A Comparison of Cognitive Heuristics Use between Engineers and Industrial Designers

Seda Yilmaz, Shanna R. Daly, Colleen M. Seifert, and Richard Gonzalez
University of Michigan, USA

The present study focuses on an exploration and identification of design heuristics used in the ideation process in both industrial designers and engineering designers. Design heuristics are cognitive strategies that help the designer generate novel design concepts. These cognitive heuristics may differ based on the design problem, the context defined, and designers' preferences.

In a think-aloud protocol study, five engineers and five industrial designers were asked to develop product concepts for a novel problem. We analyzed these protocols to document and compare industrial designers' and engineers' concept generation approaches, and the use of design heuristics in their proposed solutions. The results show evidence of heuristics use, and that they are effective in generating diverse, creative, and practical concepts. Some differences were observed between the designers from the two domains in their approaches to the design problem and in the design heuristics used in generating alternatives.

Introduction

How do designers explore design spaces? Does the concept generation phase differ between engineers and industrial designers? Both groups are often called upon to create new products and innovative redesigns; yet, their training in creative techniques differs greatly. In industrial design, training emphasizes repeated experience with design concepts along with a critique process. In engineering, greater emphasis is typically placed on solving technical issues within a design; however, training also includes

J.S. Gero (ed.): *Design Computing and Cognition'10*, pp. 3–22.

creativity techniques, as engineers are often called upon to create novel designs [1].

Past studies have examined general approaches used in ideation [2] and [3], and the importance of design heuristics is well recognized [4]; however, it is still unclear how multiple and varied ideas are generated. What cognitive strategies do designers really use, and how do these strategies differ between the domains of engineering and industrial design?

In previous work, we found evidence for specific design heuristics that supported designers in exploring the space of potential designs, leading to the generation of varied and creative solutions [5], [6]. This was particularly noted for heuristics that connect the design context to specific concept transformations [7]. Design heuristics may guide the designer's exploration of possible solutions by varying overall strategies, product characteristics, or element modifications. An example heuristic is "*Adding on, taking out, or folding away components when not in use*," evident when the designer minimized added components by creating concepts integrated within an existing product. Because design heuristics appear to support the generation of multiple and diverse concepts, it seems likely that explicit training in effective heuristics may support the development of ideation skills for designers.

Design Heuristics

The aim of this research was to explore and identify both the types of design heuristics and the frequency of their use in the ideation process. By including both industrial designers and engineers, we hoped to learn about the generality of design heuristics across these domains. Following Newell and Simon [8], we define design as occurring within a "design space" consisting of all feasible designs. Some of these potential designs are easy to consider because they involve simple combinations of known features, or involve already-known elements. However, a designer may never consider some of the possible solutions within this space because they do not naturally come to mind. An alternative process to assist in this exploration is the application of cognitive strategies, defined as "design heuristics," that help to move the designer into new parts of the design space. The key to innovative solutions, then, is to apply different heuristics to assist in creating novel designs within this potential design space [5] [6].

Research in psychology describes heuristics as simple, efficient rules to explain decision making, judgments, and problem solving, especially when faced with complex problems with vague information [9]. Behavioral research shows that experts can utilize heuristics effectively, and suggests that their use of heuristics is one feature that distinguishes them from novices (e.g., [10]). Design heuristics may vary with regard to where and how they are applied, how they impact a design or trigger moves within the design space as a whole, and the amount of time invested in applying them. The usefulness of a particular heuristic will depend on the problem context, so that by definition, there is no determinate heuristic that will lead to a definitive solution.

We propose design heuristics differ from other approaches used in idea generation. Some existing approaches, such as brainstorming, brainwriting, and checklists, are open-ended to allow naturally occurring ideas to flow, often prompted by criteria, constraints, or other ideas. Other approaches have proposed more directed approaches, which can also be called heuristics; specifically, SCAMPER [11], Synectics [12], and TRIZ [13]. These heuristic approaches have a similar foundation in that they provide specific prompts to support the generation of new concepts. However, the heuristics proposed in SCAMPER and Synectics are quite general (e.g., "amplify a feature"), while the heuristics proposed in TRIZ focus more specifically on mechanical devices and systems and are most applicable in later stages of design. None of these approaches have observed heuristics in studies of designers, nor have they been empirically validated. Thus, the present study aims to examine the heuristics that arise in idea generation.

In previous work [14], we characterized three types of cognitive design heuristics that prompted different types of movements in the design space:

- *Local* heuristics define characteristics and relationships of design elements within a single concept, for example, adjusting functions by moving the product's parts.
- *Transitional* heuristics provide ways to transform an existing concept into a new concept, for example, substituting a form.
- *Process* heuristics prompt a designer's general approach to idea generation; for example, changing the context to give rise to new aspects of the product. They serve as cognitive tools used to initially propose ideas by directing the designer's navigation of the solution space.

These heuristics serve as a base set of hypotheses for the types of heuristic use we expect to see in both engineering and industrial designers as they create novel designs. The questions addressed in this study were: How does heuristic use lead designers to potential solutions in the design space? Does heuristics use differ between the two types of designers? How can evidence of heuristics guide design education across both disciplines?

Experimental Approach and Research Questions

Our design heuristics approach suggests that there are cognitive strategies that can aid in navigating and exploring design spaces. Therefore, for both groups of designers, we hypothesized that the application of design heuristics during the creative process would enhance the variety, quality, and creativity of potential designs generated during the ideation stage. We proposed that specific design heuristics would help designers explore new types of potential designs, leading to the generation of innovative solutions. The design task selected was open-ended and involved creating a new product, with very little information about constraints.

In the study, we compared those with industrial design backgrounds to engineers. We expected participants within industrial design to have learned how to generate concepts for vaguely defined design problems, and so would exhibit more creative and diverse design behavior. On the other hand, we expected engineers who have learned to solve technical problems would exhibit more practical and methodical design behavior. Specifically, we hypothesized that, compared to the industrial designers, engineers will: (1) have more technical and practical, but less creative design concepts, and (2) have less diverse concepts since they may have less experience with open-ended design tasks.

Participants

Participants were recruited from professional conferences and a mid-western university. In this study, we report a set of ten case studies. The list of participants with their age, gender, and experience level is shown in Table 1. These ten cases represent a range in domain experience for both fields, as well as a range in performance through the sessions. Within these case studies, we hope to find some suggestive differences between industrial designers and engineers that may be addressed in future studies.

Method

In a think-aloud protocol study, we documented designers' approaches to generating concepts in a single design task. The problem involved designing "a solar-powered cooking device that was inexpensive, portable, and suitable for family use." The design problem statement also specified some design criteria and constraints, but it was intended to serve as an open-ended problem with many potential solutions. The instructions prompted participants to generate diverse creative ideas for the solutions.

Participants were given thirty minutes for the task. After ten minutes, the experimenter provided a few paragraphs of additional information about transferring solar energy into thermal energy in case participants did not feel they had the technical knowledge to proceed. This information encouraged the designers to move past the need for specific technical information for their solutions. Throughout the session, the experimenter asked the participants to keep talking if they became silent at any point.

Table 1 Participants' age, gender, and design-related experience

Participant	Age	Gender	Design-related Experience
Ind. Designer 1	27	Female	2+ years in industry, 2+ years in design graduate school
Ind. Designer 2	29	Male	1+ years in industry, 5+ years in design graduate school
Ind. Designer 3	21	Female	Senior in design school
Ind. Designer 4	21	Female	Senior in design school
Ind. Designer 5	20	Male	Junior in design school
Engineer 1	53	Male	25+ years in industry, 4 years in design management graduate school
Engineer 2	27	Male	4+ years in engineering graduate school
Engineer 3	25	Male	2+ years in engineering graduate school
Engineer 4	23	Female	1+ years in engineering graduate school
Engineer 5	22	Male	Senior in engineering school

The designers' drawings were captured, along with their verbal comments, using an electronic audio recording pen, which also captured the movements of the pen during sketching. After the task was over, participants were asked to review their drawing, and to verbally describe the concepts they had generated, how they moved from one concept to another, and their approaches to ideation. Finally, they were asked to provide demographic information, and rate their performance.

Verbal data from the experimental sessions were transcribed to supplement the audio and visual sketching data, and all data was analyzed for evidence of heuristic use. Two evaluators, one experienced in industrial design and the other in engineering design, examined all of the protocols. The goal of the analysis was to characterize the various decision patterns evident in participants' performance on the task. Thus, the analysis included identifying each concept generated as a separate idea, categorizing characteristics of the solution concepts generated, determining the number and diversity of the concepts, and determining specific design heuristic evident in the concepts. These features were coded for each concept, between concepts, and over the experimental session. The coders worked independently, and then resolved any disagreement through discussion. Initial interrater agreement was 80% across the protocols.

In majority of the cases, heuristics were not consciously articulated by the participants; however, heuristic use was evident in comments such as, "I'll use both a magnifying glass and a mirror, since I'm not sure if the energy will be enough to cook the food." This was evaluated as indicating the use of a "*Using multiple components to achieve one function*" heuristic. The sketches also provided separate evidence of heuristic use in the specified characteristics of the products, the product contexts drawn, and the relationship of these concepts to other solutions. Thus, both verbal and visual (sketched) data were considered for any evidence of heuristic use.

Additional coding was performed on each concept using two criteria: creativity and practicality. First, questions characterizing creativity and practicality for the given design task were identified by the two evaluators, and then each concept was coded by both raters individually. Some of the questions considered for rating creativity included: "Does it address a design criterion unique from the other designers' concepts? Is it considerably different from an existing well-known product? Does it use unexpected materials?" For practicality, some of the questions included: "Is it easy to use? Is it going to work? Is it portable?" The questions were used as guidelines, and the ratings completed in a subjective manner [15].

Results

The results reported here include a discussion of the types of solutions generated, instances of local, transitional, and process heuristics observed, and the relationship of the heuristics used to the diversity of the concepts generated, along with creativity and practicality. In each of these analyses, emphasis was given to differences between protocols from industrial designers and engineers. Because the sample size is small, comparisons across the two groups are likely to be limited in their generalizability.

Types of Concepts Generated

Major elements and key features of the concepts were identified in terms of functionality, form, and user-interaction, Table 2. This allowed us to see the diversity of concepts generated from within this design space. For example, solutions could direct sunlight using mirrors, maintain heat by creating a closed product with a clear lid (so the sunlight could get in), or include straps so the product could attach to the user. Alternatively, a solution could use a magnifying glass to direct sunlight, an insulated box to maintain heat, or a foldable container for easy transport. These were each coded as distinct concepts.

Table 2 Solution characteristics for the solar-powered cooker problem

Diversity Criteria	Examples	Industrial Designers	Engineers
Way of Directing Sunlight	1. Magnifying glass / Lens	10	11
	2. Reflective surface / Mirror / Aluminum foil	9	14
Method of	1. Closed product	6	11

Maintaining Heat	2. Glass / Plastic lid	3	5
	3. Insulation	1	8
	4. Metal	0	2
Method of Cooking or Warming Food	1. Direct sunlight	20	20
	2. Hot surface	5	1
	3. Incorporating fluids	0	5
	4. Solar panels	4	2
	5. Steam / Smoking / Fire	1	2
Product Materials	1. Flexible material	2	4
	2. Open surface	11	7
	3. Pot	6	7
	4. Tube	0	3
Approach to Compactness or Portability	1. Attachment to user	1	1
	2. Carrying case	0	1
	3. Detachable components	3	7
	4. Foldable components	9	4
	5. Rollable components	1	3
	6. Separate pieces	2	10
	7. Wheels	1	0
Other Features	1. Attached to pre-existing things in the environment	0	2
	2. Adjustable settings	6	8
	3. Stand	2	4
	4. Thermometer	1	1
Total number of concepts generated		**28**	**23**

The number of concepts was defined, in part, through the use of cues from participants as they indicated the beginning and ending to a given concept. New concepts were also evident in drawings when moving to a new illustration of an idea. However, number of concepts generated alone does not necessarily reflect the diversity of the concepts, as similar concepts or evolution of one concept could appear at any point within the session. Thus, we report the number of *different* concepts generated by each participant. Criteria used to classify the content of designs and understand the diversity of the space is presented in Table 2.

A difference in technical knowledge was evident in comparing the engineers' solutions to the industrial designers' solutions. For example, the five engineers used insulation more frequently, while the five industrial designers' solutions did not commonly consider the need to maintain the heat. The engineers also created closed surface products more often, while the industrial designers were more likely to have open surfaces for cooking, which would not allow heat to be maintained as effectively.

Another engineering solution was to use multiple mirrors to collect sunlight, reflecting concern about the function of the product, while only one of the industrial designers included this feature. In most cases, industrial designers selected a hot surface as the method of cooking, with open surface designs. In other concepts, engineers generated solutions incorporating fluids like water or oil for cooking; while none of the industrial designers did so. This may reflect a lack of technical knowledge among industrial design compared to the engineers, which may have resulted in more frequent use of existing products as models.

Another interesting difference was that engineers more often used separate pieces and detachable components, while industrial designers more often created single unit products that folded inside. Because of these dissimilarities, it is possible these two groups of designers could benefit from sharing their different approaches with each other.

Evidence of Heuristic Use

The main focus of this study was to document how subjects moved through the design space; that is, the ways they approached concept generation, developed solutions, and transitioned between design concepts. The coding for the evidence of heuristics began with a base set of heuristics from TRIZ principles [13], and from our previous work [7]. We adapted some of these, and added other heuristics to better describe the changes in concepts apparent in the protocols. Table 3 presents the local and transitional design heuristics coded in the concepts generated by the ten participants. Local and transitional heuristics are listed together because the same heuristic can be used for defining the relationship of the elements within one design concept, or as a transition in moving from one concept to a new one. Whether the heuristic was observed as a local or transitional heuristic, or both, is indicated in Table 3.

Table 3 (continues on next page) Partial list of Local (LH) and Transitional (TH) heuristics identified in the content analysis of concepts generated by engineers and industrial designers

Heuristic	**Heuristic Description**	**LH**	**TH**
Adjust functions by moving parts	By moving the product's parts, the user can achieve a secondary function	X	X
Attach components with different functions	Adding a connection between two parts that function independently	X	
Attach the product to another existing item	Utilizing an existing product as part of the function of the new product	X	
Attach the product to the user	The user becomes part of the product's function	X	
Change the configuration of elements	Performing different functions based on the orientation or the angle of the design elements in the product	X	X
Change the geometrical form	Using different geometrical forms for the same function and criteria		X
Compartmentalize	Separating the product into distinct parts or compartments with different functions	X	
Cover	Overspreading the surface of the product with another component to utilize the inner surface	X	X
Combine into a system	Connecting parts with different functions to develop a multi-stage process to achieve the overall goal	X	
Detach / Attach	Making the individual parts attachable /detachable for additional flexibility	X	X
Elevate	Raising up either the entire product or its parts from a lower place to a higher one	X	
Fold	Creating relative motion between parts by hinging, bending, or creasing to condense the size	X	X
Nest	Placing a component inside another identical component or an existing product, entirely or partially	X	
Offer optional components	Providing additional components that can change the function or adjustability	X	X
Provide sensory feedback to the user	Returning some of the output of a system as input to provide control in the process	X	

Heuristic	**Heuristic Description**	**LH**	**TH**
Repeat	Dividing single continuous parts into two or more elements, or repeating the same design element multiple times, in order to generate modular units	X	X
Replace solid material with flexible	Changing a product's material into a flexible one for creating different structural and surface characteristics	X	X
Roll	Revolving a part or the entire product over on a center point or a supporting surface	X	
Rotate around a pivot point	Changing an object's function by manipulating its geometrical surfaces around an axis	X	
Scale	Changing the size of a feature of the product	X	X
Split	Taking a piece of the previous concept to generate a new concept		X
Substitute	Replacing the material, form, or a design component with another to achieve the same function		X
etc			

Table 4 presents the process heuristics observed. Process heuristics are those applied by the designers to the idea generation process as a whole, and reflect a designer's general approach to ideation within the session. The process heuristics observed do not include all possible heuristics for any design task; however, they represent a set of possible heuristics appropriate for idea generation for this design problem.

The protocols demonstrated evidence of all three types of heuristics (local, transitional, and process heuristics) found in our previous work [14]. In sum, heuristics were identified 259 times (local heuristics=216, transitional heuristics=29, and process heuristics=14). The total number of local heuristics per concept ranged from 1 to 10, and multiple heuristics were observed in most of the concepts (47 of 51). Concepts with only one local heuristic seemed to be either very simple solutions (i.e. a plate capturing sunlight), or were vague and undefined. Concepts not emerging from transitional heuristic use indicated that the designer had abandoned the prior concepts and began a new search for a different concept, either with or without the use of a process heuristic.

Table 4 Process Heuristics (PH) identified in the content analysis of concepts generated by engineers and industrial designers

Process Heuristic	**Heuristic Explanation**
Brainwriting	Using naturally occurring ideas, without judgment, as starting points for concepts
Constraint Prioritizing	Putting more emphasis on certain criteria than others and using the emphasized criteria to focus and guide concept development
Contextualizing	Changing the context in which the product would be used, and using that context to inspire a concept that satisfied the nature of the context
Elaborating	Building on a foundational concept by increasing the details of the concept
Evaluating	Placing value to a concept and generating additional concepts by building on what is seen as effective or adjusting problems found in the evaluation of the concept
Problem Restructuring	Shifting or redefining what the actual problem is and generating products that satisfy the identified real problem
Redesigning	Re-designing existing products with similar functions
Simplifying	Generating and building on the simplest way to solve the problem
Using a Morphological Approach	Identifying different ways of achieving each function the product needs to perform and combining them in different ways to generate concepts

For both engineers and industrial designers, one of the most commonly applied local heuristics was "*Attaching components that have different functions*". For example, in Figure 1, Engineer 5 attached the handle to the pot and the lens, connecting both, and Industrial Designer 4 attached a continuous mirror inside the pot, wrapping it entirely.

Fig. 1. Examples using "*Attach components that have different functions*"

The other most common local heuristics for both groups were, "Covering", "*Elevating*", "*Folding*", and "*Repeating*". The least frequent local heuristics were "*Stacking*", "*Wrapping*", "*Attaching the product to the user*", and "*Using the environment as part of the product*". These differences appear to arise from the specific functions within the design problem. Thus, the context of the problem seemed to impact heuristic use. Applying the last two heuristics could have had a notable impact on the function of the product; however, we did not observe the designers utilizing these heuristics. The most common transitional heuristic for designers from both domains was "*Changing the configuration*". The designers simply rearranged the orientation of the design elements to structure new concepts.

There was little difference in the total number of heuristics used by each group; however, we did observe differences in the type of heuristic used. Engineers more often used "*Repeating*" (11 vs. 6) as a local heuristic, repeating elements such as mirrors to enhance the function of capturing sunlight. Many engineers mentioned their concerns about the adequacy of the energy produced for cooking food, which may have led them to repetition. "*Combine into a system*" was also used by engineers, but not by industrial designers (5 vs. 0). This might also be related to engineers' common practice of systems design as part of their education and experience. Engineers used the heuristic "*Use multiple sources to achieve one function*" in 8 of the 23 concepts that they generated, while this heuristic was evident in only one of the concepts that an industrial designer created. The reason may be that engineers were concerned about function, and continuously evaluated whether or not their concepts would work.

Industrial designers, on the other hand, used "*Elevate*" more frequently than engineers (11 vs. 6), perhaps because they were considering the interaction between the user and the product, which would lead to adjusting the height of the product for the user. In fact, industrial designers included representations of users in multiple concepts, while no engineers did so. The other heuristic more commonly used by industrial designers was "*Attach the product to another item*". Perhaps some of the industrial designers may not have had the technical knowledge or confidence to feel comfortable generating a novel concept from scratch, and do built from a related product. Local heuristics were evident in greater numbers than transitional ones; so, rather than developing early ideas further, they appeared to generate new ideas from scratch each time.

Finally, process heuristics, used as problem solving strategy for the entire session, were observed for some of the designers, which served to move them throughout the design space. For example, one designer strategically chose to consider different potential foods for heating in the oven, resulting in generating several new designs. Based on this data set, there were no distinctions in types of process heuristics used by designers from both disciplines.

Characterizing Design across Sessions

To understand the results, it is helpful to follow individual designers through their session, and explore how heuristics were applied in their work. The following paragraphs describe a sample of engineers' and industrial designers' protocols, including those who generated many diverse concepts and those who produced just one. We highlight the use of local, transitional, and process heuristics in these examples.

Engineer 1 generated seven diverse concepts, Figure 2. For his first concept, he chose a container that could be transported by users to a larger community gathering. The second concept was a large Fresnel lens, adjustable to the angle of the sun as well as to the best angle for cooking. For his next concept, he extended the previous one by segmenting his original lens into four separate lenses. The fourth concept was a spit cooker, which utilized a lens to focus on a line of heat, rather than a point. The fifth concept was a double boiler, consisting of a system pumping hot water from a boiler into an outer pot. Concept 6 was a synthesis of previous concepts: the design combined a double boiler with a Fresnel lens. The seventh concept was a blanket with reflectors and a drying rack. The reflective blankets are lightweight, allowing them to be transported easily, while serving as a windbreak. The eighth concept proposed a smoking chamber. It also included a Fresnel lens, and had two box-like structures on top of the other. The final concept was a three-stage boiler, comprised of a solar heater to warm up water to be utilized for steaming or boiling food.

To generate these diverse concepts, Engineer 1 used multiple process heuristics. One that he applied was the heuristic "*Contextualizing*". For most of his concepts, he first suggested a type of food, and then generated a concept that could cook that food. For example, he said "Other things to eat. We've got shish-kabobs, jerked meat, the dried herbs, the soups and things; um, let's see." He also emphasized different constraints from the problem as he worked; in concept 3, he focused on "maximizing the intensity of the sunlight", while in concept 7, he emphasized the constraints of being "inexpensive and portable".

A number of local heuristics were also documented in the concepts Engineer 1 generated. For example, in concept 3, he applied "*Adjust functions by moving the product's parts*", as the angles of the lenses on all four sides could be altered to change the amount of sunlight directed onto the food. He also applied "*Repeat*", as he added multiple lenses to direct the sunlight. Engineer 1 also used transitional heuristics; for example, he moved from concept 5 to 6 by using "*Cover*" as the transitional heuristic, where he covered the container with a Fresnel lens.

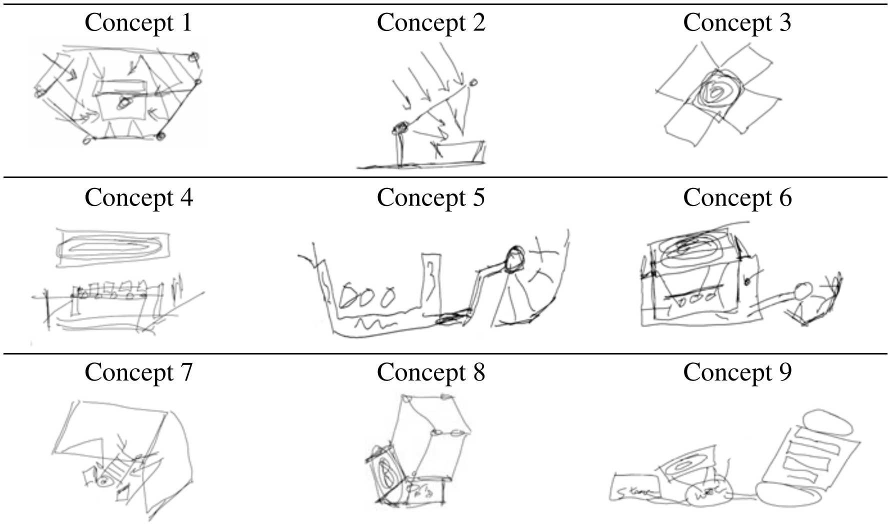

Fig. 2. Sequential concepts generated by Engineer 1

Industrial Designer 2 generated four concepts; all were considered diverse, Figure 3. In the first concept, he described a context in which the user was a hiker, and designed an integrated backpack with a heat pot attached to it. The second concept was a barbeque using solar panels on one side, and a cooking surface on the other. Solar energy was captured when the panels were unfolded fully, and the product was used when it was folded. The next concept used multiple mirrors to direct sunlight onto one part of the product that could be attached to another part for cooking. The location of those components could be switched; the heat unit was on top of the pot for collecting sunlight, and switched below it for providing heat from the bottom when cooking. His final concept was a set of small black cubes that could be utilized to absorb heat, and their orientation could be changed for cooking according to users' needs.

In this ideation process, we observed evidence of the local heuristic '*Change the configuration of elements*" in his third concept, where two components of the product were switched from top to bottom depending on the function to be achieved (cooking or trapping heat). With no evidence of transitional heuristics, Industrial Designer 2 seemed to use an approach of sampling from very different ideas within the problem space. The only consistency among his design ideas was capturing the heat during one time period and using it at another. He also used "*Contextualizing*" as a process heuristic throughout his ideation process. Using this heuristic allowed this designer to compose diverse ideas for very different settings.

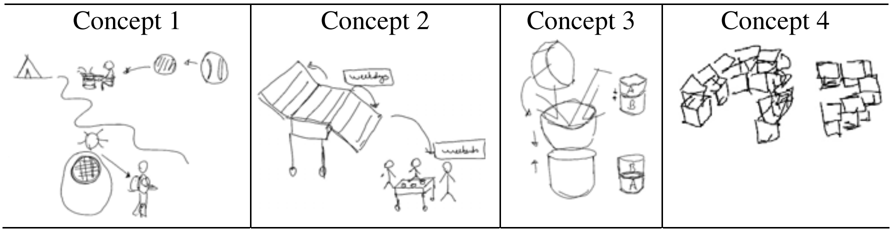

Fig. 3. Sequential concepts generated by Industrial Designer 2

We saw a similar approach in Engineer 2's protocol. He seemed to leave each concept behind and started a new one rather than continue to transform a current concept. Each of this engineer's concepts was an expanded idea from an explicit "brainstorming" session he conducted at the beginning of the session.

In contrast, Industrial Designer 3 limited her generation to only one concept; however, she then worked through 7 iterations of that concept, Figure 4. The designer began by attaching two existing components to each other -- a magnifying glass and a griddle -- to create a surface with focused sunlight. In her second concept, she transformed the magnifying glass to a square magnifying glass attached to the tray. In the following concept, she made the lens height adjustable, and, in the forth concept, she added sides to it to maintain the heat more effectively. She then considered portability by adding a rigid handle, which was changed to a flexible handle in concept 6. In addition to all of the features included in the previous versions of the concept, the final concept also included an attachment that held utensils and a spout for draining fluids from the cooking surface.

Industrial Designer 3 applied "*Elaborate*" as a process heuristic, and further developed the first concept in succeeding concepts to explore the design space. She was successful in utilizing transitional heuristics to move about and explore within this concept's range. For example, from concept 2 to concept 3, she used transitional heuristics, "*Adjust functions by moving the product's parts,*" and "*Fold*", and then from concept 5 to concept 6, the transitional heuristic, "*Replace solid material with flexible*", as she changed the material of the handle. Table 5 displays the local heuristics within each concept. The total number of local heuristics increased in each concept while maintaining the changes already introduced. The designer did not leave the heuristics she used in the previous concepts, but instead carried them along, iterating on the concept and adding more to further the design.

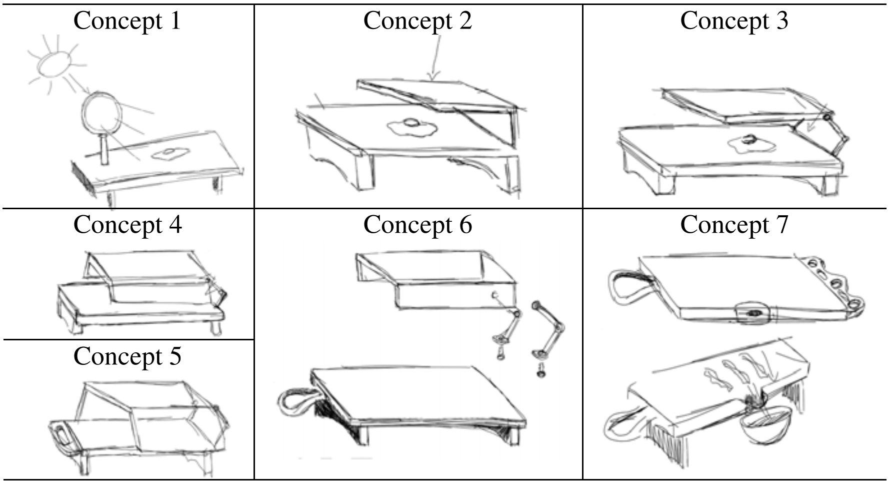

Fig. 4. Sequential concepts generated by Industrial Designer 3

Another example of a designer who generated only a few concepts was Engineer 3, who generated two concepts with no apparent process heuristics. Her first concept was a parabolic reflector in which the shape of the reflector allows the sun to be targeted onto a specific point. The second was a water-heating device in which heat would be stored in water that is heated by the sun.

In this case, two separate ideas are evident, but their generation did not lead to further transformations of concepts, nor to more novel ones. Heuristic use was not evident in these design concepts, suggesting a relationship between the use of design heuristics and the generation of multiple, diverse concepts.

Table 5 Local heuristics observed in Industrial Designer 3's concepts

	C1	C2	C3	C4	C5	C6	C7
Attach components that have different functions	•	•	•	•	•	•	•
Elevate	•	•	•	•	•	•	•
Compartmentalize		•	•	•	•	•	•
Adjust functions by moving the products' parts			•	•	•	•	•
Fold			•	•	•	•	•
Rotate around a pivot point			•	•	•	•	•
Cover				•	•	•	•
Detach or Attach					•	•	•
Replace solid material with flexible						•	•
Offering optional components							•
Repeating							•

Design Heuristics and Concept Diversity, Creativity, and Practicality

We next examined how the use of heuristics throughout the session related to the number and variety of design concepts produced by each individual designer. Figure 5 displays the number of diverse (meaning different in content) concepts for each participant, and characterizes how the use of multiple process heuristics was associated with those concepts. However, as noted above, those with the most diverse concepts were not necessarily the designers who generated creative solutions. There were examples in the case studies that prove both designers with diverse concepts and designers following a single concept through multiple iterations could produce creative outcomes in design.

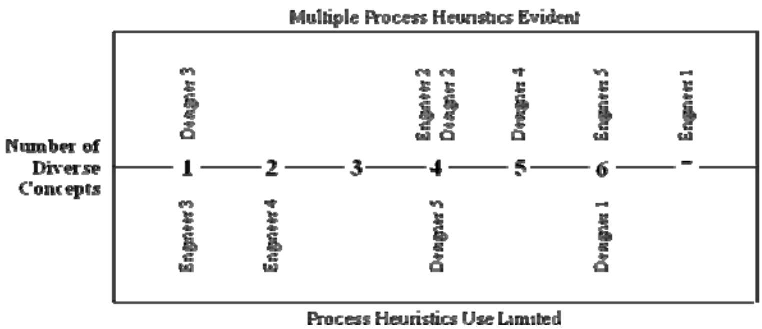

Fig. 5. Number of diverse concepts generated per participant

Comparing the engineers to the industrial designers, the average ratings show there were no mean differences between the engineers and industrial designers on either creativity or practicality (*t*s < 1). This is not surprising because there is relatively little power (five subjects in each group). However, across the whole sample of difference design concepts, the averaged creativity (r=.54) and practicality (r=.53) scores correlate highly with the number of heuristics identified in each ($p<.01$ for both criteria). That is, the designs with more heuristics observed were also rated as more creative and practical.

These correlations are driven almost entirely by the industrial designers' data. This suggests that engineers may have also used other means, such as their technical knowledge, to generate alternative concepts, whereas industrial designers tended to use heuristics to identify different solutions. This result also suggests that the industrial designers were not blocked by their lack of technical knowledge; instead, they may have used design heuristics to compensate for this lack of knowledge.

Discussion

The results provide empirical evidence of heuristic use in design, and show that heuristics are effective in generating diverse concepts. Design heuristics may, at times, be sufficient to stimulate divergent thinking. Furthermore, the study reveals some differences between these two types of designers in how they approached this open-ended, novel design problem. Specifically, we found that engineers produced a more diverse set of designs from among all of the concepts generated. Industrial designers, however, generated more design concepts in the same period. Nevertheless, the number and ways in which they used heuristics was very similar in the two groups, which suggests that design heuristics may be an effective means of ideation in each of the two design domains.

The differences observed in industrial and engineers may arise directly from the type of training emphasized during the educational process, and the types of problems typically experienced during training. Despite lacking technical knowledge, industrial designers generated more concepts. On the other hand, engineers' solutions were more diverse, and they used more diverse criteria (see Table 2). Their concepts were also more detailed, and provided more technical information about their practicality. Industrial designers structured the context and approached the problem from a user perspective, such as families versus individual hikers, the product's use in kitchens versus backyards, and the product as a single entity versus attached to existing products (such as a grill or stove).

It also appeared that engineers did not propose concepts unless they felt it was viable. They constantly evaluated their solutions according to functional principles and practicality in use. On the other hand, industrial designers were not as concerned about carrying the idea to a realistic level. Since this ideation stage was more about generating as many concepts as they could, industrial designers seemed more comfortable proposing concepts with less regard for how they would function.

The results of this empirical study must be considered in context. Certainly, there were differences in experience among the engineers and industrial designers participating in the study, and the number of participants was small. Second, the study was specific to one design task, constraining the generalization of findings across other tasks. Another limitation is that the design task was an isolated, one-time, half an hour session, not a typical work setting for many designers.

However, the success of this heuristic analysis method in characterizing differences among designers may suggest ways to assist designers in adding to their ideation skills. Further, the identification of heuristics may suggest ways for computational tools to assist in design. For example, the frequency of heuristics applied could be analyzed to understand which of the heuristics are most commonly used, what kind of design problems they were frequently applied to, what kind of new concepts they generated, and which heuristics may be relevant given the observable patterns. In particular, this approach may hold promise in instruction for novices as they build their experience with heuristic use and design in general.

Conclusions

Pedagogy for enhancing design creativity is essential because most engineering and industrial design problems demand innovative approaches in the design of products, equipment, and systems. The present study showed that design heuristics can enhance innovation effectively in both engineering and industrial design domains. How can design heuristics be effectively taught?

Exposure to a variety of heuristics and experience in applying them on many different problems may lead to the development of expertise in innovation. For many design students, simply having an arsenal of design heuristics to try might lead to improvement in concepts generated. In fact, one factor may be motivational: it is possible that demonstrating the effectiveness of heuristics for creative tasks may, through feelings of efficacy, motivate creative efforts, just as the outcomes of creative efforts lead to an appreciation of creative work [16].

This study suggests that in design problems, making use of specific design heuristics may lead to more varied, creative, and practical solutions. Future research will continue to study the hypothesis that design heuristics developed by expert, innovative designers may be useful to all practitioners, including novices.

Acknowledgement

This research is supported by The National Science Foundation, Engineering Design and Innovation (EDI) Grant 0927474.

References

1. Court, A.W.: Improving creativity in engineering design education. European Journal of Engineering Education 23, 141–154 (1998)
2. Christiaans, H.H.C.M., Dorst, K.H.: Cognitive models in industrial design engineering: a protocol study. In: 4th International Conference on Design Theory and Methodology, ASME, vol. 42, pp. 131–140 (1992)

3. Park, J.A., Yilmaz, S., Kim, Y.S.: Using visual reasoning model in the analysis of sketching process. In: Workshop Proceedings of 3rd International Conference on Design Computing and Cognition, DCC (2008)
4. Finke, R.A., Ward, T.B., Smith, S.M.: Creative cognition: theory, research, and applications. The MIT Press, Cambridge (1992)
5. Yilmaz, S., Seifert, C.M., Gonzalez, R.: Cognitive heuristics in design: Instructional strategies to increase creativity in idea generation. Journal of Artificial Intelligence in Engineering Design and Manufacturing (AI EDAM), Special Issue: Design Pedagogy (2009)
6. Yilmaz, S., Seifert, C.M.: Cognitive heuristics employed by design experts: A case study. In: 4th International Conference of International Association of Society of Design Research, IASDR, Seoul, Korea
7. Yilmaz, S., Seifert, C.M.: Cognitive heuristics in design ideation. In: 11th International Design Conference, DESIGN 2010, Dubrovnik, Croatia (2010)
8. Newell, A., Simon, H.A.: Human problem solving. Prentice-Hall, Englewood (1972)
9. Nisbett, R.E., Ross, L.: Human inference: Strategies, and shortcomings of social judgment. Prentice-Hall, Englewood Cliffs (1980)
10. Klein, G.: Sources of power: how people make decisions. The MIT Press, Cambridge (1998)
11. Eberle, B.: Scamper, Prufrock, Waco, Texas (1995)
12. Gordon, W.J.J.: Synectics. Harper & Row, New York (1961)
13. Altshuller, G.: Creativity as an exact science. Gordon and Breach, NY (1984)
14. Daly, S.R., Yilmaz, S., Seifert, C.M., Gonzalez, R.: Cognitive heuristic use in engineering design ideation. In: Daly, S.R., Yilmaz, S., Seifert, C.M., Gonzalez, R. (eds.) 117th American Society for Engineering Education Annual Conference. ASEE (2010)
15. Amabile, T.: Social psychology of creativity: a consequensual asessment technique. Journal of Personality and Social Psychology 43, 997–1013 (1982)
16. Basadur, M.S., Graen, G.B., Wakabayashi, M.: Identifying differences in creative problem solving style. In: Parnes, S.J. (ed.) Source book for creative problem-solving, Creative Education Foundation Press, Buffalo (1992)