AC 2010-1032: COGNITIVE HEURISTIC USE IN ENGINEERING DESIGN IDEATION

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Abstract

Research in engineering design has revealed approaches and processes used by engineers to move through a design task. While studies have made evident general approaches in ideation, it is unclear how multiple and varied ideas are generated. When faced with a design problem, how do engineers generate multiple alternative solutions? How do they move from one idea to another? Research in psychology has shown that decision-making often relies on simplified cognitive heuristics. Heuristics are reasoning processes that do not guarantee the best solution, but often lead to potential solutions by providing a "short-cut" within cognitive processing[1]. Using a case-study framework, this research identified and categorized types of heuristics engineers used to explore potential designs solutions. Using a think-aloud protocol, five engineers with varying levels of experience were asked to develop conceptual designs for a solar-powered cooking device that was inexpensive, portable, and suitable for family use. Following the think-aloud session, the engineers participated in a retrospective interview designed to provide additional information on the sources of ideas, and their awareness of their own methods of ideation. The protocols were analyzed for evidence of heuristic use, and the relationship between heuristic use and the success of the designs. The results showed extensive use of a variety of design heuristics, characterized as process, local, and transitional in nature. However, the engineers in this study did not report conscious application of local heuristics, suggesting they were not aware of applying them during concept generation. Evidence for the utility of cognitive heuristics in the ideation stage is examined and suggestions for their use in engineering design pedagogy are provided.

Key Words: design, concept generation, heuristics, design strategies

Introduction

Understanding both successful and unsuccessful concept generation is key to developing strategies for improving design education. Presumably, the goal of generative reasoning is to create more, and more varied, solution conjectures. The result of engineering design activity is often expected to be original, adding value to the base of existing designs by solving technical problems in new ways. Diversity in concept generation provides multiple pathways that designers can pursue and merge as they progress in design tasks, and thus concept generation can be considered successful if designers provide multiple pathways for exploration in later design phases.

However, studies have reported engineering student designers have difficulties with concept generation compared to experts in the field [2, 3]. In less-experienced engineering designers, deductive reasoning has been observed, which leads to additional, and sometimes too much, problem analysis[4]. They have trouble generating diverse ideas and often fixate on a single concept[5].

What accounts for engineers' success at generating diverse ideas? What aspects of their overall approaches to concept generation and their local approaches to developing each concept are they aware of and consciously apply? This paper presents an empirical approach to the study of cognitive processes in design idea generation. We examined protocols of five engineers working on a simple design task, and identified the strategies evident in their proposed conceptual solutions. We propose that explicit instruction on strategy use may be helpful in engineering design education.

Background

Conceptual design in engineering is the process of creating ideas for new product or system functions, forms, and behaviors[6]. In successful design approaches, as has been shown in the approach of experts[7], initial ideas are generated, and the design problem is vigorously reframed by interpreting specifications and constraints. The influence that such early decisions have on the entire design process is foundational for successful design outcomes. To achieve this, divergent thinking is encouraged, where designers create plenty of options to increase the likelihood that a good design can be attained.

Jansson and Smith[5] were the first to document fixation in an engineering design task. They hypothesized that design fixation might be caused by the examples that sometimes accompany problems given to designers. Although intended to suggest other possible solutions, those examples might, instead, have an inhibiting effect, restricting the problem solver to the components in the example designs. They found that designers are sometimes trapped by the characteristics of a possible solution that has been developed as an example, and by existing precedents for the design.

Purcell and Gero[8] extended Jansson and Smith's[5] findings by examining the possible occurrence of fixation across different design disciplines and levels of experience. They found that there was a clear fixation effect observed for two groups of mechanical engineering students. In contrast, the fixation effects for the students in industrial and interior design were only marginally significant. They suggested that the complex pictorial example provided to the designers might have affected them in using their own cognitive resources, so that they relied more on the provided examples in order to create a design solution.

There are multiple theories of how ideas are generated in design. Finke et al.[9] divided these creative processes into two categories: *generative* (analogical transfer, association, retrieval, and synthesis) and *exploratory* (contextual shifting, functional inference, and hypothesis testing). Shah et al.[10] proposed a model (called "Design Thought Process") involving brainstorming. Linsey et al.[11, 12] suggested a method for identifying analogies as part of the ideation process, and showed that memory representations influence the ability to use analogy to solve a design problem. Nevertheless, little is known about these cognitive strategies, how designers apply them, and how they affect the quality or creativity of the resulting design.

Observational studies of designers at various levels have demonstrated the use of strategies in design such as accessing information, monitoring progress, clarifying and examining key concepts, and verifying how solutions meet design objectives (e.g. Adams & Atman[13]). Kruger and Cross[14] found that designers using a *problem-driven* design strategy tended to produce the best results in terms of the balance of overall solution quality, except creativity, compared to designers using a solution-driven strategy. However, these strategies are not specific to the initial concept generation phase of design tasks, especially for design tasks with a relatively low number of constraints and the possibility for many alternative design concepts to be explored.

Several competing theories exist in regards to specific design strategies for concept generation. SCAMPER[15], Synectics[16], and TRIZ[17], have provided suggested heuristics, but none have provided empirical validation and are not based on observing designers and documenting their thought processes in action. These three approaches appear to differ drastically, but also have many similarities among them. The TRIZ approach was developed from identifying trends in designs of products and systems with similar functions over time based on data gathered from mechanical engineering patents. Its technical “contradiction matrix” of 39 common engineering problems and 40 possible solution types provide a strategy that can be applied to the design problem at hand. For example, in designing a soda can, a designer employing the TRIZ system may first analyze the technical conflicts caused by engineering parameters; specifically the wall thickness of the can has to be strong enough for stacking purposes yet as light as possible for cost. Then, using “Increase the degree of an object's segmentation” heuristic, the wall of the can could be redesigned from flat to corrugated to increase strength. In order for the TRIZ heuristics to be employed, a base concept must exist and the specific characteristics that must be achieved identified. The TRIZ manual suggests that the approach must be learned and practiced to be successfully utilized. The majority of the TRIZ heuristics do not overlap with Synectics or SCAMPER, as they are focused on specific engineering mechanisms (such as pneumatics), parameters, and related conflicts and trade-offs.

The two other approaches provide design heuristics defined at a much more general level. Developed not specifically for design problems, but as a general problem-solving approach, the SCAMPER method suggests a series of modifications that can be used alone or as a group to spur additional design ideas, specifically substitute, combine, adapt, magnify, put to other uses, eliminate, and rearrange/ reverse. Each modification technique has further descriptions and a series of questions to prompt new ideas, however, no specifics are given to guide the designer about how or when to apply them to a problem. For example, given a problem like redesigning a hand soap dispenser, applying the heuristic, "modify," provides little direction for creating potential redesigns. The Synectics framework combines more and different heuristics to address needs at different phases of ideation. These focus on the fusion of opposites through the use of past experiences and analogies. For example, a designer utilizing Synectics may try to “animate” the soap dispenser by applying human qualities, such as adding a "smiley face" to the dispenser. The heuristics proposed in Synectics provide very general theme suggestions, including parody, prevaricate, metamorphose, and mythologize. These seem to focus on the in-context setting or meaning of the product, comparing it to competing products. Both the SCAMPER and Synectics techniques provide a broad set of suggested alterations in generating design concepts, however, more specificity in terms how to apply the alterations might more directly support designers in guiding their ideas. Also, these strategies were not extracted from the analysis of designers’ concept generation phases; these were suggested, prescribed methodologies for creative solution in a more general perspective.

We propose that designers employ cognitive heuristics in order to enhance the diversity, quality, and creativity of potential designs they generate during the ideation stage. Specific design heuristics may help the designer to explore the problem space of potential designs, leading to the generation of creative solutions. These cognitive strategies are applied to a design problem to take the designer to a different part of this space of potential design solutions.

Evidence for Design Heuristics

In a previous study, the application of heuristics that transformed previous concepts was observed within an expert designer's ideation process[18]. For example, in one design concept, the expert combined three structural heuristics: (1) *changing the configuration of the identical design elements* utilized in the previous concept in order to repeatedly use a swiveling motion around a common base, while (2) *changing the physical interaction of the user with the system*, and (3) *adding multiple functionalities to the same component*. In a set of designs that were quite varied, several specific heuristics were observed occurring together repeatedly. The study first analyzed fifty designs from a larger set of sequential concepts generated by a professional designer. Among these fifty concepts for a universal access bathroom, over 348 specific applications of heuristics were evident, with 21 different heuristics identified.

The observation of these heuristics within an expert's sequential design concepts, and in the transitions among the concepts, suggest that they may be a key component of the development of expertise in design ideation. But the prior study involved industrial design rather than engineering design. Thus, the goal of this work was to study the use of heuristics in engineers' design approaches to concept generation as a starting point for later explorations of expertise in engineering design ideation. In this study, we examined engineers' designs to uncover what heuristics they used and how they used them to better understand ways engineering designers generate and transition between candidate designs.

Research Questions

The proposed heuristic model raises several key questions about the way heuristics are implemented in conceptual design: What are the most commonly used heuristics? Does heuristic use influence design quality? And, do certain types of heuristics, and the number of heuristics used, increase the diversity of design ideas and the effectiveness of the concept generation process? In the present study, we were guided by the following research questions:

- What heuristics do engineering designers use to generate multiple, diverse design concepts? What heuristics are evident in their concepts?
- How did the heuristics impact design outcomes?
- What level of conscious reflection do designers have about the use of these heuristics within their own cognitive processes?

Research Methods

The methodology for the study included think-aloud protocol during the design task, followed by retrospective interviews. Data from engineers of various levels of experience were collected to illuminate decisions made in generating and developing concepts. Atman and Bursic[19] noted that researchers have effectively used verbal protocol studies to identify how designers introduce information or knowledge into the design process. The think-aloud method[20] was selected because of the advantage of the sequence of information that can be revealed without altering cognitive processes. The studies conducted by Atman and Bursic[19] demonstrated that participants who verbalized concurrently with a task could provide information that did not change the nature of their thinking. Thus, it is assumed that retrieval from memory, mental computations, logical conclusions, summarization, etc. were not altered when the subjects were asked to verbalize their thinking as they worked on the cognitive task. Participants were also asked to verbally elaborate their concepts in a retrospective interview at the end of the session. Retrospective interviews have also been used in studies analyzing expert designers' concept generation process from different perspectives and served as additional data to aid in understanding the engineering designers' strategies and what strategies they consciously applied[18, 21].

Participants. Participants were recruited from a variety of contexts, including an international engineering conference and engineering students enrolled in a mid-western university. In this study, we report a set of five cases from a larger study with over fifty subjects. These five cases represent a range in domain experience, as well as a range in the number of diverse concepts generated through the sessions. With these case studies we hope to find some suggestive heuristics use experienced by the participants.

Table 1. Participant Demographics

	Age	**Gender**	**Design-Related Experience**
Engineer 1	53	Male	25+ years in industry, 4 years in design management graduate school
Engineer 2	22	Male	Senior in engineering school
Engineer 3	27	Male	4+ years in engineering graduate school
Engineer 4	23	Female	1+ years in engineering graduate school
Engineer 5	25	Male	2+ years in engineering graduate school

By characterizing their heuristic use, we can begin to understand not only how heuristics influence exploration of the design space and what awareness engineers have of their application, but also what differences exist between designers with low, mid, and high diversity in their concepts.

Procedure. Participants were asked to generate concepts for a design task that was given to them at the start of the session, and to talk out loud as they went through the task, verbalizing any thoughts they had as they wrote notes and drew concepts. They used an electronic pen that recorded both the audio and the drawings simultaneously throughout the study session. They were given half an hour for the task.

The main criteria in selecting the design problem was to structure a new and conceptual task in which designers would not be biased by existing solutions and would not require too much technical knowledge. The design problem was relatively open to various kinds of solutions in the short time allowed for the task and was stated as follows:

> 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. Do not worry about the specific quantity of heat that can be generated. Please focus on conceptual designs. Please consider both the ways of capturing the light, and the structural variety of the concepts.

Please draw as many concepts as you can on the papers provided to you. The concepts can be iterations of concepts you generate, or they can be entirely new ideas. Please try to use one page for each concept. Also, elaborate on each concept in writing, using labels and descriptions. Give specifics about what the concepts represent and how you came up with each idea. We want you to create concepts that are creative and appropriate.

Participants were also provided with an information sheet that briefly summarized ways solar energy could be converted to thermal energy (see Appendix). This was included to avoid problems with a potential lack of technical knowledge about solar and thermal energy.

Following the design task, retrospective interviews were conducted for approximately five minutes. Participants were asked to describe what they recalled about each concept sketch and how they conceived of it while examining their sketches in sequence. Finally, they completed a written demographic survey of their design experience.

Data Analysis. The verbal protocols and visual sketching process were simultaneously analyzed by two experienced coders. First, each design concept was identified; then, each concept was analyzed and coded for heuristic use as well as characteristics of the solution (see Table 2). Protocol transcriptions were also used in order to code for subjects' actions and choices of heuristics in concept generation. The goal of the analysis was to identify heuristic use and its impact on the design concepts. The coders worked independently, and then discussed any disagreements in categorization.

We defined individual concepts through the use of cues from the participants as they indicated when they were beginning and ending a given concept. New concepts were also evident in their drawings when moving to a new illustration of an idea. However, the number of concepts generated may not reflect the diversity of the concepts, as concepts sometimes separated within the session were often quite similar. Thus, the number of concepts reported here is a count of the distinct concepts generated by each subject throughout the session as defined by the researchers.

Concepts generated by participants in this study differed in the ways that heat was captured by the sun and transformed into energy suitable for cooking. However, there are only a limited number of ways that heat can be transformed into energy in the context of this problem. Thus, diversity of the concepts was not determined on this criterion alone. Other features of the product concept contributed to defining diversity, and a sample of these criteria are listed in Table 2, with examples of various ways that criteria could be met.

Table 2. Types of solutions generated for the solar oven problem.

Diversity Criteria	Examples
Way of Directing Sunlight	Magnifying glass, Lens; Reflective surface, Mirror, Aluminum foil
Method of Maintaining Heat	Closed product; Glass, Plastic lid; Insulation; Metal
Method of Cooking / Warming Food	Direct sunlight; Hot surface; Incorporating fluids into a system; Solar panels; Steam, Smoking, Fire
Product Materials	Flexible material; Open surface; Pot; Tube
Approach to Compactness and Portability	Attachment to User; Carrying case; Detachable components; Foldable components; Rollable components; Separate pieces; Wheels
Other Features	Ability to attach to pre-existing things in the environment; Adjustable settings; Stand; Thermometer

For example, a designer could create one concept using a metal pot with a glass lid (closed product, metal material) and mirrors that could be set up to surround it that fit inside of the product when not in use. A concept that would be considered distinct from that one could be a black cylinder made of cardboard with magnifying glass attached to the top. These concepts would achieve similar criteria in different ways. From just the example criteria and some of the potential ways they could be achieved given in the table above, it is evident that multiple diverse solutions were possible given the problem statement.

In coding for the strategies and heuristics evident in the protocols, the design heuristics in TRIZ and in a prior study[22] were used as starting points, but heuristics were removed and added as needed to describe heuristics in the context of this particular design task.

Results

The number of distinct concepts generated by participants in this study ranged from a low of 1, where the same design concept was considered in repeated close variations, to a high of 7 distinct concepts, as detailed in Table 3.

Table 3. Participant Concept Numbers

Participant	Total Number of Concepts	Number of Diverse Concepts
Engineer 1	9	7
Engineer 2	6	6
Engineer 3	5	4
Engineer 4	2	2
Engineer 5	2	1

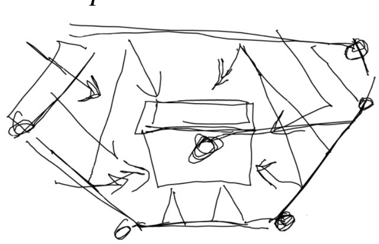
Considering just the initial stage of both the design process -- the idea generation phase -- it is difficult to know how concepts will be transformed as the process continues. For example, an idea that may seem impractical or unfeasible in the designers' sketches may become viable with further development in the design process. Thus, for this study, we did not evaluate the ideas with regard to how well they may "work." Instead, we focused on how heuristics helped designers explore varieties of designs within the design space.

The engineers appeared to have general heuristics that they applied in their creation of designs. We categorized these into three types: process, local, and transitional. Process heuristics served as cognitive tools used to initially generate ideas by directing an approach to the solution space. Local heuristics are characterized as providing detail for a concept, and transitional heuristics provided a way to transform an existing concept into a new concept through intentional, systematic variation. Examples of each of these heuristics are provided below in describing designers' thought processes.

Each case is described below, and these three types of heuristics are presented within the context of the engineers' proposed concepts. We present the results of the analysis of Engineer 1's protocol, with 9 concepts in total including 7 distinct concepts, in greater detail to elucidate our data analysis process. The remaining designers' concepts and heuristics are summarized more briefly.

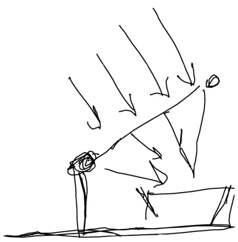
Case Study 1: Engineer 1. Engineer 1 called his first concept an "oven," which was based on the idea of keeping heat inside a closed container. He also utilized a reflective surface to direct the sunlight to the container. Considering the portability criteria, he chose a container that could be transported by those who were cooking to a casing that could be set up within the community. "The inner piece could be used, provided by the community, the person, the family." Thus, the design consisted of a permanent fixture, as well as the actual cooking vessel that could be transported to and from the fixture. He also incorporated hinges in his design to further facilitate transportability. His sketch, the heuristics included in his design, and a description of the local heuristics in the context of his solution is included in Table 4.

Table 4. Engineer 1 Concept 1

Concept Sketches	Local Heuristics	Description in Context
Concept 1 	Adjusting functions by moving the product's parts	Adjusting the sides of the box change the reflective angle of the sunlight.
	Attaching the product to an existing item as an additional component	Outer form of product is permanent; inner box is brought by family to be used with permanent fixture.
	Covering	Inner part is the main product; outer part is existing in the community, or can be owned by the family.
	Folding	Hinges are located at the corners.
	Using multiple surfaces	The outside of the inside box is used, and the inner surface of the outer box is used.

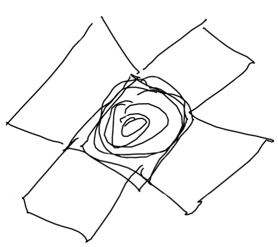
The second concept was a large, adjustable Fresnel lens. It was made of plastic and had an external stand for the food. Thus it was adjustable to the angle of the sun as well as to the best angle to cook the food. He extended this concept by adding reflective shields as well as segmenting his original one lens into four lenses, with the cooking surface in the middle of the four lenses. It is represented in Table 5.

Table 5. Engineer 1 Concept 2

Concept Sketches	Local Heuristics	Description in Context
Concept 2 	Adjusting functions by moving the product's parts	Adjusting the lens changes the reflective angle of the sunlight.
	Elevating (when not expected)	The lens is mounted to the top of a large stand.
	Rotating around a pivot point	The lens angle can be adjusted.
	Scaling	Fresnel lens is scaled up to increase the strength of concentration of the sunlight.

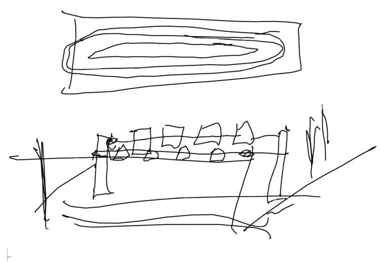
Use of a transitional heuristic was evident between some of his concepts. For example, he transferred concept 2 to concept 3 using the repetition heuristic. His intention was to increase the amount of heat directed at the food, thus he created a new concept through intentional variation of concept two; he repeated it four times and attached those repeated components together.

Table 6. Engineer 1 Concept 3

Concept Sketches	Local Heuristics	Description in Context
Concept 3 	Adjusting functions by moving the product's parts	Adjusting the lenses change the reflective angle of the sunlight.
	Elevating	Each of the four lenses are mounted on a stand.
	Repeating	Multiple lenses are used.
	Rotating around a pivot point	The lens angles can be adjusted.
	Scaling	Fresnel lens is scaled up to increase the strength of concentration of the sunlight.

This fourth concept was a spit cooker, which utilized a lens shaped to focus on a line rather than a point. The spits would be set up inside a box that was foldable, increasing transportability, and using the container for carrying for multiple purposes, as it served as the cooking stand for the skewers as well [Table 7].

Table 7. Engineer 1 Concept 4

Concept Sketches	Local Heuristics	Description in Context
Concept 4 	Elevating	Components are elevated from the ground using vertical design elements.
	Folding	Spits are folded when not used.
	Repeating	The spits are repeated multiple times within the product.

The fifth concept was a double boiler, consisting of a cooking pot inside of another pot. The system would pump hot water from a boiler into the outer pot. The boiler water would be heated by a mirror array around the boiler, with the boiler as a focal point of a variety of mirrors [Table 8].

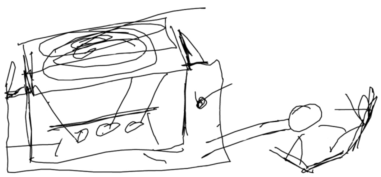
Table 8. Engineer 1 Concept 5

Concept Sketches	Local Heuristics	Description in Context
Concept 5 	Attaching components that have different functions	The water heater and pot are attached through a tube.
	Creating a system	The system pumps hot water from a boiler into the outer pot, and the boiler water is heated by a mirror array around the boiler.
	Repeating	Mirrors are repeated multiple times and placed around a focal point.

The next concept was a synthesis of previous concepts; thus, it was not considered a distinct concept in the total count. He seemed to arrive at this concept through the application of three transitional heuristics: using multiple sources to achieve one function, synthesizing, and covering. He took the previous two concepts, merged them together to increase functionality, and covered the previously uncovered solution idea in concept 5.

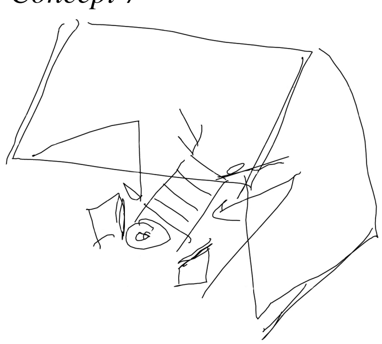
The design combined a double boiler with a Fresnel lens. The designer said, “So we combine the two ideas, where we have a double boiler bottom, with a cooking surface that food can sit on.” The food was heated by the water in the double boiler as well as by the concentrated light coming through the Fresnel lens—“The food gets heated two ways” [Table 9].

Table 9. Engineer 1 Concept 6

Concept Sketches	**Local Heuristics**	**Description in Context**
Concept 6 	Attaching components that have different functions	The water heater is attached to the cooking pot through a tube.
	Creating a system	The system pumps hot water from a boiler into the outer pot, and the boiler water is heated by a mirror array around the boiler.
	Nesting	External components are nested inside the boiler when not used.
	Using a common component for multiple functions	Fresnel lens is used both to concentrate the sun light and as the lid.
	Using multiple surfaces	The food is heated on the bottom surface through the water and on the top surface through a lens.

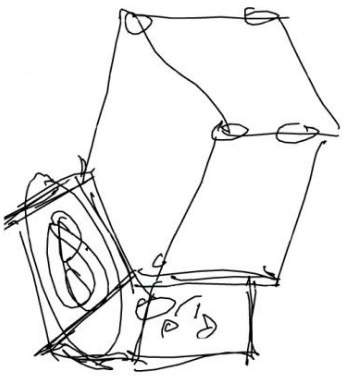
The seventh concept was a blanket with reflectors and drying rack. The reflective blankets are lightweight allowing them to be transported easily. The blankets also serve as a windbreak. This design would be used to dry food like noodles and herbs. The temperature directed at the food was expected to be less for this design so the foods that it was compatible with were different. “The temperatures wouldn’t need to be as hot for this, so this could offer a way to commercialize and save some of the materials” [Table 10].

Table 10. Engineer 1 Concept 7

Concept Sketches	**Local Heuristics**	**Description in Context**
Concept 7 	Attaching or incorporating the product to an existing item as an additional component	Reflective blankets are combined with drying rack.
	Repeating	Blankets are repeated for additional reflection and providing different angles.
	Changing the flexibility of the material from the expected	Reflective blankets are used due to their lightweight and practical nature.
	Using a common component for multiple functions	The blankets are used for both reflecting the sunlight and breaking the wind.

The next concept also included a Fresnel lens, and had two box-like structures on top of the other, “but the bottom box having a Fresnel lens pulled out at a certain distance aiming to cause the smoking… So the sun comes, comes down to the Fresnel lens. It focuses on the wood, which is used to smoke material- smoke the food.” This was counted as a distinct design even though it used the same mechanism as other designs because it was adapted to add the "smoked" food function [Table 11].

Table 11. Engineer 1 Concept 8

Concept Sketches	**Local Heuristics**	**Description in Context**
Concept 8 	Attaching components that have different functions	The lens is attached to a bottom compartment, which is attached to a smoking chamber at the top.
	Compartmentalizing	The bottom part is separated from the top part to achieve a different function.
	Covering	The food and the smoked wood is covered.
	Folding	The bottom part is folded inside the top part using hinges.
	Transferring the function	The folded product can be used as a box to carry other items.
	Using a common component for multiple functions	The lens acts as a cover to the wood chamber as well as direct the sunlight to the wood.

This final concept was a three-stage boiler. The use of “changing the configuration” and “detaching/ attaching” as the transitional heuristics was evident in moving from concept 8 to concept 9. The engineer detached the top and the bottom components and aligned them next to each other, and connected them with tubing. It was a system comprised of a solar heater to warm up water to make it boil a little more quickly, and would be utilized to steam or boil food [Table 12].

Table 12. Engineer 1 Concept 9

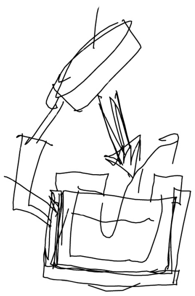
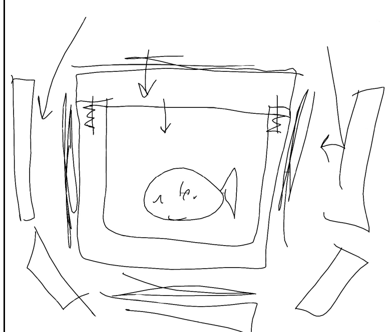
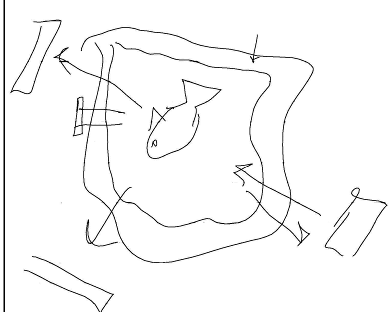
Concept Sketches	**Local Heuristics**	**Description in Context**
Concept 9 	Attaching components that have different functions	Three connecting parts are used for boiling the water.
	Creating a system	System starts with cold water container, warms up in the second container via the lens, and boils in the last part which is heat exchanger.
	Elevating (when not expected)	The Fresnel lens is elevated from the ground to allow for adjustment to direct the sunlight.
	Using multiple sources to achieve one function	The water heater and Fresnel lens were both utilized to heat the food.

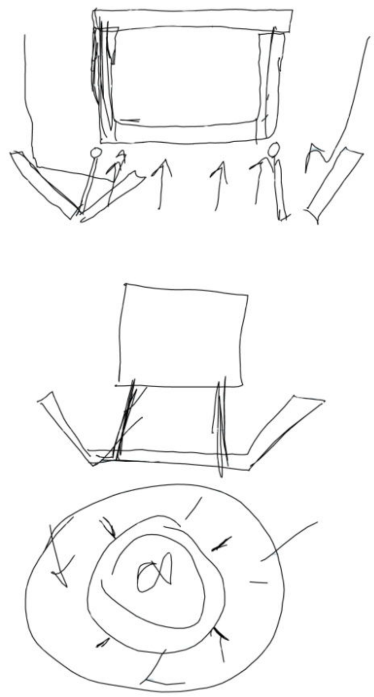
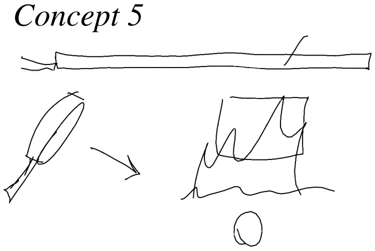
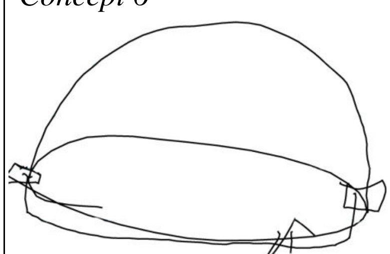
Arguably, Engineer 1 provides a compelling example of the power of the ideation stage. He generated a large and diverse set of concepts at the end of the short design task. His success involved moving between designs that were distinct, and so offer alterative directions for further refinement following the ideation phase. This protocol included technical functions and elements, but avoided becoming too concerned with implementation questions such as the exact temperatures that could be generated by any given design.

To generate these concepts, Engineer 1 seemed to use multiple strategies to generate a number of diverse concepts throughout his ideation process, what we call process heuristics. One process heuristic that he employed was imagining different contexts and designing products that would fit within that context. For most of his concepts, he first suggested a food that could need to be cooked with his product. He seemed to go through a list in his mind of the foods, and diversified his designs by suggesting different foods he had not previously considered. For example, he said before generating concept 9, "Other things to eat. We've got shish-kabobs, jerked meat, the dried herbs, the soups and things, um, let's see." For one of his concepts, he utilized the process heuristic of synthesizing by combining two previous concepts (concepts 3 and 4) into one new, superior concept (concept 5). Engineer 1 also emphasized different constraints from the problem as he worked. For example, in concept 2, he focused on "maximizing the intensity of the sunlight," while in the generation of concept 7, the drying rack, he emphasized the constraints of "inexpensive and portable." He also indicated flexibility in the way he interpreted the problem statement: The problem indicated the need to design a food cooker, but he recognized the deeper problem was that users' goals were to eat. Thus, he expanded from a strict definition of "cooking" to include designs for warming and drying other foods.

Case Study 2: Engineer 2. Six diverse concepts were identified in Engineer 2's work. His first concept was a magnifying glass aimed at a metal pot with a cover. "Basically we're going to magnify the sunlight, if it were frying ants. Hopefully that will fry the water and people will be happy." His second concept was a black pot with the driving factor being to absorb the maximum amount of sunlight possible. He tried to maximize the surface area that could be hit with solar light, made it out of black material, and designed for a tight seal. He also included optional mirrors that could be placed around the pot to increase the solar energy available. His next concept was a bag made out of light-absorbing material. It was water-tight, compact because it could be rolled or folded, and also had optional mirrors that could be set around it to increase its functioning. The fourth concept was a box with mirrors surrounding it on all sides "to try to maximize the light to the bottom." His fifth concept was a day-long cooker with solar panels. He chose a highly conductive dark material, and it was to be left in the sun for the day. The same product that served for the preparation of the food, like cutting or seasoning, was also to be utilized for the cooking. The solar panels were included as a feature if the cooker did not get hot enough. His final concept was a light box that included a lens and a mirror. It included a component from the natural environment—a polished stone that can maintain heat. "It's a closed system, food would just heat up and pressurize." These concepts are summarized with the corresponding heuristics in Table 13.

Table 13. Engineer 2 Concepts and Heuristics

Concept and Sketch	**Local Heuristics**	**Description in Context**
Concept 1 	Attaching components that have different functions	Magnifying glass, the arm and the container all function separately, yet create a system to achieve the goal.
	Scaling	Magnifying glass's size is exaggerated to fit to the size of the container.
Concept 2 	Adjusting functions by moving product's parts	The mirrors can be rearranged to better direct the sunlight.
	Covering	The cooking product is covered.
	Offering optional components	The mirrors are optional if additional sunlight direction is necessary.
	Repeating	Optional mirrors are repeated around the pot.
	Using a common component for multiple functions	The top of the product is a cover and a lens for intensifying the sunlight.
	Using multiple sources to achieve one function	Both the black pot and the mirrors are used to collect sunlight.
Concept 3 	Adjusting functions by moving the product's parts	The mirrors can be rearranged to better direct the sunlight.
	Folding	The bag can be folded for portability.
	Offering optional components	The mirrors are optional if additional sunlight direction is necessary.
	Repeating	Optional mirrors are repeated around the pot.
	Changing the flexibility of the material from the expected	The solid pot is replaced with a flexible bag
	Rolling	The bag can be rolled.
	Using multiple sources to achieve one function	The bag is made of a light absorbing material and the mirrors provide additional means to direct the sunlight.

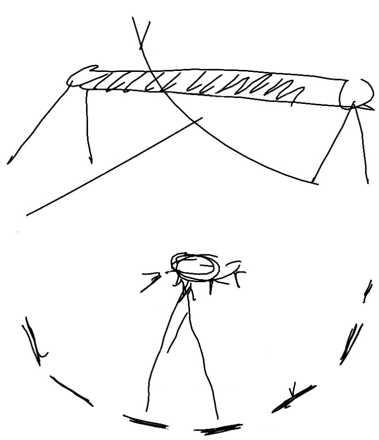
Concept 4 	Adjust functions by moving the product's parts	The angle of the reflectors can be changed.
	Covering	The cooking device is covered.
	Detaching/ attaching	The support structure can be detached suggesting portability.
	Folding	The bottom component is folded towards the inside of the product for portability.
	Repeating	Mirrors are repeated to increase the strength of collected sunlight.
	Rotating around a pivot point	The reflectors can be adjusted by rotation.
	Stacking	Mirrors are stacked to be carried together.
	Using multiple surfaces	Sunlight is directed at to the top of the product as well as to the bottom of the product.
	Offering optional components	Solar panels are suggested as optional components.
	Using a common component for multiple functions	The surface designated for cooking the food is also used for preparing it.
	Using multiple sources to achieve one function	Both the solar panels and the dark-coating are used for collecting sunlight.
Concept 5 	Offering optional components	Solar panels are suggested as optional components.
	Using a common component for multiple functions	The surface designated for cooking the food is also used for preparing it.
	Using multiple sources to achieve one function	Both the solar panels and the dark coating are used for collecting sunlight.
Concept 6 	Using the environment as part of the product	Polished stone is used for reflecting and gathering heat from sunlight.

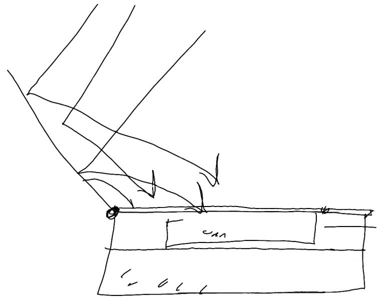
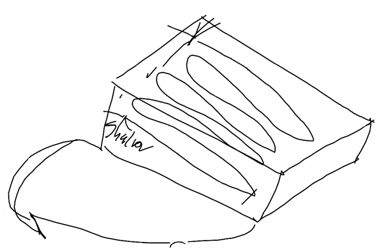
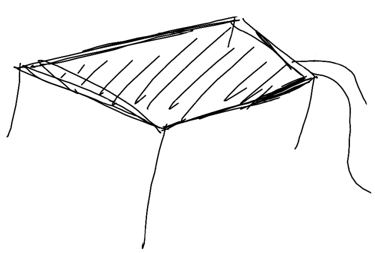
Engineer 2 utilized the process heuristics of "covering" and "repeating" to help him transition from concept 1 to concept 2. He covered the open pot of concept 1 with a lid and created multiple mechanisms for concentrating sunlight on the food. As he moved from concept 2 to concept 3, he changed the flexibility of the material from a metal to a light absorbing flexible bag. Additionally, concept 4 showed evidence of the transitional heuristic of "changing the configuration" from concept 2 as he rearranged how the reflectors would concentrate the sunlight on the food.

Engineer 2 expressed the opinion that he felt like he was recycling ideas if he was using the same way to capture heat, and did not see the variation in the forms and other design parameters as being different enough. He did give context to some of the design solutions, thinking about the people that would be using the oven, but wasn't as specific as identifying different types of food, users, or locations. Throughout his protocol, he seemed to focus on a different constraint for each design: first compactness, then portability, then expense, etc.

Case Study 3: Engineer 3. Engineer 3 generated five concepts; four were considered diverse. His first concept was a black tube with oil and reflective mirrors: "A tube, black, and maybe you have it set up on a swing set type thing. Each mirror focuses on the tube and bounces, the sun comes in and bounces… the tube has oil in it… then out of it would come some hoses. And what happens is as the sun comes in, it heats, and then it rises and goes out." The food is cooked from the heated tubes of oil, which are connected to a device with a grill on it. The second concept was similar to a Crock-Pot. It was comprised of a double-insulated pan, an optional rack, a thermometer, a glass top, and hinges to focus heat. The third concept was designed to heat liquids running through tubes, as well as to keep other foods warm that were close to the liquid tubes. The tubes were on the outside of a backpack, which were covered by a glass or plastic lid, and had a Fresnel lens to intensify and direct the sunlight toward the tubes. The final concept cooked food with energy from roll-up solar panels that could be unrolled and set up in the sun with poles. The design also included an option to use the power from the solar panels for mixing and stirring. Table 14 summarizes these concepts and the corresponding heuristics.

Table 14. Engineer 3 Concepts and Heuristics

Concept and Sketch	**Local Heuristics**	**Description in Context**
Concept 1 	Attaching components that have different functions	The product is composed of a portable tube on a tri-pod, while the mirrors are stationary and the there is a system which lets the oil flow as the source of the heat.
	Creating a system	A system heats oils and brings it through the tube.
	Detaching/ attaching	The support structure can be detached from the main component.
	Elevating (when not expected)	The oil tubing is lifted from the ground.
	Repeating	Mirrors are repeated around the tubing.

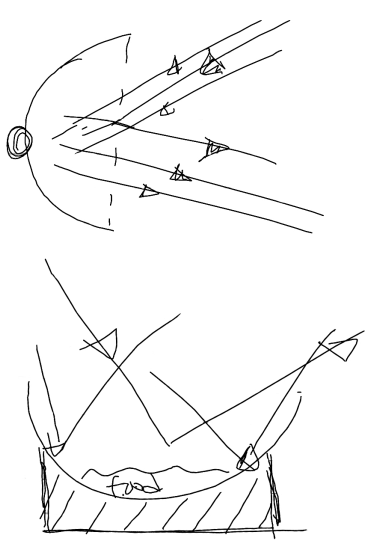
Concept 2 	Adjusting functions by moving the products parts	The reflector can be adjusted to better direct the sunlight.
	Attaching components that have different functions	The reflector is attached with a hinge to the cooking and insulation compartments.
	Compartmentalizing	The product is separated into two layers.
	Covering	The product is covered with a piece of glass.
	Folding	The lens can be folded down.
	Providing sensory feedback to the user	A thermometer is used for providing feedback.
	Rotating around a pivot point	The lens can be rotated to better direct the sun.
	Transferring the function	The lens directs sunlight and also covers the product when not in use.
Concept 3 	Attaching components that have different functions	The heating tubes are connected to a lens, which is connected to a backpack.
	Attaching the product to the user	The product will function when the user carries it.
	Covering	The tubes are covered by the backpack material and the lens.
	Using multiple sources to achieve one function	Both the heated tubes and the Fresnel lens are used as the heat source.
	Using multiple surfaces	Inner surface of the product is used for warming up the food.
Concept 4 	Attaching or incorporating the product to an existing item as an additional component	Flexible solar panels can be attached to existing cooking devices.
	Detaching/ attaching	The supporting structure can be detached.
	Elevating when not expected	The solar panel is elevated on a stand.
	Changing the flexibility of the material from the expected	Solid solar panels are replaced with flexible ones for portability.
	Rolling	The flexible panel is rolled up when not in use saving the space and suggesting portability.

We did not see evidence of many transitional heuristics in Engineer 3's work. In his think-aloud protocol, he indicated a need to make concept 2 more portable, which caused him to scale down the size. Thus, we identified "scaling" as a transitional heuristic in his work

In regards to process heuristics, Engineer 3 seemed to follow an initial free-flow brainstorming session, and then developed each of those concepts individually. In one of his concepts, he emphasized "portability," and in that same concept he provided a context of a campground.

Case Study 4: Engineer 4. Engineer 4 generated two concepts. Her first design is a parabolic reflector in which the shape of the reflector allows the sun to be targeted to a specific point. The reflector is adjustable so that the user can maximize the reflection capability. The second concept was a water-heating device in which heat would be stored in the water that is heated by the sun. The design has a water circuit in which one section of the circuit has mirrors that direct the sunlight to the water and another section the heated water contributes energy to warming or cooking the food. The food section of the circuit also has parabolic mirrors, thus there are two methods utilized to heat food. She also suggested other fluids besides water could also be used in the circuit.

Table 15. Engineer 4 Concepts and Heuristics

Concept and Sketch	Local Heuristics	Description in Context
Concept 1 	Adjusting functions by moving the product's parts	The parabolic mirror can be rotated to better capture the sun.
	Detaching/ attaching	The parabolic reflector is place on a separate stand for stability.
	Rotating around a pivot point	The parabolic reflector is rotated according to maximize the sunlight.
	Using a common component for multiple functions	The parabolic mirror directs the sunlight and hold the cooking food.

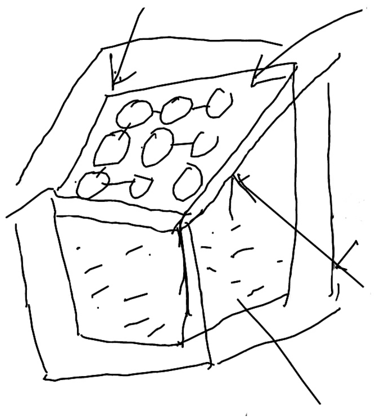
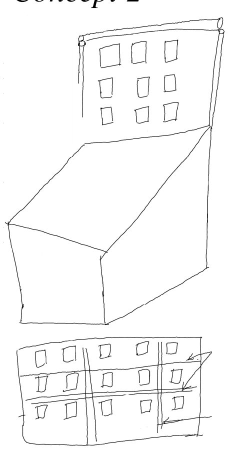
Concept 2 	Adjusting functions by moving the product's parts	The parabolic mirror can be rotated to better capture the sun.
	Attaching components have different functions	The water circuit is connected to mirrors, which direct the sunlight to the water and food.
	Creating a system	A water heating system is used to provide an additional mechanism for cooking.
	Repeating	Mirrors are repeated and arranged around the system.
	Using multiple sources to achieve one function	Both the water circuit and the parabolic mirrors are used to capture sunlight.
	Wrapping	The water heating tubes are wrapped around the food container.

Engineer 4's concept 2 was prompted by her desire to increase the amount heat on the food. She applied the transitional heuristic "using multiple sources to achieve one function."

Process heuristics were not as apparent in Engineer 4's ideation stage as in the others, but was marked by speed in settling on the concepts. Engineer 4 noted, "I should comment on this that I think my concepts are not very creative, so if I should have like this, should right now hire five people to have a creativity session with me." It is possible the test evoked a rapid loss of confidence about the process of generating ideas.

Case Study 5: Engineer 5. Engineer 5 generated two design concepts. The first concept was a box-like product with magnifying glass pieces on the lid of the box to intensify the heat directed to the food inside. The product also included storage pockets on the outside and could be taken apart for easier transport. The second concept generated by Engineer 5 was similar to the first, which was also stated by the designer: "The concept number two is kind of an alteration to concept number one." Instead of magnifying glass pieces in the lid of the box structure, this concept had mirrors on the lid. This concept also included side pockets for storage, and features that allowed for the product to be taken apart and transported easily.

Table 16. Engineer 5 Concepts and Heuristics

Concept and Sketch	**Heuristics**	**Description in Context**
Concept 1 	Attaching components that have different functions	The magnifying glass pieces are attached to the container for heating food as well as pockets for carrying the pieces when not in use.
	Compartmentalizing	The insulation, the container with water and the magnifying glasses are placed in a side pocket on the product.
	Covering	A lid with magnifying glass pieces covers the product.
	Detaching/ attaching	Magnifying glasses are carried in the separate pockets for ease in transportation.
	Repeating	Magnifying glasses are repeated multiple times.
Concept 2 	Attaching components that have different functions	The mirrors are attached to the container for heating food as well as pockets for carrying the pieces when not in use.
	Covering	A lid with mirrors covers the product.
	Detaching/ attaching	The mirror pieces are carried in the separate pockets for ease in transportation.
	Repeating	The mirrors are repeated and placed on the lid of the container.
	Rolling	The carrying case of the mirrors could be rolled for easy and compact storage.

As Engineer 5 explained his first concept, he repeated the same details multiple times without further elaboration of details. However, of the changes he made, the use of the transitional heuristic, “substituting” was evident. He decided to substitute mirrors for the magnifying glass pieces he was using in concept 1, and tweaked other details of the concept accordingly.

In his description of thought processes during concept generation, he emphasized the constraint of "portability," which prompted him to construct the small box shape and the side pockets attached to the product to store breakable pieces during transport. In his overall approach, he did not seem to be continually using heuristics to guide his process, but within his approach, he emphasized one constraint more than the others, which guided his design concepts.

Discussion

Based on these five cases, we can draw some conclusions about the strategies for concept generation that resulted in a larger and more diverse set of potential designs. Engineer 1 used multiple process heuristics, and applied them continuously, not just for a single concept. The primary process heuristic evident was considering a variety of contexts; however, for some of his concepts, he also utilized emphasizing different constraints for each concept and interpreting the problem statement flexibly. Engineer 1 generated the largest number of diverse concepts. Engineer 2 used two process strategies, which were to diversify the method of solar cooking and combine them in different ways (similar to a morphological technique), and emphasize different constraints. Using these strategies, he generated six diverse concepts. He did consider a general context of people that would be using the product, but did not situate each of his concepts into a more specific context. Comparing his concepts with Engineer 1's, Engineer 2's design solutions seemed less diverse in form. This could be a result of the fact that he was less focused on generating variety in other aspects of the design concept, as he seemed primarily focused on the different ways to direct and trap heat.

Before developing any concepts, Engineer 3 intentionally spent some time on "brainstorming" differing ways a solar cooker might be designed. As he worked through his concepts, he referred back to his brainstorming page to give him ideas. With this process heuristic, he generated four diverse concepts in the allotted time period. In one of his concepts, his idea was initiated by an emphasis on portability within the context of camping. He did not specify detailed context or emphasize certain constraints in his other concepts. His use of process heuristics was less specific than Engineers 1 and 2’s heuristics. While Engineer 3 had a couple of examples that could have been characterized as distinct strategies, such as emphasizing certain constraints or considering specific contexts, his protocol seemed to be guided by a single process heuristic: the development of an initial free-flow brainstorming session.

Engineer 4 and Engineer 5 did not appear to utilize any process heuristics in their overall approach for generating their concepts. While there was some evidence they utilized process heuristics to guide their approach for one concept, they did not continually apply the process heuristic in different ways to generate more and diverse concepts. Engineer 4 evaluated her ideas very quickly, perhaps limiting herself from exploring further. She may have limited her ideas because she did not feel she was creative, which she said multiple times during the session. Engineer 5 emphasized the constraint of "portability" in generating his concepts; however, unlike Engineer 1, he did not also consider emphasizing other constraints to help him generate different concepts.

Throughout our analysis, we identified evidence of heuristic use, however, the designers were not aware of most of the heuristics they were using, specifically the local and transitional ones. They were most aware of the process heuristics they used to guide their overall approaches to the session. For example, when asked about their overall approaches, Engineers 1, 2, and 3 were able to describe the process strategy they used in generating concepts:

> Engineer 1: “The [next] concept I got to by thinking about different types of food that people would be eating.”

> Engineer 2: "Initially my goal was to do one and champion each of [the basic principles of transferring solar to thermal energy]…You know, they all play off each other, so then I found it was kind of silly to isolate it, because you can always use solar panels to increase the amount of light going in, you're trying to maximize the absorption of light."

> Engineer 3: "First I brainstormed ideas after I read the design task sheet though and it gave me a lot of ideas…I used it to trigger ideas in my head of different things."

Engineer 1 also intentionally used a synthesis strategy to generate additional concepts: "So the next idea was sort of combining the two." It did not seem that he consciously chose to emphasize certain constraints over others, but he did recognize when a certain constraint was driving his design idea. Similarly, it did not seem he was viewing the problem statement flexibly as a conscious strategy, but he was aware that he did it when he reflected back on his process: "And then I thought, well you might not just want to cook, you might want to dry foods. So, drying herbs and things like that you wouldn't need it to be nearly as hot… And then, uh, I thought, okay, so instead of just drying food there's also the whole idea that you could slowly smoke food." The problem statement indicated a need to cook food, but he flexibly interpreted the word "cook." This type of problem reformulation has been shown to be key in successful solutions[18].

Two of the engineers' work (Engineers 4 and 5) did not indicate any process heuristics to facilitate concept generation, and this could be a key reason for the lack of diverse concepts in their protocols. On the other hand, the strategic approaches observed in other participants' processes—considering a variety of contexts, emphasizing different constraints for each concept, interpreting the problem statement flexibly—led to greater success in identifying diverse design concepts. These findings suggest that process heuristics can be used helpful in guiding the generation of design concepts. Consequently, they may serve as part of a potential pedagogy for design students.

In addition to process heuristics used as strategic overall approaches, we could readily identify characteristics of concepts that fit local and transitional heuristics. Cases with higher diversity and lower diversity in generated concepts all displayed local heuristics, as shown in the tables. The expert engineer generated more designs, and he also demonstrated the use of more, and more varied, heuristics. Previous work has shown that designers who suggested more ideas during concept generation used a greater number of what we call "local" heuristics in this paper. There may be several reasons why we did not observe as many transitional heuristics in this study. In previous work, transitional heuristics were seen in problems in which 1) the possible design solutions were more narrow, i.e. the redesign of salt and pepper shakers[23] and 2) the design concept was more solidified, as the designer was in a more detailed phase of the task, using heuristics to refine the details of concepts rather than generate diverse concepts[18]. In this study, the designers were in the preliminary phase of the process, generating as many and as varied ideas as possible to a novel problem. Thus, the present scenario was different in both respects than in the problems where transitional heuristic use was readily observed. It is possible that transitional heuristic use impacts design process once a foundational concept has been established, whether as a function of redesign, or because it occurs later in the design process when selected concepts are translated into more detailed designs.

These case studies emphasize the importance of the engineer's conscious strategy use in generating a diverse set of concepts. Process heuristics, such as varying the importance of constraints, and contextualizing the concepts, helped some engineers to "paint the space" of categories of possible designs. This appeared to help them diversify the set of concepts generated. While designers with many diverse solutions were aware of their overall strategic approaches, they did not seem as aware of any local and transitional heuristics used to diversify form and functional characteristics of their concepts.

The heuristics that were evident in the participants' concepts were consistent with the heuristics previously identified in other design ideas and existing products[22]. This is an important finding because it builds a case that many of these heuristics are applicable independently of the specific design problem. While some may be more applicable than others depending on the context, the use of heuristics is consistently observed across problems.

This protocol study examined only five engineers, and so is limited in the conclusions that can be drawn about the efficacy of heuristics in the design ideation process. This study was also limited by the constraints of time, and task definition, which may not reflect typical working conditions for engineering designers. Additionally, concept generation may occur more often in a team environment. Nonetheless, even this restricted task and small set of observed designs showed evidence of process, local, and transitional heuristic use. The evidence of the contribution of these heuristics to generating diverse design concepts suggests a direction for engineering training that will enable students to gain the needed expertise for using heuristics in the generation of diverse concepts.

Conclusions

Knowledge of a variety of design heuristics, and experience in applying them on many different problems, may lead to the development of expertise in innovation. For many engineering students, simply having an arsenal of design heuristics to try might lead to improvement in the diversity of concepts generated. As a pedagogical alternative, it may be possible to learn to adopt design heuristics through engaging in generative processes, providing a medium for learning when and how to apply them in new engineering problems.

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Appendix

The Basic Principles of Transferring Solar Energy into Thermal Energy:

- Concentrating sunlight: Using usually a mirror or some type of reflective metal to concentrate light and heat from the sun into a small area makes the energy more concentrated and therefore stronger.
- Converting light to heat: Any black colored material will improve the effectiveness of turning light into heat, as black absorbs light.
- Trapping heat: Once the light is absorbed and converted to heat, trapping the heat inside makes it possible to reach similar temperatures on cold and windy days as on hot days.