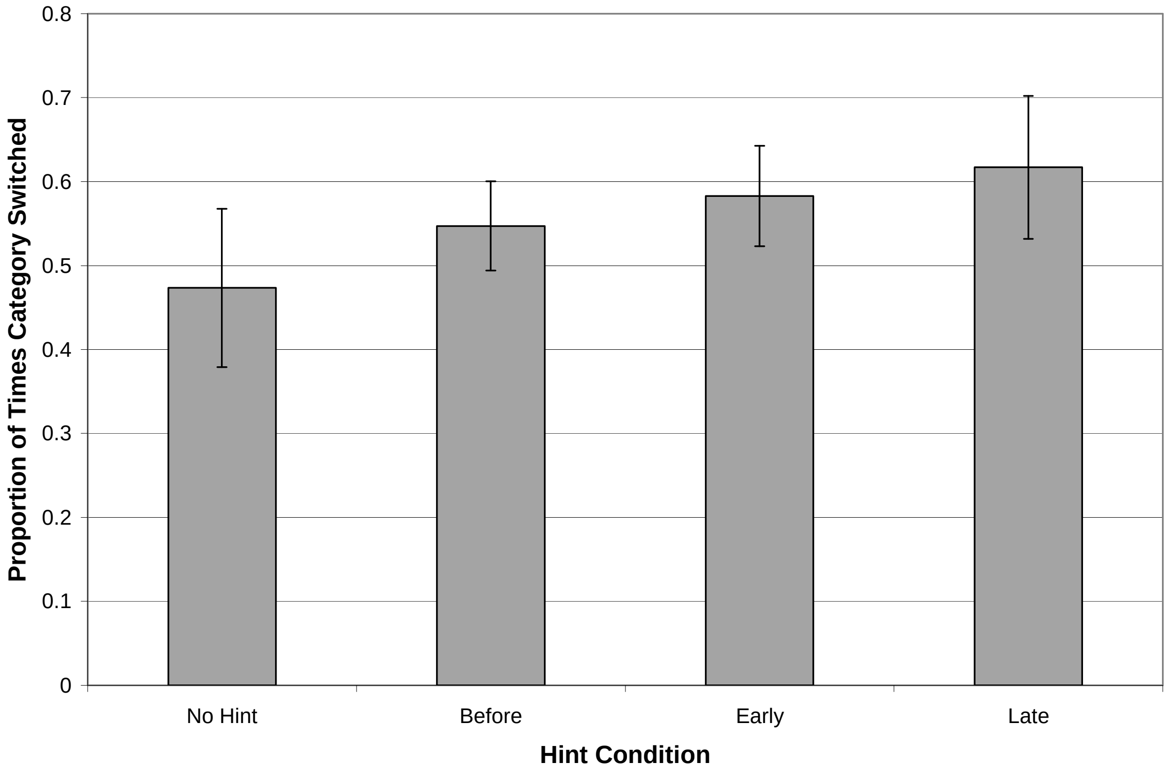

Figure 2. Proportion of iterations on which participants switched design category

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A more direct way of examining the effect of the hint on representation change is to look at the design iteration directly following the presentation of the hint. It is only possible to use this measure in the early and late conditions since these are the only conditions where the hint was presented after a participant had produced one of more candidate designs. The control condition was used as a baseline in which it is seen that participants change design category 47% of the time. In the early hint condition, participants changed categories in the design iteration immediately following the hint 80% of the time, which was significantly more often than in the control condition, $p = .08$. Participants in the late hint condition changed categories immediately after the hint 64% of the time, $p = .35$. These results indicate that the hint may have been most effective after there was an open goal, but before participants became committed to a particular type of design as they may have done in the late condition where they worked on the problem for 20 minutes before seeing the hint.

2.2.2 Hint Effectiveness

The original hypothesis was that the hint would increase the number of participants who solved the problem as well as decrease the time it takes to solve the problem. The number of participants who solved the problem in each of the four conditions is presented in Table 1. Examination of the table shows that participants who received the hint appeared to solve the problem more often than those in the control condition. In order to test the significance of this apparent difference, the three hint conditions were compared as a group to the control condition using Fisher's exact test. The difference was not statistically significant, $p = .15$. This lack of significance is likely due to a lack of power as there were only about 10 participants in each condition.

Table 1. Number of participants who solved the problem in each condition

	No Hint	Before	Early	Late
Solved	2	7	4	5
Unsolved	7	4	6	7

Another way of examining the effectiveness of the hint is by examining how long it took participants to solve the problem. For those participants who solved the problem, the amount of time taken to solve it not including the time spent reading the text passages is presented in Figure 3. While it appears that the hint may have been most effective after problem solving had begun and that participants in the late condition took longer to solve the problem, these differences were not statistically significant, $F(3,13) = 1.36$, $p = .30$.

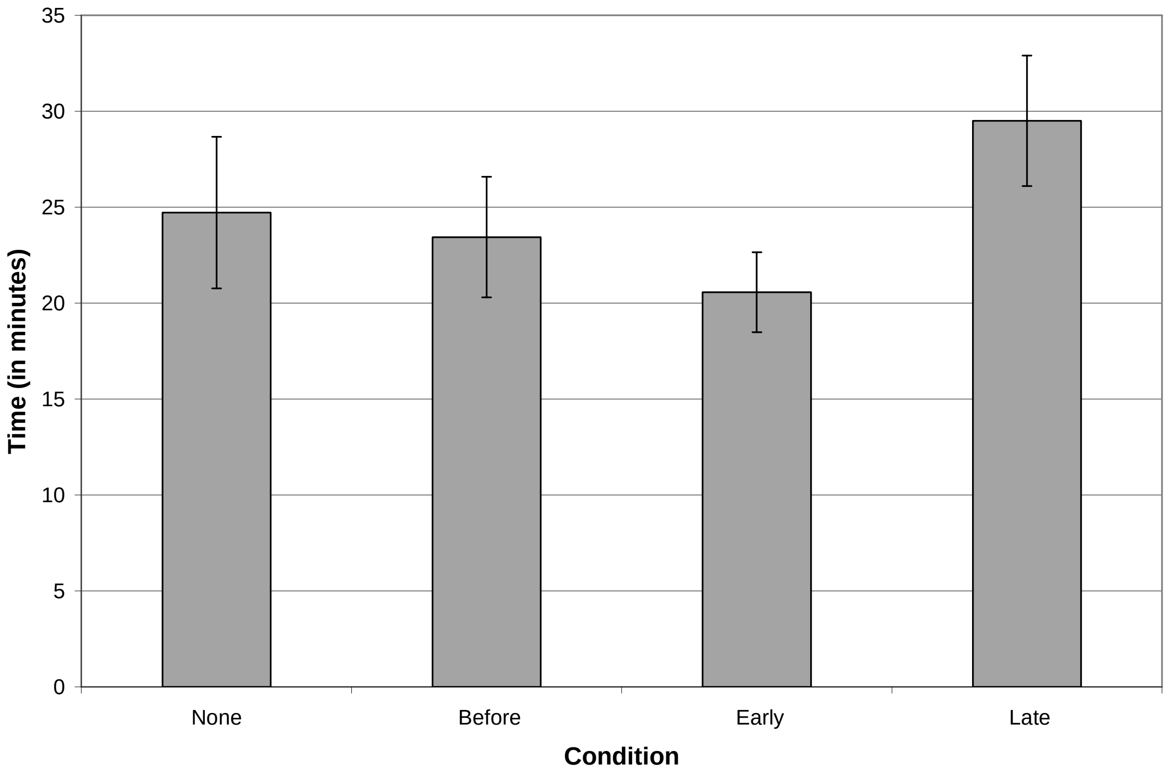

Figure 3. Total time to solve problem for participants who solved problem

The time between when the hint was presented and when the problem was solved would be expected to decrease if participants in the early and late conditions were more likely to notice and use the information in the hint because of their more developed representations of the problem. Figure 4 presents the amount of time that was required after seeing the hint to solve the problem for the participants in the three hint conditions who solved the problem. It can be seen that the expected pattern was obtained and that the hint conditions did differ significantly, $F(2,11) = 6.01$, $p = .02$, which supports the idea that participants are more likely to use the hint after developing a better representation of the problem. However, it is hard to interpret these results as participants in the early and late conditions worked on the problem for awhile before seeing the hint and it could be that the hint is having no effect but that Figure 4 just eliminates the time before the hint which produces the observed effect. This interpretation seems less likely since the hint did have some impact upon the designs produced as shown in the representation change data above.

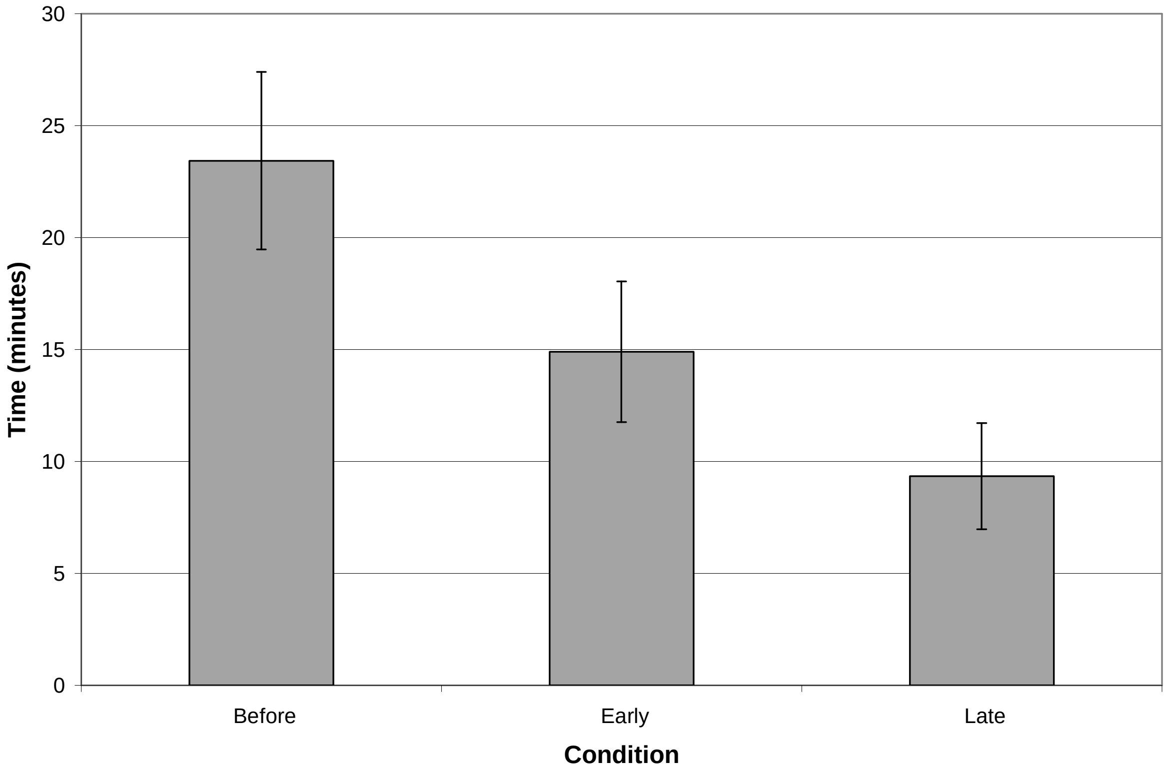

Figure 4. Time from presentation of hint until solution for participants who solved problem

2.2.3 Fixation
One of the features in the city design task interface was that participants could save a design and use that initial design as the basis for future design iterations. This feature was included because designers often start a new design iteration based on sketches or prototypes from prior iterations of the design process. However, starting from a prior design may have made the participants more likely to fixate on prior unsuccessful ideas.

In order to assess this possibility the number of participants who used prior saved designs was calculated. Of the 14 participants who used this feature, only 4 eventually solved the problem. Of the 28 participants who did not use a saved design, 14 eventually solved the problem. This pattern of results indicates that fixation of past designs may have prevented the solution of the design problem, but this result only approached statistical significance, $p = .16$.

2.3 Discussion
The results presented here demonstrate that an analogical hint related to an unsolved design problem affected the representation of the problem. This result is an important step because our previous results concerning the effect that open goals have on the acquisition and use of problem relevant information only dealt with cases where the hint was the answer to the problem [1-3]. The results presented here indicate that even information contained in a distant analogy can be incorporated into problem solving without the problem solver’s awareness.

One of the initial hypotheses was that the hint would be more likely to impact the unsolved problem when there was an open goal. Our results generally support this hypothesis as there was some evidence that the representation of the problem was more likely to shift in response to the hint when there was an open goal and the time taken to solve the problem after the hint was shorter in the case where there was an open goal.

The second hypothesis was that presenting the hint later in problem solving would lead to an increased use of the hint. The results concerning this hypothesis were less clear. The results on time to solve the problem and design category shifts following the hint indicate that presenting the hint early after problem solving has begun was better than late in problem solving. The time from hint to solution was the only result where the late condition did better than the early condition. One possibility is that participants have become committed to their representation of the problem or even fixated on prior ideas which impacted the effectiveness of the hint.

These results are still preliminary and need to be followed up on with a similar study with more participants to increase the statistical power of the experimental design. However, the results presented here tend to agree with our other results using much simpler problems [1-3]. We have also begun to pilot another design study to determine the types of information that participants notice when they have an open goal. This pilot work also seeks to examine how fixation interacts with the influence of open goals on the acquisition of problem relevant information.

3 EXPERIMENT 2

An analogical hint was effectively used by participants in Experiment 1. However, there can be many kinds of similarity including visual or semantic similarity. As part of a project to determine which types of similarity may be noticed and acquired by some sort of open goal cognitive mechanism, we designed what was intended to be a simple design problem. This problem is presented in Figure 5. The basic problem is to design a column support structure, and the constraints of the problem make it impossible to meet all constraints with just one column. The solution is to use two columns. We originally thought that engineering students would begin with the single column representation but then encounter an impasse as they needed to reconceptualize the problem.

- Your company manufactures solid wood columns for a particular application where a load of 300,000 lbs must be supported 96 inches above the ground.
- The manufacturing cost associated with producing a column of a given radius and weight is given by the cost formula below
- Your goal is to find a solution that will enable you to achieve a manufacturing cost of less than $346
- If a column fails, it will fail by buckling not normal stress, the buckling equation is given below
- Assume the factor of safety is 1
- Design a solution to this problem and specify the details including cost.

$$W = \rho \pi r^2 L$$

$$P \leq \frac{r^4 \pi^3 E}{L^2}$$

$$Cost = c\left(\frac{r^5}{2} + W\right)$$ (radius measured in inches)

- P is the applied load, W is the weight of a column, ρ is the density of the material, L is the length of a column, r is the radius of a column, E is the modulus of elasticity, c is the cost factor, π = 3.14

Modulus of elasticity	Density	Cost factor
Wood = 1x10^6 psi	.014 lb/in^3	$2

Figure 5. Column problem used in pilot study

Our initial hypothesis was that the time spent at an impasse could be shortened by presenting a hint to the task implicitly in another task. The hint could be visually, functionally, or both visually and functionally similar to the solution. For instance showing a picture of a bridge with multiple columns includes both visual and functional similarities while a story describing the solution to a problem through the use of parallel forces is an instance of a hint with functional similarity.

Our initial work with this problem showed that it was very difficult even for senior mechanical engineering majors. Participants were allowed up to half an hour to solve the problem, but out of the 6 participants that did not receive an implicit hint in our pilot study only 2 solved it; the rest were stuck on a single column representation. This result was surprising given that the problem was designed to be relatively easy to solve. The hints did improve performance as 8 out of the 10 participants who received some form of the hint did solve the problem, $p = .09$. The 5 participants who received the story describing a functionally similar solution all solved the problem, and 3 of the 5 participants seeing a picture of a bridge solved the problem.

Participants were recorded while solving the problem, and reviewing these recordings revealed that participants hard great difficulty in re-representing the problem. The majority of the participants did begin with the single column representation. When the students ran through the calculations and determined that their first attempt had failed, they almost always assumed the problem was in their manipulation of the equations or their calculations. The participants who did not solve the problem spent the remainder of their time running through unnecessary analysis.

These pilot results are very interesting as this is not the problem solving behavior that was predicted. Students became fixated on their initial representation of the problem and only rarely were they able to re-represent the problem appropriately. These initial results demonstrate how difficult fixation can be to overcome, and they highlight the importance of understanding the relationship between representation, fixation, and open goals. Open goals influence which information gets incorporated into problem solving, and this process may explain how new ideas arise. However, the representation of the problem and in particular the interference that arises from prior solution attempts may inhibit the generation of new ideas.

4 CONCLUSIONS

The results reported here demonstrate that the influence of open problem solving goals can potentially explain the source of new design ideas. This mechanism operates even when the problem solver is not actively engaged in problem solving, and it appears to operate without conscious awareness. In addition to explaining how new ideas enter the design process, this mechanism may also explain how it is possible to overcome impasses in design problem solving.

These initial results highlight the importance of understanding the cognition underlying design. In particular, understanding the processes of problem representation, fixation, and impasses in design as well as how new ideas become incorporated into problem solving has implications for improving the design process as well as for how computational design aids should be designed in order to encourage the generation of creative and innovative design ideas. Some of our prior work indicates that the point of impasse may be the optimal time to introduce problem relevant information as this is the time when there is relatively little fixation [2]. Future work should build upon these results to see if the results generalize to more complex real-world problems. If they do, then understanding the properties of these cognitive mechanisms and how they interact with the design process should make it possible to aid designers and encourage creative and innovative design.

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