INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
2 & 3 SEPTEMBER 2010, NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY, TRONDHEIM, NORWAY

DESIGN HEURISTICS IN IDEATION ACROSS ENGINEERING AND INDUSTRIAL DESIGN DOMAINS

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ABSTRACT
How do designers explore a design space to generate diverse solutions? This work focuses on the identification of design heuristics used in the ideation process in the domains of industrial design and engineering design. Design heuristics are cognitive strategies applied to a design problem to help designers create novel solutions. In a think-aloud protocol, engineers and industrial designers with varying levels of experience were asked to develop multiple concepts for a novel design problem. The results show evidence of frequent heuristic use, and that heuristics are effective in generating diverse, creative, and practical concepts, which, as a result, may stimulate higher-quality designs.

Keywords: Design heuristics, pedagogy, strategies, protocol studies

1 INTRODUCTION

The idea generation phase in the design process requires developing concepts either intuitively or through systematic processes. Some important characteristics of this phase are that it is creative, is unpredictable, and provides a foundation for the rest of the design task. Empirical studies have observed that the ideation process is also opportunistic, as design activities vary depending upon the creative process [10]. These characteristics of the ideation process make it challenging to study empirically. Past studies have examined general approaches that designers use in ideation [2]; however, it is still unclear how multiple and varied ideas are generated during the ideation stage, and what strategies designers use to generate ideas.

In previous work, we proposed that designers use specific *design heuristics* to explore the space of potential designs, leading to the generation of creative solutions [10] and [11]. Design heuristics were found helpful in the ideation stage because they increased the variety of proposed concepts. This was particularly true for heuristics that provided a connection between the design context and specific transformations that could create new variations in designs. Thus, there is some evidence that explicit training on how to use heuristics may improve ideation skills [10].

How might these design heuristics differ between engineering design and industrial design domains? The aim of this research was to explore and identify design heuristics used in the ideation process by both industrial designers and engineers. Because of relative differences in emphasis on design function (engineering) vs. design aesthetics (industrial design), there is some reason to suspect their design processes in ideation may also differ. Alternatively, design heuristics may be evident in work by both types of designers as they attempt to create a diverse set of design concepts.

Following Newell and Simon [8], we define ideation as occurring within a “design space” consisting of all possible designs. Some of these potential designs are easy to generate because they involve simple combinations of known features, or already-known elements. However, a designer may never consider some designs within this space, missing the opportunity to discover other types of solutions that do not come to mind during the ideation process. The key to generating diverse design solutions may be to successively apply different design heuristics to generate varied candidate designs, increasing the percentage of total concepts considered from the potential design space.

We propose these design heuristics differ from other approaches used in idea generation. While many existing approaches are mainly discussion-related, such as brainstorming, brainwriting, and checklists, design heuristics employ idea "triggers" that assist in creating concepts using simple transformations.

Although the importance of design heuristics is well recognized [5], little is known about whether designers apply them, what specific heuristics are effective, and how they affect the quality and creativity of the resulting design. Kruger and Cross [7] found that designers using a "problem-driven" (rather than solution-driven) strategy tended to produce the best results in terms of the balance and creativity of their designs. Several other theories describing specific heuristics exist, including SCAMPER [4], Synectics [6], and TRIZ [1], but these have not been empirically validated. This work attempts to uncover the design heuristics used by both engineering and industrial designers as they create novel concepts.

2 EXPERIMENTAL APPROACH AND RESEARCH QUESTIONS

We hypothesized that the application of design heuristics in the creative process would help designers explore the space of potential designs, enhancing the variety, quality, and creativity of their design concepts. We explored two questions related to this hypothesis: what heuristics lead designers to novel product concepts, and do their applications differ between engineering and industrial designers?

Ten participants were recruited from two design conferences and a mid-western university. They represent a range in domain experience for both fields, from one year of training through ten years of professional experience. Five participants had a background in industrial design (two males, three females), and the other five had a background in engineering design (four males, one female). Their ages were between 20 and 29, except one with the age of 53. Data was collected using an audio pen and sketch pad that preserved the real-time drawing and writing created by each participant. The participants followed a think-aloud protocol to describe their approaches to generating concepts during the thirty-minute design task. The task was to design "a solar-powered cooking device that was inexpensive, portable, and suitable for family use." The problem statement also specified design criteria and constraints, and prompted participants to generate a variety of creative concepts. After the task was completed, participants were asked to verbally describe the concepts they had generated, how they moved from one concept to another, and their approaches to ideation.

All data was analyzed for evidence of heuristic use by two evaluators, one experienced in industrial design and the other in engineering design. The drawings and labels generated by the participants and their comments while working in the retrospective interviews were used to identify the proposed concepts and the ideas in their generation. Initial rater agreement was 80%, and disagreements were resolved through discussion. The analysis included categorizing characteristics of the concepts generated, determining the number and diversity of the concepts, and determining specific design heuristics evident in the protocols.

3 RESULTS AND DISCUSSION

The results reported here include a discussion of the types of solutions generated by designers, the heuristics identified within and among the concepts, and participants' process descriptions. In each of these analyses, we identified differences between the industrial design and engineering participants.

3.1 Types of solutions generated

Major elements and key features of the concepts were identified in terms of functionality, form, user-interaction, and physical state. The criteria used to classify the content of designs are presented in Table 1, along with counts of each criterion used by industrial designers and engineers.

Table 1. Solution characteristics for the solar-powered cooker problem

Diversity Criteria	Examples of designer applications	Industrial Designers	Engineers
Way of Directing Sunlight	1. Magnifying glass / Lens	10	11
	2. Reflective surface / Mirror / Aluminum foil	9	14
Method of Maintaining Heat	1. Closed product	6	11
	2. Glass / Plastic lid	3	5
	3. Insulation	1	8
	4. Metal	0	2
Method of Cooking/ Warming Food	1. Direct sunlight	20	20
	2. Hot surface	5	1
	3. Incorporating fluids into a system	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 / 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. Ability to attach to environment	0	2
	2. Adjustable settings	6	8
	3. Stand	2	4
	4. Thermometer	1	1
Total number of concepts generated		**28**	**23**

The difference in technical knowledge was evident when comparing the engineers' solutions with the industrial designers' solutions. For example, engineers used insulation more frequently, while the industrial designers' solutions did not commonly consider the need to maintain heat. Engineers also used multiple mirrors to direct the sunlight, suggesting a focus on the function of the product; however, only one of the industrial designers' solutions included this feature. In most cases, industrial designers focused on a hot surface as the preferred method of cooking, which resulted in concepts with an open surface. Engineers generated a wider range of concepts to achieve the needed functions based on technical knowledge. For example, many of the engineers considered solutions that incorporated fluids (like water or oil) for cooking food, while none of the industrial designers did so. By contrast, industrial designers frequently used existing products as a base for formulating ideas. Another interesting difference was that engineers often used separate pieces and detachable components, while industrial designers often created one-piece products that folded up for portability. In spite of the dissimilarities in common solutions, there was also substantial overlap in the types of design heuristics employed across groups.

3.2 Which design heuristics were used?

The main focus of this study was to document the ideation process: specifically, we were interested in the transitions between design concepts, and how the design elements were combined in each concept. The protocol analysis demonstrated the existence of three types of heuristics: process, local, and transitional. Process heuristics represent a designer's general approach throughout the idea generation process, local heuristics define changes in relationships between design elements within each concept, and transitional heuristics introduce intentional, systematic variation to create a new candidate design following from a previous concept.

Nine different process heuristics were identified in the protocols. These included more general approaches taken throughout the session, assisting the designers throughout the design process. For example, one designer strategically chose to consider different potential foods for heating in the oven, resulting in generating several new designs. The observed process heuristics were (1) identifying different ways of achieving the same function, and combining and substituting each way to generate a new concept, (2) re-designing existing products with similar functions, (3) assigning a context for each concept, (4) giving form to each function separately, and creating a relationship between these forms; for example, directing sunlight using a magnifying glass and attaching it to a pot that can hold water for cooking food, (5) using the same foundational concept and gradually changing the type and the number of heuristics with additional concepts, (6) using a brainstorming session at the beginning of the session, and improving each idea into a more developed concept, (7) synthesizing different concepts to create a new concept, (8) evaluating continuously, and then keeping the idea or leaving it, and (9) prioritizing certain constraints.

In sum, 254 design heuristics were identified (local heuristics = 216, transitional heuristics = 29, and process heuristics = 9). The average number of local heuristics evident in each concept ranged from 1 to 10, and in most of the concepts (47 of 51), multiple heuristics were observed. There were no significant differences in the total number of heuristics used by engineers (n = 120) and industrial designers (n = 134); however, there were differences in the types of heuristics used. Table 2 presents local and transitional design heuristics evident in the concepts generated by the ten participants.

Table 2. Local and transitional heuristics identified in the content analysis of concepts generated

Design Heuristic	**Explanation of Heuristic Use**
Adjusting functions by moving parts	By moving the product's parts, the user can achieve a secondary function
Attaching parts with different functions	Adding a connection between two parts that function independently
Attaching to an existing item	Utilizing an existing product as part of the function of the new product
Attaching to the user	The user becomes part of the product's function
Changing configuration	Performing different functions based on orientation or angle of design elements
Compartmentalizing	Separating into distinct parts or compartments with different functions
Covering	Overlaying the surface with another component to utilize inner surface space
Creating a system	Connecting parts with different functions to create a multi-stage process
Detaching / Attaching	Making the individual parts attachable /detachable for additional flexibility
Elevating	Raising up either the entire product or its parts from a lower place to a higher one
Folding	Creating relative motion between parts by hinging, bending, or creasing to condense size
Nesting	Placing a component entirely or partially inside another identical component
Offering optional components	Providing additional components that can change or adjust the function
Providing sensory feedback to user	Returning feedback to allow the user to control and adjust input settings
Repeating	Dividing single, continuous parts into two or more elements, or repeating the same design element multiple times to generate modular units
Replacing solid with flexible material	Changing a product's material into a flexible one for creating different structural and surface characteristics
Rolling	Revolving a part or the entire product over a center point or a supporting surface
Rotating around a pivot point	Changing function by manipulating geometrical surfaces around an axis
Scaling	Changing the size of a feature
Splitting	Taking a piece of the previous concept to generate a new concept
Substituting	Replacing the material, form, or a design component with another
Stacking	Resting a product on top of another one in a vertical direction
Synthesizing	Combining previous concepts into a new concept
Transferring function	Converting components to another function in a different time period
Using one component for multiple functions	One design elements performs more than one function in the same physical state
Using multiple components for one function	Different parts of the product contribute to the same function
Using multiple surfaces	Using more than one surface for the same function
Using environment as a product part	Utilizing a feature of the environment as part of the function of the new product
Wrapping	Covering the product by placing other components around its parts

Engineers more often used "*Repeating*" (11 vs. 6, Fisher's exact test p=.045) as a 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 try repetition. "*Creating a system*" was used by all of the engineers, but by none of the industrial designers. This might also be related to engineering practices since they typically analyze and design systems as part of their education. Engineers used the heuristic "*Using multiple sources to achieve one function*" in 8 of the 23 concepts they generated, while this heuristic was evident in only one of the concepts that the industrial designers created (Fisher's exact test p=.004). The reason may be that engineers continuously evaluated whether or not concepts would actually work well in the field.

Industrial designers used "*Elevating*" about the same as engineers in their concepts (11 vs. 6), perhaps because they were focusing on the interaction between the user and the product, which leads, for example, to adjusting the height of the product for the user. Another heuristic more commonly used by industrial designers was "*Attaching the product to an existing item*" (8 vs. 3). We believe the use of this heuristic was due to the nature of the problem, as some of the industrial designers may not have had the confidence in their technical knowledge to feel comfortable generating a concept from scratch.

3.3 How did design heuristics lead to new concepts?

The use of design heuristics is evident when following the sequence of concepts generated by an individual designer. For example, Engineer 1 generated seven diverse concepts (Figure 1).

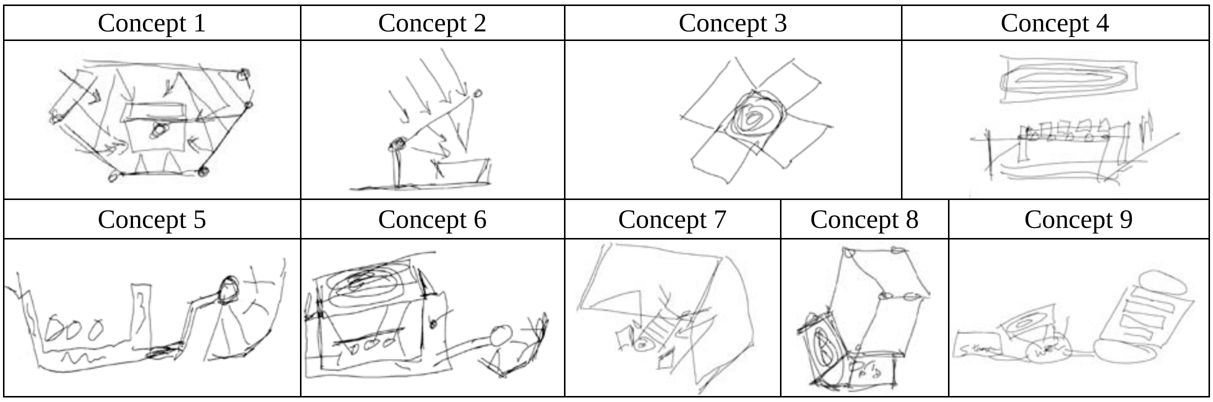

Figure 1. Sequential concepts generated by Engineer 1

To generate these concepts, he used multiple process heuristics; for example, "*Changing the context for each concept*". A number of local heuristics were also documented in the concepts Engineer 1 generated. In concept 3, he applied "*Adjusting 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 on the food. He also applied "*Repeating*", as he used multiple lenses to direct the sunlight. There was also evidence of transitional heuristics in this protocol. For example, he moved from concept 5 to 6 by using "*Covering*" as the transitional heuristic, where he covered the container with a Fresnel lens.

A different approach to the generation of new concepts is demonstrated by following the sequence of designs generated by an industrial designer (see Figure 2).

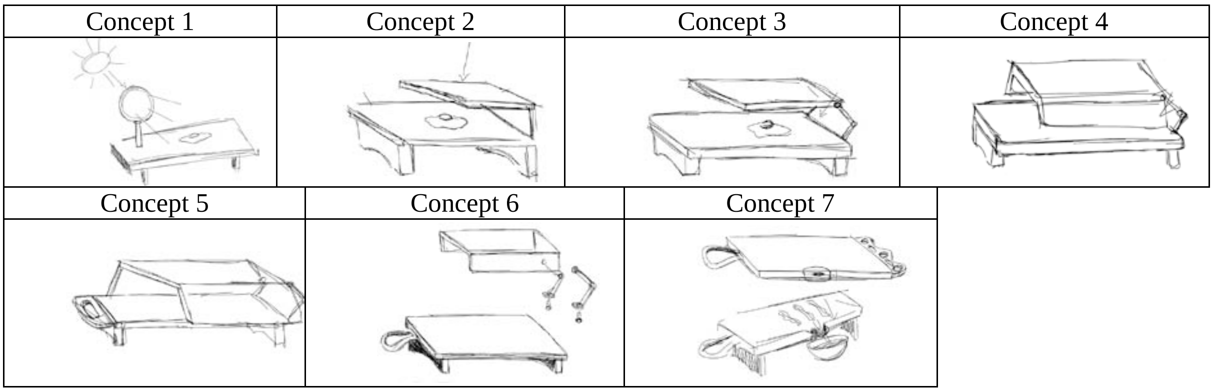

Figure 2. Sequential concepts generated by Industrial Designer 3

Industrial Designer 3 was limited in the number of diverse concepts generated, as she only generated one concept; however, she worked iteratively through 7 generations of that concept. The designer initiated her process by attaching two existing components to each other (a magnifying glass and a griddle) to create a surface with focused sunlight, and she was successful in utilizing transitional heuristics to develop this single concept. For example, from concept 2 to concept 3, she used transitional heuristics, "*Adjusting functions by moving the product's parts*" and "*Folding*", and from concept 5 to concept 6, another transitional heuristic, "*Replacing solid material to flexible material*", as she changed the material of the handle. This sequence shows the repeated application of local heuristics while working within the same general concept.

In sum, designers used heuristics to generate diverse concepts. These findings may suggest ways to assist designers by advancing their ability to generate diverse concepts in the ideation phase. For example, specific design heuristics could form the basis for pedagogy for designers in training. In particular, this approach may hold promise in instruction for novices as they build their experience with design and concept generation. Further, design heuristics may suggest methods for the development of computational tools to assist in design; the frequency of the heuristics applied could be analyzed to understand which heuristics are most commonly used, in which kind of design problems they are applied, and what kind of novel concepts are generated.

4 CONCLUSIONS

Exposure to a variety of heuristics and experience in applying them on different problems may lead to the development of expertise in innovation. For both industrial designers and engineers, design heuristics appeared helpful in generating diverse and novel concepts. For many design students, simply having an arsenal of design heuristics might lead to improvement in the diversity of 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. This research demonstrates that designers in both domains have a set of heuristics available as tools for creating concepts. A next step is to provide a means for teaching designers when and how to apply them.

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