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How do Design Heuristics Affects Outcomes?

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Abstract
How do designers explore design solution spaces? The typical paradigm underlying design education is project-based learning focusing on solving design problems. However, this learning approach provides open-ended design tasks for students to work on through the entire process of design. It assumes a high level of independent learning within the specific project context, and require students to transfer lessons learned to new design problems [Pietersen 2002]. When students later face a new unstructured, ambiguous design problem, they may find it challenging to apply lessons from prior project experiences. The critique method is often used to help students think more critically about their work; however, it does not provide training on how to make use of the experience in later design tasks. How do students successfully learn to address design problems? An important stage in the design process is "ideation," which, when successful, entails applying creative thinking skills to generate novel solutions. Designers often experience limitations in generating diverse concepts [Bruseberg and McDonagh-Philp 2002]. In design pedagogy, the need for divergent thinking (generating many, varied possible solutions) is well recognized; however, instructors often do not have specific strategies about how to generate designs to teach to their students. Creative tools would help designers to generate more creative and diverse ideas during design.

In previous work, we identified successful creative strategies in the fields of engineering design and industrial design [Yilmaz et al. 2010], [Yilmaz and Seifert 2010], [Yilmaz and Seifert 2011]. When tested with engineering students, the "Design Heuristics" were shown to improve the creativity of resulting designs and to produce more variety in the designs generated [Daly et al. 2011]. In the present study, we tested whether providing Design Heuristics to industrial design students would improve their design outcomes.

Keywords
design heuristics, concept generation, design education

Disciplines
Industrial and Product Design | Industrial Engineering | Industrial Technology | Operational Research

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HOW DO DESIGN HEURISTICS AFFECTS OUTCOMES?

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1. Introduction

How do designers explore design solution spaces? The typical paradigm underlying design education is project-based learning focusing on solving design problems. However, this learning approach provides open-ended design tasks for students to work on through the entire process of design. It assumes a high level of independent learning within the specific project context, and require students to transfer lessons learned to new design problems [Pietersen 2002]. When students later face a new unstructured, ambiguous design problem, they may find it challenging to apply lessons from prior project experiences. The critique method is often used to help students think more critically about their work; however, it does not provide training on how to make use of the experience in later design tasks. How do students successfully learn to address design problems? An important stage in the design process is "ideation," which, when successful, entails applying creative thinking skills to generate novel solutions. Designers often experience limitations in generating diverse concepts [Bruseberg and McDonagh-Philp 2002]. In design pedagogy, the need for divergent thinking (generating many, varied possible solutions) is well recognized; however, instructors often do not have specific strategies about how to generate designs to teach to their students. Creative tools would help designers to generate more creative and diverse ideas during design.

In previous work, we identified successful creative strategies in the fields of engineering design and industrial design [Yilmaz et al. 2010], [Yilmaz and Seifert 2010], [Yilmaz and Seifert 2011]. When tested with engineering students, the "Design Heuristics" were shown to improve the creativity of resulting designs and to produce more variety in the designs generated [Daly et al. 2011]. In the present study, we tested whether providing Design Heuristics to industrial design students would improve their design outcomes.

2. Creative design strategies

Design undergraduates are typically provided with general instructions about concept generation techniques, such as how to "brainstorm" [Osborn 1957]. But it is less common to teach specific cognitive strategies that may help to generate more creative and diverse ideas. Providing specific strategies for design students to help them formulate novel ideas may be just as important as instruction in the technical skills for the development of functional elements of designs.

There are a variety of possible design tools available. A sample includes those aimed towards: (1) facilitating the flow of ideas, such as brainstorming [Osborn 1957]; (2) stimulating the formation of an initial idea, such as Synectics [Gordon 1961]; and (3) transformations of existing ideas into more or better ones, such as TRIZ [Altshuller 1984]. However, none of these approaches have been tested in experimental studies of designers, nor have they been empirically validated.

3. Design heuristics

Specific design ideation strategies were identified from protocols of students and professionals performing design tasks. We call these strategies Design Heuristics because they serve as cognitive "shortcuts" that aid designers in creating novel concepts. Design Heuristics are intended to help designers explore a solution space, guiding them towards generating non-typical, non-obvious ideas that also differ from one another. The Design Heuristics can also help designers become “unstuck” when they have worked on a task and are struggling to generate more, and more different, ideas.
Based on our previous research, a total of 77 separate Design Heuristics have been identified (see Table 1) [Yilmaz and Seifert 2010], [Yilmaz and Seifert 2011].

Table 1. The complete set of 77 design heuristics identified from engineering and industrial designers

Add features from nature	Distinguish functions visually	Reorient
Add gradations	Divide continuous surface	Repeat
Add motion	Elevate or lower	Repurpose packaging
Add to existing product	Expand or collapse	Reverse direction or change angle
Adjust function through movement	Expose interior	Roll
Adjust functions for specific users	Extend surface	Rotate
Align components around center	Extrude	Scale up or down
Allow user to assemble	Flatten	Separate parts
Allow user to customize	Fold	Slide components
Allow user to reconfigure	Hollow out	Stack
Animate	Impose hierarchy on functions	Substitute
Apply existing mechanism	Incorporate environment	Synthesize functions
in new way	Incorporate user input	Telescope
Attach independent	Layer	Texturize
functional components	Make component multifunctional	Twist
Attach product to user	Make components attachable	Unify
Bend	or detachable	Use alternative energy source
Build user community	Make product reusable or recyclable	Use common base to
Change contact surface	Merge functions with same	hold components
Change direction of access	energy source	Use continuous material
Change flexibility	Merge surfaces	Use human-generated power
Change geometry	Mirror or Array	Use multiple components
Compartmentalize	Nest	for one function
Convert 2-D to 3-D	Offer optional components	Use packaging as
Convert for second function	Provide sensory feedback	functional component
Cover or remove joints	Reconfigure	Use recycled or recyclable materials
Cover or wrap	Recycle to manufacturer	Utilize inner space
Create system	Reduce material	Utilize opposite surface

We translated them into specific strategies that we represented on two sides of a 5.5 x 8 inch card. Each Design Heuristic card includes a specific description of a heuristic, an abstract image depicting how to apply the heuristic, and two product examples that show the application of the heuristic to existing consumer products (Figure 1).

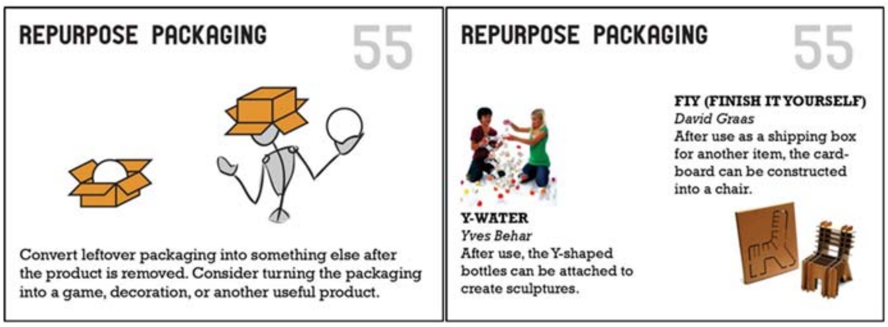


Figure 1. Design heuristic card example (front and back of the same card)

4. Experimental approach

We hypothesized that the application of Design Heuristics would enhance the creativity and the diversity of the resulting solutions, leading to a more comprehensive exploration of the design space. Our research questions were:

1. How does the use of Design Heuristics impact the exploration of the solution space for students?
2. How do sophomore industrial design students interpret the ease of use and applicability of the Design Heuristic cards?

4.1 Participants

Twenty sophomore industrial design students between the ages of 18 and 24 (15 males and 5 females) taking the same "Introduction to Industrial Design" course at a large Midwestern university participated in the study. The course covered the history, definition, scope and basic principles of industrial design, including research, idea generation, visual communication and sketch modeling. This class was the first the students took in the industrial design program after completing the core program in their first year. The students are considered novices as they reported little or no previous experience in industrial design.

4.2 Data collection

The study was conducted in a classroom setting under the supervision of the instructor. Students participated in one 80-minute session focusing on creative concept generation. The session included twenty minutes of introduction about Design Heuristics, where 3 heuristics cards were provided as examples to guide the students in their use. The three heuristic cards presented were Bend, Synthesize functions, and Use packaging as a functional component.

Next, students were given a simple design task, and asked to generate as many concepts as possible within 25 minutes while using the heuristic cards. Each participant received a subset of 12 cards determined at random. A total of 74 heuristics (the 3 example cards were excluded) were employed in the study; across the 20 students, each card was assigned between 1 and 5 times. The students were instructed to use any Design Heuristic or combination of heuristics they chose. The task involved an open-ended design problem, "designing a solar-powered cooking device that was inexpensive, portable, and suitable for family use" (Table 2).

Table 2. Instructions for the design task

Sunlight can be a practical source of alternative energy for everyday jobs, such as cooking. Simple reflection and absorption of sunlight can generate adequate heat for this purpose. Your challenge is to develop products that utilize sunlight for heating and cooking food. The products should be portable and made of inexpensive materials. It should be able to be used by individual families, and should be practical for adults to set up in a sunny spot. Note: Specific materials for a targeted temperature can be postponed to a later stage. Please focus on conceptual designs. Please consider both the ways of capturing the light, and the structural variety of the concepts.

After ten minutes of working on the task, the students were given additional information about transferring solar energy into thermal energy. This was provided to alleviate potential concern among the students that they may not have the technical knowledge needed to generate solutions. The students created rough sketches and labeled their designs. After completing the task, they were also asked to write notes describing each concept, how they came to the idea, and which heuristics, if any, they used in each concept. Finally, at the end of the experiment, they were given a questionnaire addressing how well they thought they did in the task, and how helpful the heuristic cards were in concept generation.

4.3 Data analysis

The concept sketches, written descriptions, and questionnaires were analyzed by two coders trained in identifying Design Heuristics. One coder had a background in engineering and art & design, and the other in industrial design. These coders scored:

- *Evidence of heuristic use:* Both the sketches and the descriptions were assessed for whether the heuristics provided in the set were evident in the participants' concepts. They also noted whether the participant claimed that he/she used the heuristic for that specific design concept. If the heuristic was both observed by coders, and claimed by the participant, then the heuristic was coded as "evident and claimed".
- *Design solution type:* Key features of the concepts were identified in terms of the primary design criteria defined in the problem. This coding scheme consisted of six categories differentiating concepts: 1. Using solely direct absorption; 2. Using solely a reflector; 3. Using solely a refractor; 4. Using solely a greenhouse; 5. Using solely a solar panel; and 6. Complex designs, where more than one of the first five categories were combined, more criteria defined in the task were used, and any ideas that did not fit into the above categories.

Separate from the above analysis, coding took place for two outcome criteria: the creativity of each concept, and the diversity (differences among concepts) of each concept set. To do this, we used a variation of the widely accepted Consensual Assessment Technique [Amabile 1982] where concepts were sorted on a relative scale by two independent coders. These two coders had no prior experience with Design Heuristics, and were seniors in the School of Art and Design with a specialization in industrial design. Each rated a randomized ordering of concepts. For creativity, each coder sorted every concept on a 1 (not creative) to 7 (very creative) Likert scale. The ratings were then averaged and rounded down. For diversity, the coders followed the same procedure considering students' concepts sets.

A separate data analysis compared how different students applied the same heuristic in different concepts. Concepts created with the same heuristic were considered side-by-side and coded for similarities and differences. Additionally, student responses to survey questions about card usefulness and applicability were analyzed qualitatively.

5. Results and discussion

Our main question of interest is, "How does the use of Design Heuristics impact the exploration of the solution space?" In total, 81 concepts were generated by twenty students. The concepts varied in methods of heat collection, portability, and usability. Three of these concepts were discarded from the data set because they did not address the given design task. Nineteen out of 20 students (95%) used Design Heuristics at least once during their idea generation, and all participants claimed to have applied heuristics to at least one of their concepts. There was no relationship between the number of concepts generated and the heuristics. Each student generated between 1 and 8 separate concepts during the short session, with an average of four. Figure 2 shows the number of concepts created by student.

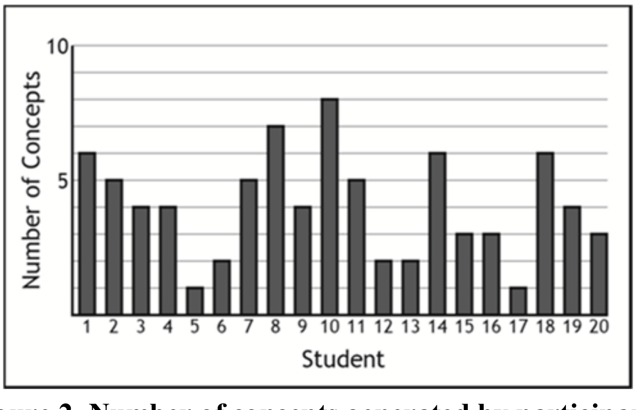


Figure 2. Number of concepts generated by participants

Of the 78 concepts, 42 (54%) showed evidence of one or more heuristics with at least one claimed by the student. In 17 (22%) concepts, students did not claim heuristic use, yet we saw evidence of it. Possible reasons for this include students forgetting to make note of the heuristic, or not being aware that they used a heuristic.
In 13 (17%) concepts, students claimed heuristic use, but we did not see evidence of it. This could result from students misinterpreting the heuristic cards, or a more complicated scenario where the heuristic started a train of thought that failed to visibly include the heuristic.
In 6 (8%) concepts, students did not claim heuristic use, and we did not see any evidence of use. In total, 59 (76%) of the 78 total concepts were coded as showing evidence of heuristic use.

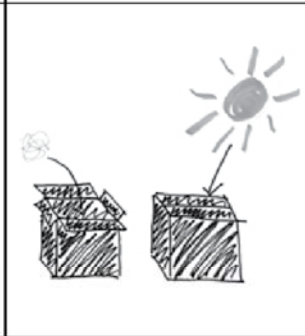
Heuristic Use Evident		Heuristic Use Not Evident	
			
Rack includes attachable grill, shelf, and cooler capturing the sunlight via solar panels. *Make components attachable detachable *Offer optional components	A black iron coil on a stand is heated through focusing sunlight with a movable lens. All parts are detachable for easy storage. *Allow user to assemble *Attach independent functional components	Sun heats up the box which then heats up the food inside.	The dome form is used as a lid to retain sunlight inside.

Figure 3. Example design solutions in which heuristic use was evident, and not evident

Figure 3 shows two design solutions in which heuristic use was apparent and claimed by the student, , and another two solutions where heuristic use was neither evident nor claimed. In the concepts where heuristics were evident, all concepts showed signs of more developed or complex ideas. For example, one participant used a magnifying glass to heat a black object, but used heuristics to address portability by making the parts detachable for easy storage.

5.1 Impact of heuristics on solutions

Based on the range of the primary criteria (cooking using solar energy), the following categories were used to code the design concepts:

1) Solely Direct Absorption: Concepts where there is no control or manipulation of sunlight, where sunlight energy is only obtained by direct absorption into food or a cooking surface. These concepts do not address the secondary criteria of the design task.
2) Solely a Reflector: These concepts use one or more reflecting surfaces to control sunlight and direct it toward food or a cooking surface. These concepts do not include any other sunlight controlling techniques, and they do not address the secondary criteria of the design task.
3) Solely a Refractor: These concepts use light refraction (i.e. magnifying glass) to control sunlight and direct it toward food or a cooking surface. These concepts do not include any other sunlight controlling techniques, and they do not address the secondary criteria of the design task.
4) Solely a Greenhouse: These concepts employ the greenhouse effect to heat a cooking surface or internal volume where food is placed. These concepts do not include any sunlight controlling techniques, and they do not address the secondary criteria of the design task.

5) Solely a Solar Panel: These concepts have a solar panel to power an electric heating element, but they do not include any sunlight controlling techniques, and they do not address the secondary criteria of the design task.
6) Complex Designs: This solution type includes all concepts that were combinations of any of the above solution types, or concepts that addressed any of the secondary criteria of the design task.

Of the original 78 concepts, 27 (35%) were coded within the first five solution types. These solutions are the more obvious, less complex concepts because they only addressed the primary criteria (cooking with the use of solar energy) of the task without consideration of secondary criteria (portability, usability, using inexpensive materials).

The remaining 51 (65%) concepts were categorized as the "Complex Designs" solution type. This category represents more complex ideas that were not adequately described by the first five categories. Within this category, 18% were combinations of heat generating techniques, and 82% included additional features to address secondary design criteria.

Of the concepts where heuristics were not evident, 53% were categorized as "Complex Designs," while 47% were categorized among the five simple solution types. Of the concepts where heuristic use was evident, 69% were categorized as "Complex Designs," while 31% fit within the five simple solution types. This difference suggests that less obvious solutions addressing additional design criteria were more common when using heuristics.

To further understand the impact of heuristics on solution types, we examined each concept in the "Complex Designs" category, and identified which heuristics were evident in each concept. Table 3 shows each solution type in the "Complex Designs" category listed with all heuristics evident.

We then identified heuristics that may have led to the consideration of additional relevant features.

Table 3. Relationship between heuristic use and design solution types in the "other" category

	Additional Features	**Heuristics Observed**
Portability	Making it Small	4,5,7,8,12,13,14,18,20,21,2224,25,29,33,34,35,37,39,40, 49,46,47,50,53,54,57,58,60, 61,62,65,68,76
	Fitting into an Exterior Container	41,55,56
	Adding Features to Make it Moveable	5,14,18,20,24,30,37,39,54,6165,68
Materials	Aluminum Foil	18,37
	Waste Materials	No Heuristics Observed
Usability	Organizational Scheme	12,20,21,28,33,41,42,44,48,55,56,60,68,76
	Additional/Secondary Functions	8,13,21,28,33,34,42,44,47,76
	Controlling Function	4,5,8,10,13,22,25,29,30,35,38,39,42,54,57,58,60

The impact of heuristic use on solution types is clear: Concepts showing heuristic use more often went beyond the simple, "typical" solutions, while those without evidence of heuristic use were more often simple solutions. Secondly, the evidence suggests that students found the heuristics more helpful in addressing the portability and usability criteria defined in the design task.

5.2 Heuristic impact on creativity of the outcomes

The creativity of individual concepts is another way to measure the success of a student's ideation process. We compared heuristic use to the averaged CAT creativity ratings (from the two blind coders) to identify what percentage of concepts within each creativity rating level showed evidence of heuristic use (see Figure 4).

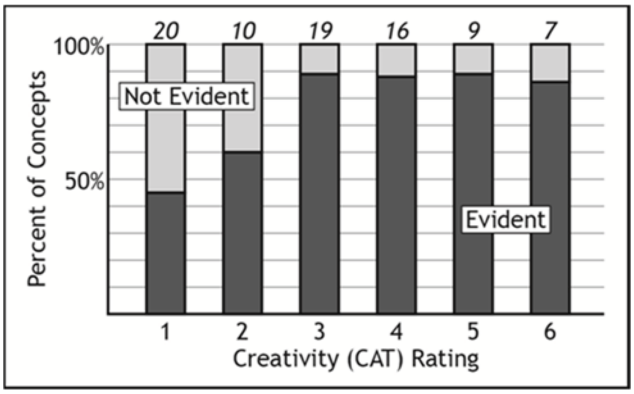


Figure 4. Creativity rating levels and evidence of heuristic use. The number of concepts per rating is shown at the top

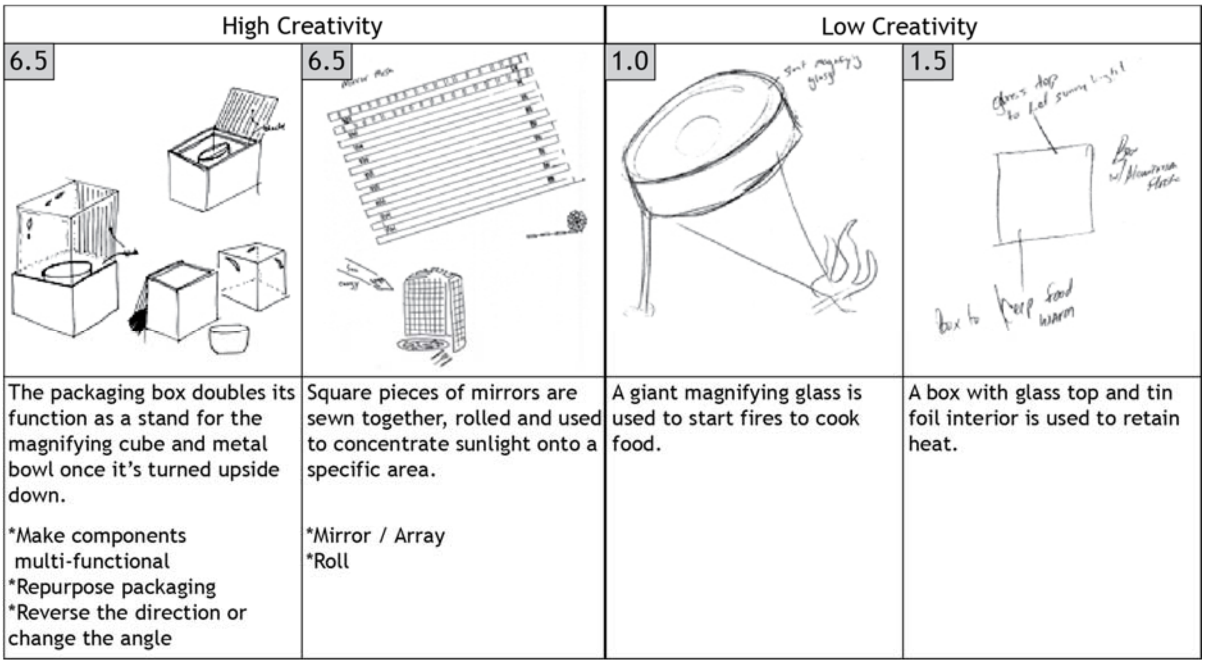


Figure 5. Concept examples with high and low creativity scores

Figure 5 shows two concepts that were rated as very creative, and two other examples that were rated as not creative. These examples demonstrate the impact of heuristics on the concepts generated. It is also evident from these examples that the heuristics were used to consider aspects beyond the primary function of collecting sunlight.

On average, concepts with evidence of heuristic use had higher creativity ratings than the ones without heuristic use. Specifically, the average creativity score of all 59 concepts with heuristic use was 3.7, whereas the average creativity score of the 19 concepts without heuristic use was 2.3. This difference is significant, $t(79) = 3.4$ ($p<.01$). Of the concepts scored above the scale midpoint, 88% had evidence of heuristic use. Of the concepts below the midpoint, only 65% had evidence of heuristic use.

5.3 Heuristic impact on concept diversity

The diversity of a set of concepts can also be used to measure the success of a student's ideation. We hypothesized that using a wider variety of heuristics, and using them repeatedly, would increase the chances of creating a diverse concept set. To measure this, we counted the total number of times a student used any of their 12 heuristics, and plotted this count against the averaged diversity rating of each student's set of drawings from the two blind coders (see Figure 6).

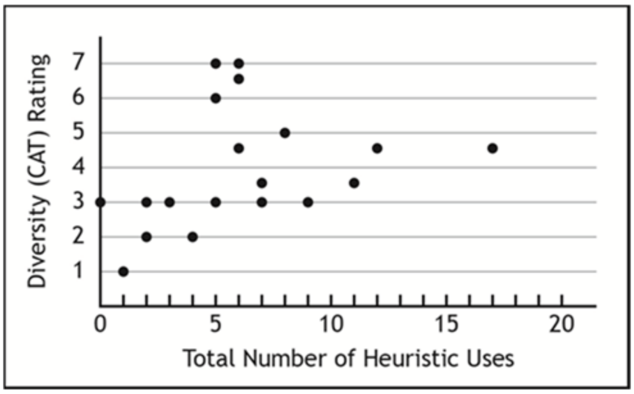


Figure 6. Diversity ratings as a function of heuristic use

From this graph, it is clear that using more heuristics repeatedly does not guarantee a higher diversity score. However, there is an upward trend, in that no student's concept set fell into the lower right corner of the graph, meaning that no students used multiple heuristics *and* had a low diversity score.

Furthermore, there is a peak in the graph between five or six heuristic uses, suggesting that there are an ideal number of heuristic uses for a highly diverse set of concepts under these task conditions. This could arise from time limitations; for example, students who applied fewer heuristics may have spent more time per application. Simply applying more heuristics repeatedly is not the key to concept set diversity, especially under time constraints. However, applying 5-6 heuristics greatly improved concept set diversity, at least under the constraints of the present task.

Figure 7 shows one example of a diverse set of concepts generated by a student using heuristics. By shifting from one heuristic to another, he addressed the design criteria in each concept in 4 different ways: (C1) folded legs; (C2) detached components; (C3) expanded body; and (C4) cylindrical form with shelving units. Less diverse solution sets involved minor modifications among the concepts, attachment of solar panels to existing products, and combinations of prior concepts into new ones.

In summary, with four different measures of design space exploration (number of concepts generated, solution type, concept creativity, and concept set diversity), we found that concepts showing heuristics were judged to be more creative and complex, considering additional features beyond primary criteria. Also, the use of five or six heuristics was related to more diverse concept sets.

Another focus of this study was to understand how students interpreted the Design Heuristic cards. To investigate this, we looked at how frequently students used each of the cards in the sets provided to them. Some students did not use any of the cards, some applied each once, and some applied them multiple times throughout concept generation. For this analysis, we counted whether the student used the card at least once.

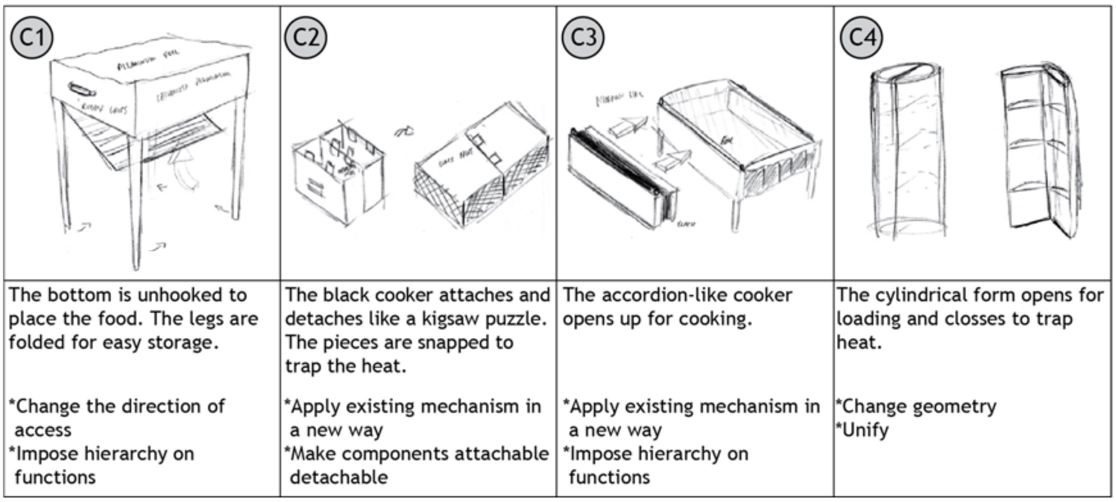


Figure 7. An example set of diverse design solutions generated by one student

Table 4 lists the heuristics according to their use; specifically, the ratio of the number of students who used the heuristic card at least once to the number of students who were given the card. Since some of the cards were provided to the students only once, further studies are needed to strengthen the statement about which cards are easiest to apply.

Table 4. Frequency of heuristic card use

Percentage	Design Heuristics
0%	2,3,6,9,11,16,17,26,27,43,49,51,52,59,66, 67,69,70,71,73,75,77
1%-20%	19,44,50
21%-40%	1,8,10,12,18,22,23,24,30,31,32,33,34,36, 37,38,41,45,47,48,53,57,62,65,72
41%-60%	7,20,21,28,40,54,55,56,61
61%-80%	4,5,14,35,39,42,46,58,60,63,68
81%-100%	13,25,29,76

Heuristic cards used by all students given them were: *Attach independent functional components* (13), *Cover or wrap* (25), *Elevate or lower* (29), and *Utilize inner space* (76). The easy application of *Attach independent functional components* was also observed in another study of first-year engineering students [Daly et al., 2011]. Twenty other heuristic cards were used by more than 40% of the students who had them.

However, 23 cards provided to the students were not used in any of the concepts. Students may have found these heuristics difficult to apply to this task. Difficulties reported by the students in the post-questionnaire were time constraints and clarity in the cards' descriptions and examples. In addition, two students reported difficulty from lack of technical knowledge about solar energy and cooking. Five students commented that the heuristic cards were easy to apply and enjoyable to work with. For example, one student said, "I really enjoyed this activity. It was awesome to get me thinking and to use the ideas of our heuristic cards."

The Design Heuristic cards are intended to guide ideation through specific prompts, but not to direct the creation of specific concepts. We expected the card prompts to be interpreted in multiple ways, and the results supported this hypothesis.

In summary, between students and across cards, the interpretation and application of Design Heuristics varied. From the students' comments, we conclude that the heuristic cards can be improved to more clearly communicate their application; and second, heuristic use may be difficult when students are limited in time, and unable reframe the design task. Finally, we observed differences in the ways students successfully interpreted the heuristic cards, such that no two solutions based on the same heuristic were alike. This provides evidence that each Design Heuristic does, in fact, lead to many possible solutions.

6. Conclusions

This study investigated the effect of Design Heuristics on novice industrial design students' exploration of the design space. The results indicated that using Design Heuristics helped students generate more creative, and more diverse, concept sets. Concepts with heuristics evident were more complex and offered additional features, such as considering the context of where and how the product would be used, how it would be carried and compacted, and whether some functions would be controlled by the user. Concepts without heuristic application were often minor modifications to existing products, attachments of solar panels to those products, or basic forms of collecting and directing sunlight, such as using solely a magnifying glass. These concepts were rarely developed further to consider context or users.

These findings confirm that the Design Heuristics approach is a sound method in ideation education for novice designers. Even for novice designers, a fifteen-minute instruction on heuristics led to the generation of multiple designs reliably judged as more creative and diverse. The ideation process was greatly facilitated by this Design Heuristic instruction. This finding supports the level of specificity the heuristics provide, suggesting they serve to aid in exploration without limiting possible concepts.

To thoroughly assess Design Heuristics as an instructional method, further studies are needed with a larger sample size and a control group. In addition, we tested our approach with only one design problem, leaving the question of investigating the applicability of heuristic cards in different problem contexts. This paper provides evidence of a promising avenue for explicit instruction on ideation techniques. As a supplement to the experiential learning approach, instruction on design heuristics may help to make explicit the strategies employed by experienced industrial and engineering designers. Given the challenges of design problems, this pedagogy for innovation is a promising development.

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