Impact of problem contexts on the diversity of design solutions: An exploratory case study

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Abstract

The role of ideation in design is to generate design solutions that have the potential for further development. Having many diverse ideas increases the potential for successful design outcomes by increasing the number of possibilities available during concept evaluation and selection phases. How do we define the problems that would allow for the most diverse solution space? The purpose of this study was to gain an understanding of how different contexts impacted the variety of solutions generated within the solution space, by a diverse group of students. In this exploratory case study, we report on (1) how we identified a set of design problems with diverse contexts appropriate for students with varied backgrounds, and (2) how we explored the impact of these problem contexts on the size of the solution space, aiming to select the contexts with the most diverse pool of ideas for our ongoing studies[1]. Our results show that diversity judged by multiple raters was consistent and provided us with evidence to support the decision of which design problems to use in our further studies.

Introduction

Innovation depends on successful idea generation, which is achieved through in-depth exploration of the solution space by considering a wide range of possible solutions[2,3]. A designer is often charged with creating an artifact that delivers specific features and satisfies particular constraints. However, in the progression through design, different designers may approach these features and constraints from different perspectives, relying on their previous knowledge and experience, creating their redefined problems that would lead them to new potential solutions.

Prior research showed that designers spend considerable amounts of time at the beginning of a design assignment analyzing, reiterating, and restructuring the type of problem they are dealing with[4]. As this phase is crucial for successful ideation, it is vital to understand how to create and define problem contexts that will elicit a diverse range of solutions. Because of the very nature of design problems, there is very often very little information about the problem and even less information about the goal. This means that design problems require a lot of structuring, a process of drawing upon knowledge to compensate for missing information and using it to construct the problem space[5].

Forster et al. have examined how different preparations, variations in goal setting, and alternative task instructions impact performance[6]. By framing given design tasks in either a novel or a familiar manner or by priming participants with reflection on novel or familiar events prior to completing a task, it was found that participants with less direct experience associated with a given problem were more open to being primed in a particular manner. Chen et al. investigated how different facilitation effects correlate with the creative performance across different cultures[7]. They tested Chinese college students and US college students by providing explicit instructions to half of the students and more general instructions to the other, learning that the facilitation effects vary for those with different artistic and mathematic creativity, but not those from different cultures. However, it is still unclear why some design problems would create more diverse solution spaces compared to others and how to structure and select such design problems.

The purpose of this study was to learn how students with different disciplinary backgrounds pursue solutions to design problems. As design education is no longer limited to college classrooms, it is important to understand how students with diverse backgrounds understand and approach design challenges differently. Furthermore, we aimed to explore the incongruities between the students' perceptions of the diversity of their solutions for a given design problem and the diversity of the solutions that were developed based on the analysis of blind coders.

Problem Structuring

Design activities can be seen as the reasoning from a set of needs, requirements and intentions to a new bit of reality, consisting of a (physical) structure and an intended use[8]. There is considerable research on design in engineering, generally, and on idea generation in particular[9-12]. In experimental studies, design problems are commonly provided to participants to provoke them towards ideation, where the researchers select a design problem or set of problems to use for prompting participants to formulate solutions. Some design problems have taken a more traditional engineering approach, such as designing a device or product to collect energy from human motion[13], to utilize sunlight for cooking food[14], or to shell peanuts[15]. Others have more general characteristics, such as redesigning salt and pepper shakers[16] or creating a novel tool for an alien race on an imaginary planet[17]. Still others chose their design problems based on a context that the intended population was likely to be familiar with[18,19], such as gift wrapping[20].

In these studies, the criteria used to choose a problem was typically defined by previous research or the relevance of the problem to the participants. However, few studies in design research have specifically analyzed the problem context in terms of how different design problems can change the diversity of the solution space itself. Instead, most of them choose a single problem based on the theoretical ideas they seek to investigate. For example, Lemons et al.[21] were interested in studying model building and therefore chose a problem that could be lead to various assembly options and could be modified by participants relatively easily. In their study, they chose the design task of creating a one-handed jar opener and instructed participants to build their ideas using LEGO materials. In another example, Jin and Chusilp[22] chose multiple design contexts with common key characteristics, to study the effect of familiarity on mental iteration in ideation. They chose one problem that their participants were likely to be familiar with and a second problem that their participants were unlikely to be as familiar with. However, they did not test multiple contexts within each of their experimental conditions. Even in studies specifically focused on assessing diversity within ideation[23], the most common approach was to choose one design context with different conditions within that design problem. This approach may create issues due to the possibility of the participants not having enough knowledge about the context, or they may be too knowledgeable about that context causing an inability to generate new and different ideas for a problem that they have already seen or experienced.

In this research, we aimed to build on these studies and explicitly examine the effect of the problem context on the diversity of ideas that participants generate. We postulated that when encouraging participants to expand their common way of thinking, presenting them with overly familiar situations may not always be the most effective method as they are more likely to fixate on a well-known solution early on in their problem solving process.

Research Questions

As our study aimed to explore the breadth of solutions student designers would generate based on different problem contexts, we were guided by the following questions:

- How broadly do student designers cover design solutions spaces for a variety of design problem contexts?
- How does the context of a design problem impact student designers' perceptions of difficulty in generating solutions?

The way a design problem is phrased can lead to radically different solutions to different students. We wanted to provide students with a diverse set of design problems that were all equally accessible, understandable, and relatable. Therefore, in this study, our goal was to evaluate which problems were more accessible, understandable and relevant for students to cover a diverse set of solutions. We were not focused on the solution sets of individual students, but instead the solution sets of the students as a group. In order to answer these questions, we designed an exploratory case study in which a small group of students (fifteen in total) were given a series of design problems and asked to generate solutions in a certain amount of time. External blind reviewers, in addition to the students themselves, then evaluated the diversity of the solutions and the size of the solution space.

Generating Design Problems

Our starting point for this research was to identify types of design problems that were used in other experimental studies focusing on design cognition. We included problems both from journal papers and conferences. Additionally, we created a set of new problem ideas based on our own experiences with engineering design, education, and research. This complete database consisted of many design problems; over thirty were pulled from previous literature, such as[24-29], and over thirty new ideas were also created by the research team.

The initial database of problems was then filtered based on the design task being an authentic engineering design task while still being accessible to a broad audience. Ten of these design problems as shown in Table 1 were framed in different contexts in order to understand the potential for diversity within in each of the design problems. The selection process was narrowed down to five design problems.

Table 1 Initial Set of Design Problems

Number	Design Problem
1	Heavy School Supplies Carrier
2	Automatic Home Duster
3	Remote Village Rainwater Catcher
4	Anti-Theft Device
5	Low-Skill Snow Transporter[22,30]

6	One-Handed Jar Opener[21]
7	One-Handed Door Opener[31]
8	Automatic Home Plant Waterer[32]
9	Different Height Water Dispenser[33]
10	Underdeveloped Area Water Transporter[34]

These five design problems also represented a range of challenges that would be ideally suited to anyone with or without engineering background. Our final decision was based on their diversity in their origin (whether generated by our research team or used by other researchers in different experimental studies), and the diversity in their contexts and criteria (appropriately framed for engineering students while still accessible to a wide range of students). The design tasks for the five selected design problems are listed in Table 2. In addition to the needs statement, when presented to participants, we included a paragraph of background context and a set of constraints for each problem context that further elaborated the problem scenario.

In order to maximize the possible solution space explored across the group of students for each problem context, we created three different versions of each problem to encourage a wide range of solution types. These problem versions were based on Abernathy's[35] definition of 'radical or the development of new solutions' vs. 'incremental or improvement of existing solutions', representing the extremes on a continuum. To support these two definitions, we constructed our design problems using Kirton's[36] cognitive diversity research characterizing two approaches for problem solving, as 'more adaptive' and 'more innovative'. In addition to structuring these problems to fit into adaptive and innovative categories, we also created an additional framing, called 'neutral', that fell between the extremes of this continuum[37]. This problem framing resulted in 15 different design problems (five problems, each framed in three ways: adaptive, innovative and neutral).

Table 2 Design Problems selected for further investigation

Design Challenge	**Needs Statement**
Low-Skill Snow Transporter	*Design a way for individuals without lots of skill and experience skiing or snowboarding to transport themselves on snow.*
Anti-Theft Device	*Design a way for someone to secure their belongings in a public area for a short time in order to prevent theft, but without disrupting the space.*
One-Handed Lidded Container Opener	*Design a way for individuals who have limited or no use of one upper extremity to open a jar with one hand.*
Remote Village Rainwater Catcher	*Design a way for villagers to catch and use rainwater.*
Heavy School Supplies Carrier	*Design a way for students to carry their heavy school supplies.*

Experimental Method

The purpose of this study was to assess students' perception of five unique design problems framed in three different contexts: adaptively, innovatively, and neutrally. Adaptively framed design problems are constrained through more quantitative measures such as a given size or weight; innovatively framed problems are constrained through qualitative measures such as novelty; and neutrally framed problems are delivered such that neither quantitative nor qualitative features are emphasized[37]. This was done with the intent of broadening the solution space among all five of the design problems uniformly. Posing each of the five design problems in each of the three different framing contexts resulted in a total of 15 different design challenge questions. Each student was randomly assigned to work on two of the five design problems, one at a time. Each problem was given to students between 4 and 5 times. Students were given 20 minutes to generate solutions for each design problem. After each ideation session, they were given a short questionnaire asking students to evaluate the diversity of their design solutions, in addition to their familiarity with the given design problem.

Participants

Fifteen undergraduate students participated in this study from various universities across the US and Puerto Rico. The group was composed of 5 males and 10 females, ages 19 to 24. The majority of the students had some exposure to computer science; however, their backgrounds ranged from disciplines such as Photography and Psychology to Biomedical and Computer Engineering. Our goal in selecting this diverse set of students was to understand whether this set of problems would lead to a thorough exploration of the solution space, regardless of students' backgrounds.

Another objective of this study was to explore possible methods for creating design problems for a diverse group of students. Our long-term goal with this study is to inform our other studies addressing ideation flexibility among participants ranging from high school students through to graduate students. The students that will be participating in future studies will have varied backgrounds, including designers and engineers, as well as high school students with interests in engineering but no specified focus yet. This is the main motivation behind selecting design problems that have a far-reaching accessibility to students of many different backgrounds.

Procedure

In this exploratory study, each student was randomly assigned to work on two of the five design problems, one at a time. They were given 20 minutes to generate solutions for each design problem. After each ideation session, they were given a short questionnaire asking them to evaluate the diversity of their design solutions, in addition to their familiarity with the given design problem. The data that was collected also included sketches of the design solutions they generated for each problem. We chose to analyze the data based only on the five core design problems rather than the different framings (adaptive, innovative or neutral)[37] as these problems were homogenously distributed, giving each design problem an equal amount of diversity. This decision was based on our interest in exploring which problem context would lead to the most diverse design solutions, rather than investigating the impact of each framing on the design solution space.

Data Analysis

As part of the study, we collected two different sets of data, verbal and visual, in addition to participants' demographic information and design-related experience. The students were asked to generate solutions to the design problems that were presented, and they were also asked to answer some general questions related to their perceptions of the diversity of their solutions and the creativity that the design challenges fostered. In addition to the analysis of the feedback from the students themselves, researchers also analyzed the design solutions that were generated by the students and evaluated the overall diversity of the design solutions developed for each of the design challenges.

Six external reviewers, both undergraduate and graduate students in engineering, blind to the experiments, analyzed the set of design solutions generated across the student participants for each design problem. The reviewers were asked to rank the diversity of the solution space for the entire set of concepts generated for each of the five design problems based on their intuition. Most of the reviewers separated the individual groups of designs into various functional categories and then ranked them based on the number of categories that each group had. Each design problem was assigned a number of points based on the ranking it received (5 points for the most diverse and 1 point for the least diverse). The points from each of the reviewers were added up and averaged. Based on this point system, the design problem with the greatest number of points was judged to be the most diverse by the reviewers, while the design problem with the least number of points was judged to be the least diverse.

In addition to the external reviewers, the responses of the participating students were also evaluated. The students were asked to evaluate the diversity of their own solutions as well as how challenging it was to generate solutions to the problem on a 7-point Likert scale, with 1 being not diverse, and 7 being very diverse. The responses were then compiled and analyzed across the entire group of students. These data were not expected to correlate to the external rater data, as those data were based on the collection of ideas from all of the students working on a particular problem, while students' own ratings were based only on the solutions they generated themselves. However, we were interested in analyzing how students perceived their own set of ideas.

Results and Discussion

The graphs below present a comprehensive summary of the quantitative results of diversity for each of the five design problems chosen initially. Figure 1 presents the diversity ranking score of the blind external reviewers. Figure 2 illustrates the results of the ratings of the study participants. The participants rated the diversity of their solutions on a 7-point Likert scale with 1 representing 'not diverse' and 7 representing 'very diverse'.

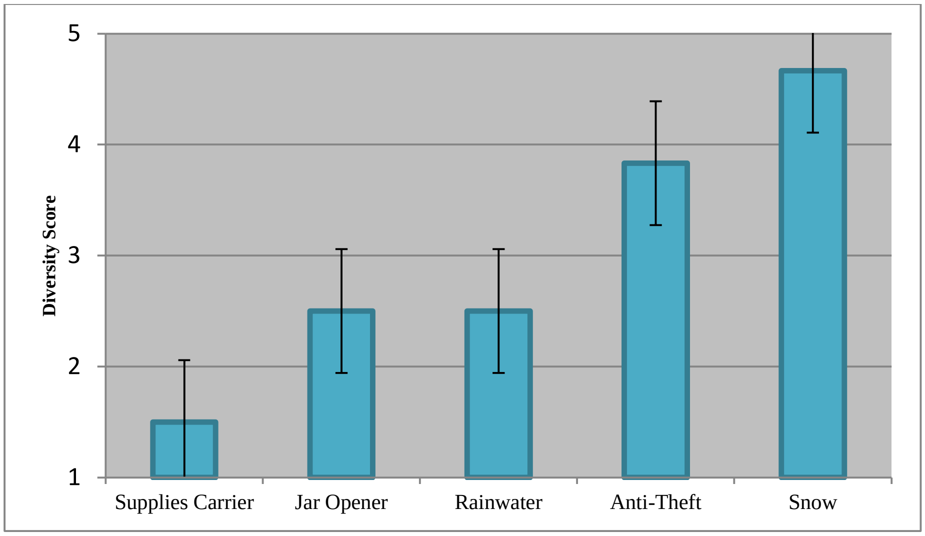

Fig. 1 Diversity Ranking from External Reviewers

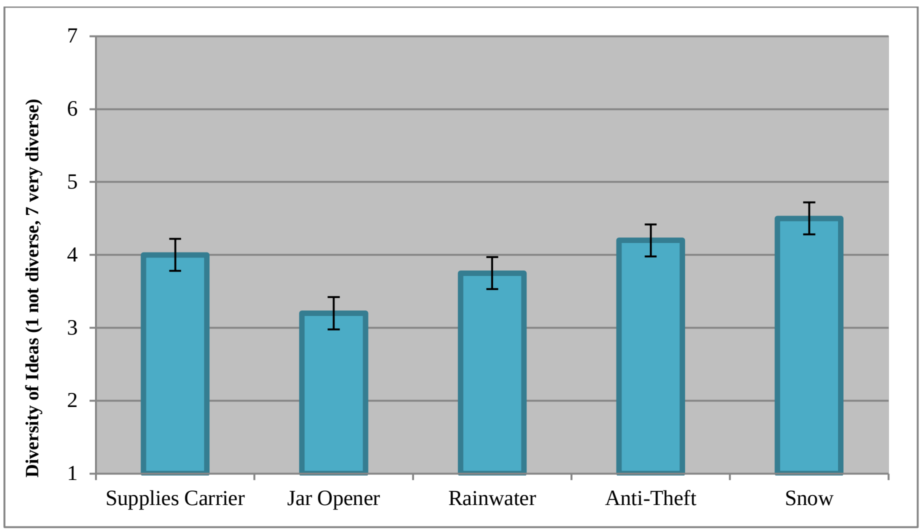

Fig. 2 Diversity Rating of Students

As is clearly shown in the above graphs, there is some discrepancy in the rankings of the external reviewers and the ratings provided by the students. The following sample sets of the student's design solutions provide some insight into these results. The results from both the external reviewers and the study participants indicate that the Low-Skill Snow Transporter was perceived as leading to the highest diversity in the solution space. The external reviewers awarded the Low-Skill Snow Transporter with an average diversity score of 4.67 out of a possible high score of five. The participants also found their solutions for the Low-Skill Snow Transporter to be the most diverse with an average score of 4.5 based on a 7-point Likert Scale with 7 indicated Very Diverse and 1 indicating Not Diverse.

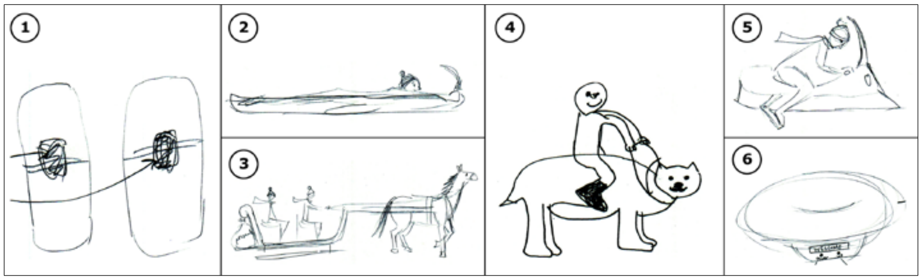

Fig. 3 A Sample of Solutions for a Low-Skill Snow Transporter

Figure 3 represents a sample selection of student sketches that demonstrates the diversity of the solution space for Low-Skill Snow Transporter. In the first concept, one of the participants focused on creating a modification of snowshoes. The second concept is a sled device that uses no external power. The third and fourth designs both use the idea of harnessing animals to provide transportation, however the third is a bit more traditional with a carriage drawn by horses while the forth design involves training polar bears to be ridden. The fifth and sixth designs use hover technology. The fifth concept is more of a vehicle where the user sits on it while the sixth concept is more of a sled-like device that is intended to be stood on.

When ranking the least diverse solutions, there was more discrepancy. The external reviewers ranked the Heavy School Supplies Carrier as being the least diverse, receiving an average score of only 1.5 out of a possible five. The students viewed the solution space as more diverse, awarding it a score of 4 on the 7-point Likert scale. It is a possibility that because students are more familiar with the idea of a backpack for carrying heavy school supplies, they were able to recognize more diversity within this specific design solution, while the external reviewers were making their judgments based on what they believed to be the broader solution space.

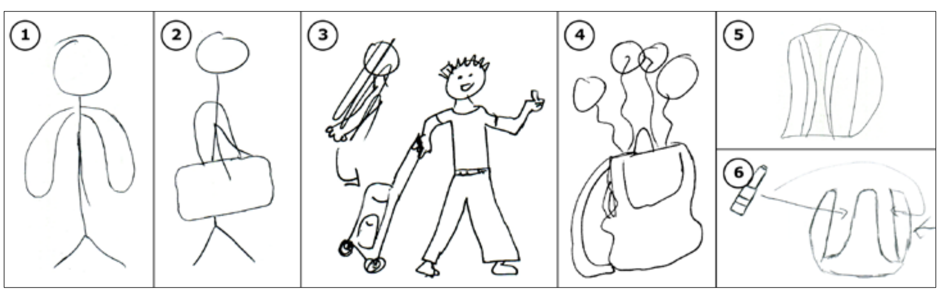

Fig. 4 A Sample of Solutions for a Heavy School Supplies Carrier

Figure 4 represents a sample selection of student sketches that demonstrates the diversity of the solution space for the Heavy School Supplies Carrier. The first design represents a bag-like device that fits over the front and back of a user. The second concept is an enlarged side bag that a user wears over one shoulder. The third carrier is a backpack on wheels that can be rolled around behind the user. The forth concept is a modification to a current backpack. The designer lightens the load on the user by adding balloons to offset some of the weight. The fifth concept is also a large backpack, however, in this design the bag is worn on the users back. The sixth design is another modification of a backpack, however the designer proposes a modification to the straps of the bag in order to make it more comfortable to carry.

The study participants rated the One-Handed Jar Opener as the least diverse. Anecdotal evidence suggests that the students felt this was the least diverse solution space because they had the least exposure to this particular context. Many students indicated that they had a challenging time putting themselves into a context that would require them to use only one hand to open a jar. This brings up an interesting point concerning how study participants perceive different design problems. While they may perceive a given design challenge as being more difficult, therefore limiting their ability to develop diverse solutions, the added challenge may push them to think outside of their usual modes of idea generation, resulting in an overall more diverse set of solutions.

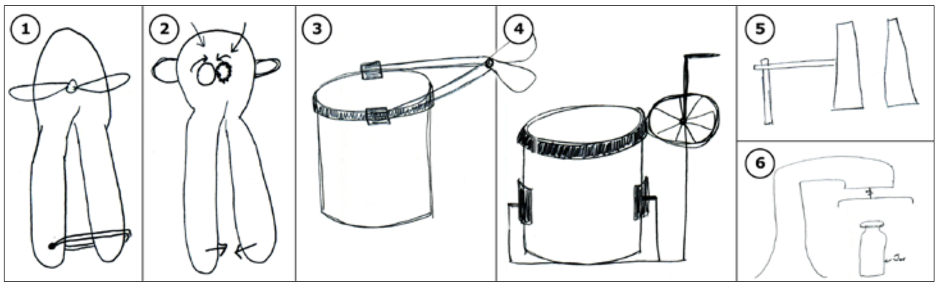

Fig. 5 A Sample of Solutions for a One-Handed Jar Opener

Figure 5 represents a sample selection of student sketches that demonstrates the diversity of the solution space for the One-Handed Jar Opener. In the first concept is a can opener that allows you to secure a small device that holds the grip together while the user rotates the handle. The second concept modifies the action of turning the handle by instead requiring the user to squeeze the grips together in order to ratchet the gears around the can while opening it. The third concept has a wider grip that clamps around the jar so that it is easier to operate with a single hand. The forth concept involves setting the jar in a device that is fixed to the table with a wheel that rotate around the top opening the jar. The fifth concept is a repurpose of traditional vice grips to hold the jar while the user uses on hand to open it. The sixth concept is a traditional electric can opener in which the user locks the can into place and a motor is used to open the jar.

While there are some obvious differences in the perceived diversity of the solution space for these various design problems (i.e. supplies carrier problem was rated as the least diverse by external reviewers whereas it was rated as the third by the participants themselves), one thing that is clear is that the design problem does play a large role in the breadth of the solution space, and some design problems are better suited to certain audiences than others. The familiarity of a design problem to a given audience does not guarantee a large solution space. Excessive familiarity with a design problem can have the same result as unfamiliarity with the design problem. The balance between proposing a problem that the participants can relate to versus a problem where they can generate novel ideas without relying on the existing functioning solutions is rather challenging. As such, it is important to evaluate the intended outcome of a design study and consider a variety of possible design problems for the intended audience.

Although this study was set up as an exploratory case study, there were some limitations regarding this set up. For instance, the study could only be administered to a small population of fifteen students. Additionally, time constraints and concerns of fatigue limited the number of design problems that could be tested by each student. Deeper analysis would enlist a larger group of external reviewers in order to more equally balance with the population of students.

Conclusions

This study suggests that students' prior experiences play an important role in their ability to generate solutions to a given problem. If there is a prototypical solution that everyone is familiar with, there is a higher chance that this kind of a problem may not lead to in-depth exploration of the design solution space. As such, if the intent of a study is to understand how students will explore a given solution space, it is important to empirically test the design contexts in order to choose a problem that will be conducive to a broad range of solutions. By exploring a larger possibility of design problems, the potential solution space can be radically enlarged. Also, providing participants with multiple design problems for a single design study can be an effective method for improving the size of the solution space and can provide valuable information about how participants with varied backgrounds approach design problems differently.

Additionally, it is important to look beyond the anecdotal responses of participants when seeking out design challenges. Participants are not always able to present a subjective perspective on the diversity of their own work, and the perceived diversity of a set of solutions can vary drastically based on the perceived size of the solution space of the problem as a whole.

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