Creativity through design heuristics: A case study of expert product design

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Research has shown that cognition often relies on simplified heuristics; however, few studies have explored the role of heuristics in design. We propose that designers utilize specific heuristics to explore the problem space of potential concepts, leading to the generation of novel and creative solutions. Design heuristic use in the early stages of product conception was examined through a case study of an expert industrial designer working on a real-world project. Sequences of exploratory concept sketches were analyzed for evidence of design heuristic use in generating concepts. This case study uncovers design heuristics that promote variation in concepts and alter existing solutions, supporting the claim that expertise incorporates the use of heuristics to maximize creativity and diversity in designs.

Keywords: product design, creative process, design strategy, case study/studies, design heuristics

What is the nature of expertise in design? Expertise in cognitive science is defined as the skilled execution of highly practiced sequences of procedures (Anderson, 1982; Ericsson et al., 2006). Several decades of research has shown that experts have acquired a variety of cognitive structures that contribute to their performance (Ericsson, 1996; Sternberg and Grigorenko, 2003), such as, access to previous solutions (Logan, 1988), and better representations that capture the more important features of the domain (Chi et al., 1981). One general finding is the use of strategies (Schunn et al., 2005). Lemaire and Siegler (1995) have proposed a four-layered account of expertise from a strategies perspective, the adaptive strategy model (ASM). In this model, experts have better strategies (strategy existence), tend to use strategies that are better overall more often (strategy base rate), are better able to select the circumstances to which a strategy best applies (strategy choice), and are better able to execute a given strategy (strategy execution).

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Within the domain of design, what heuristics do expert designers use to generate concepts? And how do heuristics impact the creation of multiple, diverse

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candidate designs? In studies of designers, Ahmed et al. (2003) found that novices (graduates) used 'trial and error' techniques in generating a single design modification, implementing it, evaluating it, and then generating another, and so on, through multiple iterations. Experienced engineers were observed to make a preliminary evaluation of multiple proposed solutions before beginning implementing and evaluating them. Kruger and Cross (2006) identified different cognitive strategies employed by designers: Solution-driven design, where the focus is on generating solutions, tended to produce the best results compared to a problem-driven strategy, which consists of gathering data and identifying constraints to define the problem. However, these strategies are not specific to the initial concept generation phase of design tasks, especially when there are a relatively low number of constraints and the possibility of many alternative design concepts.

Lloyd and Scott (1994) found that this solution-focused approach appeared to be related to the level and nature of previous experience of the designers. More experienced designers used more 'generative' reasoning by bringing something new to the design situation, in contrast to 'deductive' reasoning on the design problem. In particular, experienced designers approached the design task using general discipline knowledge, rather than through problem analysis. So, becoming an expert may not be a matter of getting faster or more accurate, but of learning alternative ways of doing design. One of the key principles behind the development of high levels of expertise seems to involve a change from a conscious struggle to effortless, even automatic, performance (Lawson and Dorst, 2009).

Understanding successful concept generation is the key to uncovering experts' strategies for design, and for improving design education and practice. Schon and Wiggins (1992) found that designers proceed through cycles of 'seeing-moving-seeing', (*re*)interpreting shapes and relationships, and transforming these (*re*)interpreted shapes. During creative periods, expert designers alternate quickly in shifts of attention between different aspects of their task or between different modes of cognitive activity (Park et al., 2008). These findings suggest that continuously exploring new perspectives on solutions results in uncovering a wider variety of designs. However, many questions remain surrounding the use of cognitive strategies.

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 (Yilmaz et al., 2010a). The term 'heuristic' has commonly referred to strategies that make use of readily accessible information to guide problem-solving (Pearl, 1984). Some heuristics provide ways to search systematically (such as 'depth-first search'), and some use evaluation functions to make 'best guesses' about which areas within the space are most promising. The term 'heuristic' implies that it: 1) does not guarantee reaching the best solution, or even a solution; and 2) provides a 'quick and dirty' (easier) method that often leads to an acceptable solution. We propose that design heuristics may guide the designer's exploration of possible solutions by varying product characteristics or elements to create novel designs. This approach focuses on cognitive heuristics (see Nisbett & Ross, 1980) that are captured in the designer's memory, and applied as needed in new design problems.

An example of a design heuristic is 'Use an environment as part of the product.' This was observed in designs where the living (an outdoor bench created from a grass-covered mound) or artificial (a kitchen cabinet turns into an oven control panel) environment is incorporated into the product by designing around it rather than distinguishing from it (Figure 1a and b).

Another heuristic promotes considering unused space within a product: 'Utilize opposite surface.' This guides the designer towards developing uses for spaces afforded by an existing concept. For example in Figure 2a, the laces of the shoes are extended towards the bottom, allowing for better mobility, and in Figure 2b, hidden storage spaces and pockets are created by using a continuous fabric and opposite surfaces. Design heuristics like these may support the generation of multiple and diverse concepts. A potential drawback of relying on heuristics, however, is that they may limit the scope of creativity. Design heuristics, in some sense, may be understood as 'rules,' a recipe that drains creativity from design. Uncovering how designers employ heuristics as points of departure will help to explain how they are used to generate and explore designs.

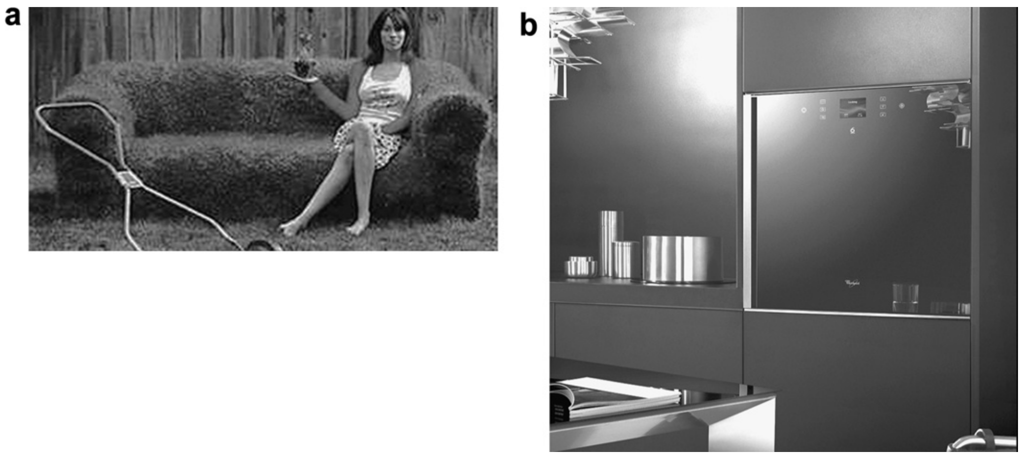


Figure 1 Product example of using an (a) (living) environment as part of the product (Earth Furniture), (b) (artificial) environment as part of the product (Whirlpool Glamour Oven)

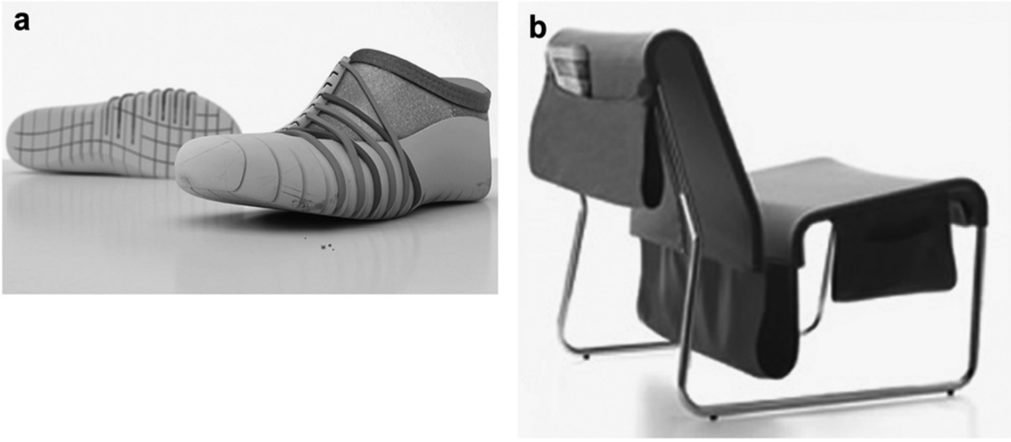


Figure 2 Product example of utilizing opposite surface (a) 980 Tatou, (b) Farallon Chair

Cognitive research shows that experts can utilize heuristics effectively, and suggests their use of heuristics is a feature that distinguishes them from novices (Klein, 1998). Expert designers may employ cognitive heuristics in order to enhance the variety, quality, and creativity of potential designs they generate during the ideation stage. However, heuristics are not, by definition guaranteed to produce a better design, nor do they systematically take the designer through all possible designs. Instead, heuristics serve as a way to 'jump in' to a new subspace of possible solutions. With the application of a heuristic, one is not merely recollecting previous solutions in order to apply them to similar problems, but instead, actively and dynamically constructing new solutions. Design heuristics may serve as a starting point for transforming an existing concept, altering it to introduce variation, or define variations among individual design elements. They may be most useful in preventing fixation or lingering on already-considered elements.

What are the basic heuristics designers use to generate alternative designs? Are heuristics applied more than one at a time (as proposed by Koen, 1991), or is it always a single heuristic that varies the concepts? And do designers have a conscious awareness about the use of these heuristics within their thinking and problem solving? To investigate these questions, an expert designer was followed through the conceptual design process for a commercial product. Previous studies of design cognition have interviewed designers (Cross, 2003; Lawson, 1994), conducted a design task in a lab while recording comments (Goel and Pirolli, 1992; Suwa and Tversky, 1997), and analyzed case studies (Candy and Edmonds, 1996; Neiman et al., 1999). However, few studies have examined real-world design projects contracted and taking place over a long period of time. In the present study, we combine these approaches to examine design process within a single, long-term project preserved in the designer's working scroll. The external representations (e.g. sketches) laid out during the design process may reveal aspects of designer's thinking process, including the use of heuristics. This approach allowed us to construct a more accurate picture of design exploration, and to identify specific strategies used in design creation. It is this type of expertise – the effortful process of attempting a variety of heuristics to generate new ideas – that is the target for this study.

1 Design heuristics

The result of the design activity is often expected to be original, adding value to the base of existing designs by solving problems in new ways. But how is variety or diversity fostered in concept generation? There are multiple theories of how ideas are generated in design. Finke et al. (1992) divided these creative processes into two categories: *generative* (analogical transfer, association, retrieval, and synthesis) and *exploratory* (contextual shifting, functional inference, and hypothesis testing). Linsey et al. (2007; 2008) suggested a more specific method for identifying analogies as part of the ideation process, and showed that memory representations influence the ability to use analogy in solving a design problem. And, Shah et al. (2001) proposed a model (Design Thought Process) involving brainstorming. But little is known about the more specific, domain-based cognitive strategies expert designers may employ, and how they affect the quality or creativity of resulting designs.

Observational studies of designers at various levels have uncovered the use of strategies in design; for example, accessing information, monitoring progress, clarifying and examining key concepts, and verifying how solutions meet design objectives (e.g. Adams et al., 2003). Several theories, SCAMPER (Eberle, 1995), Synectics (Gordon, 1961), and TRIZ (Altshuller, 1984), have proposed specific heuristics to be used by designers in the conceptual design phase. These three approaches all include a wide variety of methods and processes (including specific transformations in design, such as substitution, rearranging, iterating, and eliminating), and may be applied based on the form, function, and context of the intended design.

The SCAMPER approach (Eberle, 1995) defines seven general heuristics (substitute, combine, adapt, modify, put to other uses, eliminate, and rearrange/reverse). However, no specifics are given to guide the designer in 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 exploring potential designs. The Synectics framework (Gordon, 1961) combines even more heuristics to address needs at different phases of ideation. Some heuristics proposed include very general theme suggestions, such as 'parody, prevaricate, metamorphose, and mythologize.' A designer guided by Synectics may try to 'animate' a soda can by applying human qualities, such as a smiling face, to the can. These heuristics also consider the in-context setting or meaning of the product, comparing its markets and competing products. Synectics focuses on the fusion of opposites, the use of past experiences, and analogies. As a result, its heuristics tend to center on known, specific ideas.

Some of Synectics' 'idea triggers' are very specific and concrete, while others offer broader, even very general theme suggestions in a style comparable to SCAMPER. For example, one Synectics trigger is 'contradict,' which is very similar to the 'reverse' concept of SCAMPER. Other examples of this overlap include repeat, combine, and add vs. combine; superimpose and transfer vs. put to another use; change scale, distort, and add vs. modify; subtract and disguise vs. eliminate; and analogize vs. adapt. In sum, SCAMPER and Synectics both provide very broad heuristics at an abstract level, without providing much guidance about their application.

At the opposite extreme, the TRIZ heuristics were designed to address specific technical trade-offs in engineering design (Altshuller, 1984). These heuristics apply to a set of definite features of mechanical designs. Based on examinations of successful patents, TRIZ provides a systematic method for finding and using analogies to these past designs (stored in a relatively abstract form) in a technical matrix of 39 common engineering problems and 40 possible solution types. For example, to design a new soda can, a designer employing TRIZ may first analyze the technical conflicts caused by engineering parameters (i.e., the wall thickness of the can that has to be rigid enough for stacking purposes yet cost-effective for manufacturing). Then, using the 'Increase the degree of an object's segmentation' principle, the wall of the can could be changed from a continuous wall to a corrugated one to increase durability. Because they are quite specific to technical design problems (such as pneumatics, parameters and trade-offs), the majority of the TRIZ heuristics do not overlap with Synectics or SCAMPER.

The main goals of the present study are to determine whether design heuristics do arise within concept generation by expert designers, and to investigate the nature of the design heuristics observed in expert design. In contrast to the very general (SCAMPER and Synectics) and very specific (TRIZ) heuristics, perhaps there are domain-specific design heuristics for creating concept variations during the ideation stage. These would occur at an intermediate level between these approaches: more general than TRIZ, but more specific than the broad suggestions posed in SCAMPER and Synectics. This intermediate level of description would provide a closer link between the heuristic and its application to a design, and provide greater applicability than the specific alternations of TRIZ. By identifying the heuristics employed by an experienced industrial designer, this study will examine the appropriate level of description to characterize useful design heuristics.

2 Hypotheses

This study attempts to describe design heuristics at the level of form and function transformations that can help a designer to introduce systematic variation in their current concepts, producing a more diverse set of candidate designs. Rather than generalized principles and triggering questions typical in brainstorming sessions, we propose that design heuristics offer a means of generating possible designs by guiding specific types of variations within a problem context. The guiding principles for idea generation are difficult to find in the product design domain. One way to gain an understanding of how product designers use guiding heuristics to generate and explore designs is by examining their sequence of concept sketches. This paper presents a comprehensive analysis of an expert designer's ideation process over many months on a single product project. This case study examines two hundred and eighteen concepts preserved by the designer as a working scroll. Each concept was represented as a labeled drawing, and the scroll they are recorded on provides a record of the sequence of their generation. In addition, a retrospective protocol of the designer discussing his generation process for the first fifty sketches on the scroll was collected.

Three hypotheses were tested in this case study:

H1. Expert designers use specific heuristics in order to generate concepts.
H2. Design heuristics reflect strategies used to explore potential variations in concepts.
H3. Designers have some conscious access to their use of design heuristics.

3 Method

This study examines several key questions about the way design heuristics are used in conceptual design: What are the most commonly used heuristics? Does heuristic use influence design quality? And, does the number of heuristics relate to the diversity of design ideas in the concept generation process? To address these questions, the study reported here examines a sample of work from a single expert industrial designer, a sixty-year-old male. This designer has established a long and distinguished record for highly successful and innovative product designs, and taught a variety of design courses (including project-based studio courses) in a university industrial design program for over thirty years.

3.1 The design task

The design project selected for this study involved developing a home bathroom adapted for Alzheimer's patients and their caregivers. An additional focus was a modular approach, with the goal of planning a self-contained product to be placed as a whole into existing homes. Key issues identified for the design problem were overall configuration, lighting, visual and audible cues, storage, safety, modularity, patient transfer, and maintenance. Even though the problem had a product design focus, the designer approached the problem from a systems perspective by incorporating the architectural space. Because the product would make use of existing bathrooms, some consideration of interior design issues occurred along with the design of the products, or facilities that would be placed within the room. This approach allowed the designer to generate alternative layouts for the products beyond the definition of space within the existing bathrooms. The designer worked on the project over a period of approximately two years. He worked using a paper scroll to keep a record of each design concept as the work progressed, providing a serial record of the progression of designs generated. The designer typically labeled the sketches with design features, and used a three-color scheme to indicate areas of concepts that changed from prior concepts and that had critical functions on the scroll.

3.2 Retrospective interview

As an additional component to the study, the designer was interviewed using the scroll record as an organizing structure. For the purpose of the interview, taking place years after the project's completion, the first fifty of the drawings on the scroll were addressed. This taped interview solicited the designer's retrospective report about the design process, including his recall of his idea generation. For this interview, the designer was asked to talk about what he recalled about each of the first fifty concept sketches he had created on the scroll while examining the sketches in sequence. During the interview, the designer was not forthcoming in his descriptions of his process, so the interview was limited to 20 min. While many of his comments revealed experiential memory for his design process, he did not mention any heuristic use when recounting his idea generation. In later discussions, the designer stated he recognized clearly the characterizations of the heuristics in his work; however, he had not articulated them previously. From this, it is apparent that his use of heuristics was implicit, rather than an explicit generation process on his part.

3.3 Coding analysis

For this project, two hundred and eighteen separate concept sketches were identified and collected from the scroll.

3.3.1 Preliminary analysis

By examining the first fifty concepts, a set of potential heuristics, shown in Table 1, was generated by the first author, an industrial designer. This coder had an M.F.A. in design and a B.S. in industrial design. The process for identifying heuristics within the concepts was as follows. First, individual concepts were identified as separate units. Then, concepts were compared to see how change occurred from one to another as they progressed on the scroll. For

Table 1 Design heuristics identified in 50 concept sketches by 2 coders

#	*Observed Design Heuristics*	*n*	%
1	Adjustability according to different users' needs	38	11%
2	Applying an existing mechanism in a new way	35	10%
3	Changing how the user physically interacts with the system	33	9%
4	Changing the configuration using the same design elements*	25	7%
5	Merging a variety of components*	24	7%
6	Using a common element for multiple functions	24	7%
7	Simplifying the already existing, standard solution	22	6%
8	Putting more than one function on one continuous surface	19	5%
9	Changing the direction of the orientation	16	5%
10	Repeating the same form multiple times*	15	4%
11	Nesting one design element within another*	12	3%
12	Hollowing out space within a solid	12	3%
13	Applying portability to existing standard solutions	12	3%
14	Adding-on, taking-out, or folding away components not in use	12	3%
15	Changing the scale of elements*	11	3%
16	Substituting one for another element*	10	3%
17	Reversing the repeated forms for various functions	9	3%
18	Splitting a form into multiple, smaller elements	8	2%
19	Folding forms around a pivot point	5	1%
20	Flipping the direction of a form across an axis	4	1%
21	Cutting edges into forms	2	1%
	Total	**348**	**100%**

some in succession, there appeared to be little relationship between two nearby concepts. For example, one may address the layout of fixtures in the space, and the next may focus on the control of water through a fixture. However, in many sequences, the relationship in the development of concepts was readily apparent. For example, in one concept, a bowl was drawn to capture waste water at the sink, and in the next, the same bowl form was drawn to capture waste water for the toilet and shower, repeating the sink's form. When such a related change was observed, the coder identified it as a potential observation of a heuristic. Across the body of concept drawings, the coder attempted to maintain a consistent standard about the observed relationships between two concepts.

Whenever such a change in concepts was identified, a new heuristic was described to capture the change. Each heuristic identified captured a specific change within a concept that added variation to the previous concept. For example, one heuristic addressed a change in how the functions of the product (a water fixture) were controlled. In one concept, the product was controlled through the turning of a faucet; in the next concept, a control arm could be pressed down to turn on the water. This change was then considered for how it may play a role in other designs, and a more general description created: *Adjust/Control functions by moving the product's parts*. Each heuristic was described so as to be (1) readily observable as a new element within a given concept, and (2) applicable to many different design concepts. In this example, a change in how the product was controlled could be readily observed in concept sketches, and the heuristic of changing the type of controls could be applied to generate many other concepts, such as a paddle that flips up, a button press, or a footpad. Through this process, a total of 21 heuristics were identified for the first fifty concepts on the scroll.

To test the concept of heuristic use in design, we conducted a pilot study with six of these heuristics (marked by asterisks in Table 1) (Yilmaz et al., 2010c). These six heuristics focused on introducing variation of form, and were selected for the study because they were simple, and suitable for use by participants without any expertise in design. In the study, novices were provided with these heuristics, and asked to create new concepts using them. The results showed that novices were able to apply heuristics readily in a simple product design task, and heuristic use was found to be related to greater creativity in the resulting concepts. This study supports the notion that heuristics can form the basis for introducing variation in concepts during the ideation stage.

Next, two independent coders, both design professionals with master's degrees in art and design, conducted an examination of the first fifty concepts on the scroll in order. The coders were uninformed about the nature of the study and its hypotheses. First, the coders were verbally instructed about each heuristic, and written descriptions were provided for review as needed. Copies of the sketches were provided, sequentially ordered, and each sketch was numbered. The coders were asked to identify which, if any, of the 21 proposed heuristics listed in Table 1 appeared in the transition from one concept to the next, or in changes depicted within a concept drawing. The visual data analysis started with identifying the changes among the sequence of concepts using the form, labels, and context provided in the sketches. Each concept design was coded for new elements, focusing on aspects of the form (i.e., change the configuration, reverse, repeat, etc.) and aspects of more specific, context-oriented functions (i.e., changing how the user physically interacts with the system, adjustability according to different users' needs, etc.).

Each drawing received a score on each of the heuristics to determine how frequently the heuristics were observed, and how consistently the taxonomy of heuristics could be applied to the sketches. The entire process took approximately 2 h for each coder. The agreement between the two coders (the percent of the observations where both coders positively scored a given sketch as containing a specific heuristic, or Interrater Reliability) was 91% overall. The frequency of use for each heuristic in the first 50 sketches is shown in Table 1 above.

3.3.2 Final analysis

Because agreement was very high with the two coders in the initial analysis, a single coder (the first author) examined the larger set consisting of two hundred and eighteen concepts, requiring coding sessions taking place over multiple days. In this major coding effort, additional heuristics were added to the coding set. Whenever a new type of transition was observed in the concepts, this new heuristic was defined and added to the coding set. Within the remaining 168 new concepts coded, a total of 13 new heuristics were discovered and added to the coding list. This resulted in a total of 34 new heuristics identified through analysis of the designer's concepts on this project.

A second set of 40 design heuristics were added to the coding scheme from a separate analysis. These heuristics came from a preliminary study of new consumer products available in a variety of online repositories for award-winning products (Yilmaz and Seifert, 2010b). Designs were selected from existing, independent award competitions, appearing in web reports and in published compendiums of well-known, successful products. The information available about each product included the product descriptions, design criteria, constraints, scenarios, and sometimes critiques from professional designers. These heuristics were identified by analyzing approximately 400 products providing a variety of distinct designs. A content analysis was then performed identifying the needs, design criteria, and the design solution. After the products were analyzed, the ones with similar design features were grouped and compared in order to explore commonalities in heuristic use. The descriptions of each heuristic were then defined. Clearly, subjective interpretation is necessary to derive a potential heuristic from the description of a finished product. The standard adopted for this analysis is whether the proposed heuristic is also observed in other product designs, and whether it appears to offer a transformation that can be successfully applied in novel designs.

When comparing the set of heuristics identified, differences in the level of detail are clearly present. The changes apparent in moving from one concept to the next were a varied set. Some of the changes addressed form, and some function, while others addressed ways to add features, increase efficiency or organization, or engage the user. Each of these types of changes addresses different aspect of the concept, and appears quite different from one another. For example, a more specific type of change was 'adding recycling' to a design. This type of heuristic change introduces a criterion for design that may not be a part of the stated problem; but, applying this as a heuristic in generating alternative concepts may lead a designer to consider more varied concepts, such as easy-to-disassemble systems, or repeated use of identical components. Further investigations of heuristic use, verification of patterns of use across types of design tasks, and variations in heuristic use with expertise will be necessary in order to more fully develop a theory of design heuristics. For the present study, this merged set of heuristics was used to code the entire set of 218 separate concepts. Of the resulting 68 heuristics, 34 were defined from the analysis of the present data, and 34 were original to the product analysis study; six of the heuristics overlapped in the two sets. The goal of this analysis was to identify the patterns of heuristic use in the sequential concepts generated while using an extended set of possible heuristics. Once the final set of heuristics had been acknowledged through the analysis, a second pass through each of the concepts ensured that each discovered heuristic had been identified in the overall set of 218 concepts.

4 Results

4.1 Types of solutions

Concepts generated in a sequence largely differed in the ways that bathroom units are aligned together, and how the interaction with the user affected this change. Diversity of concepts was not determined on this criterion alone, however. Major elements and key features of the concepts were identified in terms of functionality, form, user-interaction, and structural orientation of the design components. Identifying these features for each of the concepts allowed seeing the diversity of concepts generated in this design space. For example, a solution could be multi-functional, such as a product used both as a toilet and a sink, achieving two things by one product. Alternatively, a solution could be using the common sink and snapping it into various configurations, which would provide flexibility in use. These solutions would be considered distinct in the design space. Criteria used to classify the content of designs are presented in Table 2.

In one example, the designer created a concept using a triangular central component as a base placed in the center of the bathroom with toilet and sink aligned around it (Figure 3a). A concept that would be considered distinct from that one could be aligning bathroom components on a rail system side by side by the wall (Figure 3b). These concepts achieve similar criteria (portability and easy access) selected by the designer 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 design problem. In this case study, out of 218 concepts, 210 were considered as 'different,' reflecting distinctive designs. The other 8 concepts either repeated a previously drawn idea once again, or they had only minor changes to those ideas.

Table 2 Types of solutions generated for the design problem

Diversity Criteria	*Examples*
Method of implementing multiple functions	Adjustable settings, Attached/Detached components, Hidden/Folded components, Continuous surface with different functions, Bent surfaces, Separate pieces
Method of using the bathroom	Seated/Stood/Laid, Turned around, Slid, Moved forward, Swiveled, Pulled
Way of aligning bathroom components	Around a central piece, On the rails, Around a bed, On top of each other, By the corner of the bathroom
Other features	Attached to pre-existing products, Components for privacy, Considered people with wheelchair, System vs. Individual components, Using body parts for controlling the functions

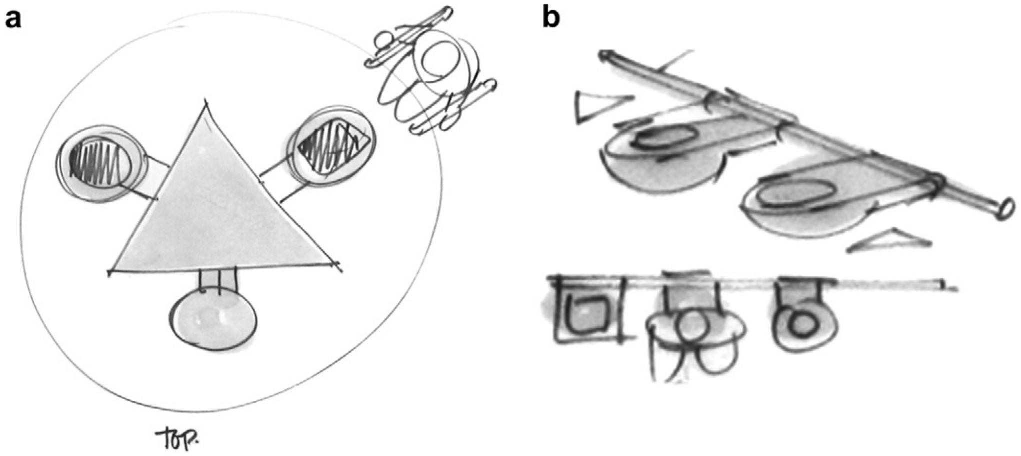


Figure 3 Example of using a (a) central base for aligning components, (b) railing system for aligning components

The designs on the scroll reflect the idea generation stage of the design process. At this initial stage of the process, it is difficult to know how the design concepts will change as the process continues. For example, an idea that may seem impractical or unfeasible in the designer's sketches may have become a practical and feasible one as they are reconsidered or combined with other ideas. Thus, for this case study, the concepts were not evaluated in regards to how well they would 'work'. The focus was on how heuristics helped the designer explore the design space.

4.2 Examples of heuristic use

The design heuristics in Table 1 attempt to describe the designer's strategies evident in the elements altered in the concept sketches. To illustrate, several examples of the concept sketches are provided from the designer's scroll, followed by the narrative the designer provided in the retrospective interview, and a description of how the cognitive heuristics appear within each sketch.

Figure 4a shows a labeled drawing where 2 bars are embedded in the sink wall, serving as controls for faucets. The labels indicate that the users can turn on the hot and cold faucets by depressing the bars with their arms as they lean in towards the sink. In Figure 4b, this concept has been altered to show a single bar that can be depressed at any point along its surface to control the faucet. This second concept has been simplified from that in Figure 4a; as a result, the faucet control is more flexibly used (by either arm or the upper body), requiring no coordination between hot and cold controls, and the design elements needed are fewer (1 bar instead of two). This (arguably) improved the design concept and coded as the application of the design heuristic, *Simplify the already existing, standard solution*. This heuristic includes a sense of an aesthetic

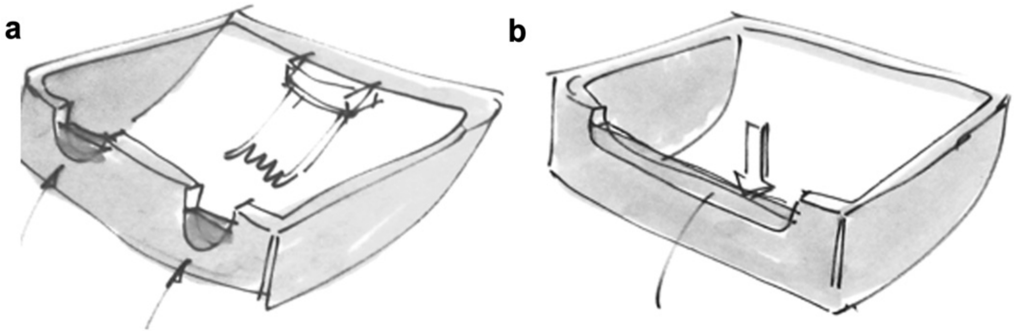


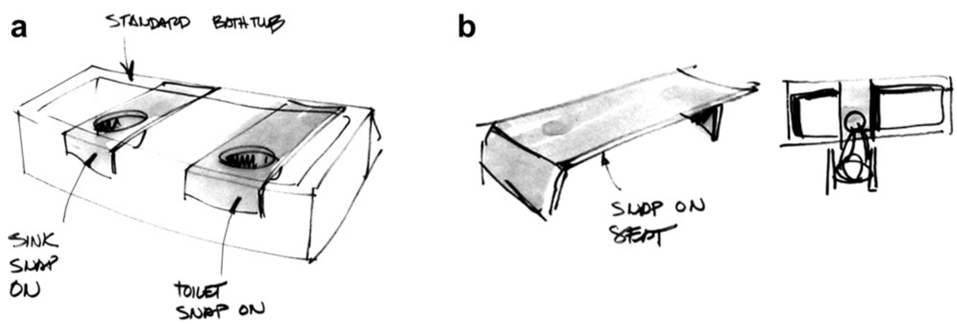
Figure 4 (a) Initial 'sink' concept, (b) Example using the heuristic Simplify the already existing, standard solution

value, where a simpler solution could also be considered more elegant or aesthetically pleasing, yet easy to manage. The point is that the change reflected through this heuristic resulted in a novel concept to consider.

The role of a simplification heuristic is confirmed by the designer within the interview, where he uses this heuristic to reframe the problem:

> Figure 4a and b: "… *controls, you can't be turning, reaching over turning, because you're not going to able to reach if you're in a wheelchair. And so I was putting controls in the front, where they're right there where your hands are. So if you're sitting in a wheel chair and you wheel underneath this, you can press these–hot, cold, on, off. Two individuals became 1 bar, terribly simple*."

In another series of concept sketches, the designer explored components for a bathroom that could be added on when needed, and taken out when not needed. The labels on Figure 5a and b indicate that the components for both the sink and toilet functions could be the same modules, and they could be snapped onto a standard tub. Using the heuristic, *Add-on, take out or fold away components when not in use*, the designer minimized the need for new materials, and created a system that integrated existing products (the tub) with the newly defined elements.



Figures 5 (a,b) Examples using the heuristic Add-on, take out, or fold away components when not in use

While the designer commented on portability, he identified his concern about using already existing products as a key requirement in the design problem:

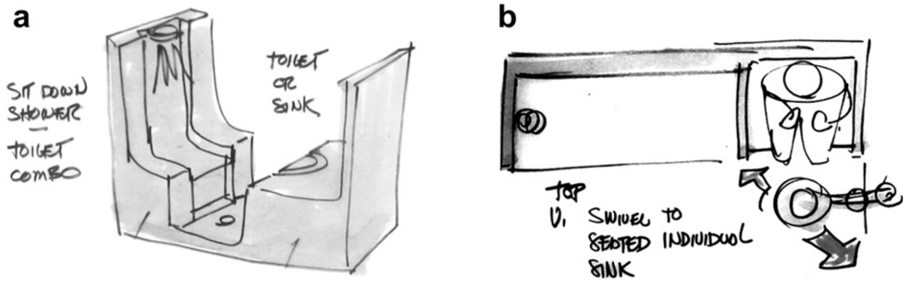
> Figure 5a and b: "… *more homes in the world have existing bathtubs than have an open room. I was inventing a new toilet and but then I got practical and said you know, wait a minute, while it's fun and nice, everyone else already has a tub. So can I do some of that this way adding onto an existing tub?*"

In a third sketch sequence, the expert seemed to focus on user interaction with the design elements, an important criterion given the physical needs of the potential users. Using the heuristic, *Change how the user physically interacts with the system* as a heuristic, the designer appeared to explore new ways of approaching elements and defining how users interact with them. In the retrospective interview, the designer commented on this change as:

> Figure 6a and b: "… *shower, toilet, it is one piece; one piece molded and put in place. But then I'm thinking about swiveling.*"

Whereas Figure 6a shows stable, mounted features, the next concept (Figure 6b) indicates a swiveling motion for the seating unit, which entirely changes how the product can be used. This change in how the user accesses the elements moves the possible designs in a new direction.

In a final example, quite early in the sketching process, the designer started employing the same modular elements multiple times for various functions. This heuristic, *Repeat the same form multiple times,* may arise from the goal of minimizing the costs of manufacturing. In addition, working out a specific element and how the user will interact with it forms a design plan that can be reused as a unit when useful for another function. While using this strategy, in numerous cases, he also reversed the identical design elements around the same base structure by removing the directional boundaries, a heuristic called, *Reverse repeated forms for various functions*. The integrated application of these two heuristics to the concept sketches can be seen in Figure 7a and b. These principles of combined system design subsequently guided the designer's generation of the basic form and the detailed design features:



Figures 6 (a,b) Examples using the heuristic Change how the user physically interacts with the system

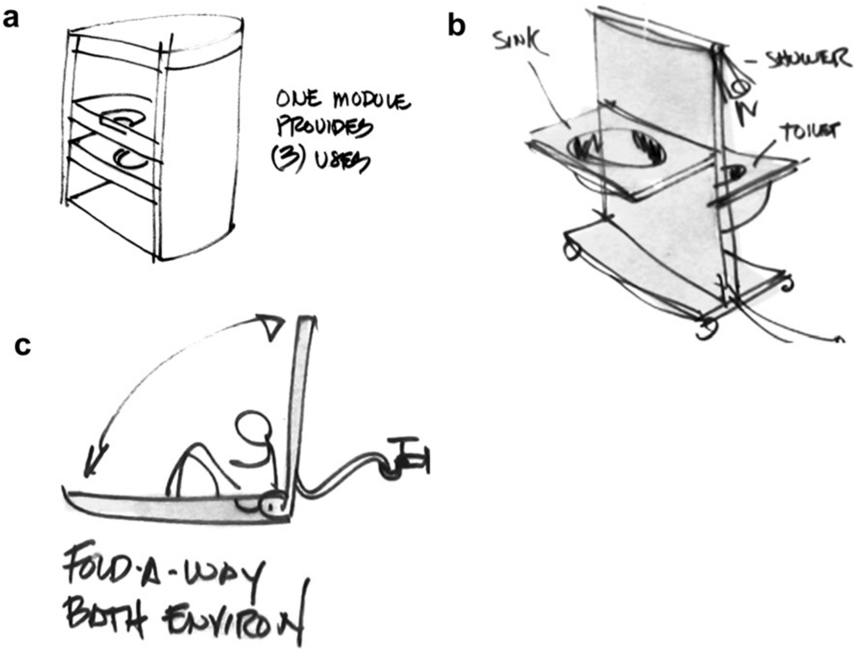


Figure 7 Example using the heuristics (a,b) Repeat the same form multiple times, and Reverse the repeated forms for various functions, (c) Repeat the same form multiple times, Add-on, take-out, or fold away components when not in use

> Figure 7a: "*So, that same shape represents the toilet to sit on, the sink to stand at, and a shower to stand under, and it just reminds me that there are three levels of function just like it said.*"

> Figure 7b: "*I guess all of that got me into issues having to do with fit and cleaning, and that led me to a whole mobile sink, bathroom, shower, soft tubing, things are starting to come together.*"

For the designer, repeating identical forms and using directional changes in their configuration created new solution spaces all throughout his idea generation process, avoiding design fixation.

As the concepts appear on the scroll, structural changes and new configurations become visible. In a considerable number of sketches, the designer used the heuristic: *Add-on, take-out, or fold away components when not in use*. An example of this heuristic can be seen in Figure 7c, where the designer considered a folding toilet. In the interview, for this concept, he commented:

> Figure 7c:"*… this is about a toilet that folds. So the environment opens and closes like the clamps show, and I don't know, soft tubing couples.*"

As seen in Figure 7c, using the *Fold* heuristic in combination with 'repeating elements,' the designer transformed the folding cover of a toilet into a toilet that folds up and out of the way. This heuristic is then applied to the other functions within the design, as a space-saving solution repeatedly to see if alternative concepts benefit from this heuristic.

4.3 Quantitative analysis of heuristic use

By defining the exploration process of an expert designer according to the observed set of heuristics used, it is possible to quantitatively analyze this process. In particular, we analyzed which heuristics this designer used most frequently when moving from one sketch to another in a sequence, and examined the patterns of heuristic use.

The observed counts of heuristics are shown in Table 3. According to this tabulation, some heuristics were used more than others, perhaps depending on the nature of the design problem, the design elements required for the functions, and the designer's preferences. For example, the problem criteria specified multiple components for the design of the bathroom system. As a result, heuristics that incorporate multiple elements (*Change the configuration using the same design elements, Merge a variety of components,* and *Repeat the design elements*) were frequently observed. The problem criteria also specified target consumers with physical challenges, and the related heuristic, *Adjustability according to different users' needs,* was also frequently observed. Finally, another problem criterion specified the flexibility of the system, and the designer utilized the heuristic, *Change how the user physically interacts with the system,* as a means to increase flexibility in his designs.

The main focus of this study is to document movement through concepts; that is, how transitions are made through concepts in the ideation stage, and how they reflect relationships among design elements in each new concept (*transitional heuristics*). A second type of observation was *local heuristic use*, characterized by its application to generate details observed within a single identified concept. These same heuristics were coded as *transitional heuristics* when observed occurring as a transition between two sketches.

In sum, the use of design heuristics was identified 1947 times in the 218 different concepts on the scroll. This case study certainly demonstrates that design heuristics do occur, in great numbers, in the work of an expert industrial designer. The frequent occurrence of these heuristics within the 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. Of these, the majority (66%) were identified through the concept analysis in this study, with 1291 instances of heuristics identified from the analysis of the expert's concepts. The additional 34 heuristics from the product analysis were counted 656 times or 33% of the observations. This shows that the heuristics derived from the independent product analysis were also frequently observed in this very different data set consisting of multiple concepts within the same design task from

Table 3 Design heuristic use as identified in the content analysis of the entire set of 218 sequential sketches generated by the designer. Separate uses are counted when observed as 'within a single concept' and 'between two concepts.' heuristics initially derived from this study are noted in gray background, while the product heuristic set is denoted in white. The corresponding rank ordering of concepts from the first 50 drawings only (shown in Table 1) are listed with each heuristic

Rank	*Design Heuristics in Coding Set*	*Within Concept*	*Between Concepts*	*Total*
1	Attach independent functional components within the product (5)	145	6	151
2	Change where or how product will be used (3)	135	7	142
3	Vary physical directions for product approach	118	6	124
4	Reverse direction or angle of component for each function (17)	93	30	123
5	Use a common base or railing to hold multiple components	73	8	81
6	Control / change in function through movement	76	2	78
7	Create modular units by using repeat, substitute, or split (10)	64	6	70
8	Make components attachable and detachable	54	13	67
9	Apply an existing mechanism in a new way (2)	64	2	66
10	Use the same surface area for multiple functions (8)	56	7	63
11	Redesign components to add on, fold in, take out (14)	57	0	57
12	Attach the product to existing item as an additional component	49	7	56
13	Use a common component for multiple functions (6)	54	1	55
14	Adjust functions to needs of differing demographic (1)	50	2	52
15	Add portability (13)	40	2	42
16	Flip the direction of orientation (e.g., vertical to horizontal) (9)	28	13	41
17	Refocus on the core function of the product (7)	37	2	39
18	Split or divide surfaces into components (18)	31	7	38
19	Extend surface area for more functions	28	7	35
20	Nest (Hide/Collapse/Flatten) elements within each other (11)	32	0	32
21	Hollow out inner space for added component placement (12)	31	1	32
22	Unify elements, color, and graphics for cost and consistency	31	1	32
23	Rotate on a pivot axis (20)	26	6	32
24	Elevate or lower product base	31	0	31
25	Fold product parts with hinges, bends, or creases to condense	25	4	29
26	Scale size up or down (15)	21	7	28
27	Offer optional components and adjustable features	25	2	27
28	Align components around a central, main function	22	2	24
29	Change the geometrical form (circle, triangle, cylinder, etc.) (4)	12	12	24
30	Cover / Form Shell / Wrap surface for other use	18	5	23
31	Use the same material all throughout the product	22	0	22
32	Return sensory feedback to the user (tactile, audio, visual)	18	1	19
33	Remove product parts to increase fit during use	16	3	19
34	Slide components across product surface	14	4	18
35	Visually separate similar functions using size and/or color	16	1	17
36	Bend into angular or rounded curves (21)	16	0	16
37	Replace solid material with flexible material	12	3	15
38	Compartmentalize functions into distinct parts	12	1	13
39	Substitute / Swap an old component with a new design (16)	10	3	13
40	Change the surface material at points of human contact	8	3	11
41	Reduce the amount of material needed for the same function	9	0	9
42	Compress product surface to create controller	8	1	9
43	Convert two-dimensional materials into three-dimensional	8	1	9
44	Transfer or convert to another function	8	0	8
45	Use an environmental feature as part of the product	8	0	8
46	Mirror shapes for symmetry	7	0	7
47	Merge functions that can use the same energy source	6	0	6
48	Visually separate primary functions from secondary functions	6	0	6
49	Add gradations or transitions to use	3	3	6

(*continued on next page*)

Table 3 (*continued*)

Rank	*Design Heuristics in Coding Set*	*Within Concept*	*Between Concepts*	*Total*
50	Replace materials with recycled and/or recyclable ones	5	0	5
51	Replace limited-use parts with multiple use ones	4	1	5
52	Use the same surface area for different functions	4	0	4
53	Flatten product surface	3	1	4
54	Stack components	2	0	2
55	Roll product around a pivot point (19)	1	0	1
56	Make the product expandable to fit various sizes	1	0	1
57	Add features from nature to the product	0	0	0
58	Animate look by using human features	0	0	0
59	Convert leftover packaging for another use	0	0	0
60	Cover joints for safety and visual consistency	0	0	0
61	Create a hierarchy of features to minimize steps	0	0	0
62	Create recycling system for returning to manufacturer	0	0	0
63	Design user activities to unite as a community	0	0	0
64	Express users' cultural values in the product	0	0	0
65	Include users in customizing or assembling the product	0	0	0
66	Twist geometric forms to add variation	0	0	0
67	Use human-generated power as energy	0	0	0
68	Use packaging as a functional component within product	0	0	0
	Expert Designer's Scroll Heuristics	1157	134	1291
	Product Database Analysis Heuristics (Yilmaz & Seifert, 2010)	596	60	656
	Total	**1753**	**194**	1947

a single expert designer. In fact, four heuristics from the product design set ranked in third, fifth, sixth, and eighth in frequency of use.

Approximately half (965) of the observations of heuristic use in the entire set of 218 concepts were coded using the initial set of 21 heuristics derived from the first fifty drawings (shown in Table 1). This suggests that there is a remarkable consistency in heuristic use by the designer across the set of concepts created over a long period of time. At the same time, an additional 47 heuristics were observed in this set of concepts. Six of these initial 21 heuristics overlapped with the product analysis heuristic set, and were highly ranked in terms of frequency of observation, providing independent support for their utility in design, as shown in Table 4.

Table 4 Six design heuristics observed in both the present data set and in the separate product analysis study (Yilmaz and Seifert, 2010b), and their frequency of occurrence

Rank	*Design Heuristics in Coding Set*	*Within Concept*	*Between Concepts*	*Total*
2	Change where or how product will be used	135	7	142
7	Apply an existing mechanism in a new way	64	2	66
8	Create modular units by using repeat, substitute, or split	64	6	70
13	Adjust functions to needs of differing demographic	50	2	52
15	Add portability	40	2	42
16	Refocus on the core function of the product	37	2	39

Some heuristics were observed very frequently both within and between concepts. For example, *Reverse direction or angle of component for each function* (number 4), and *Make components attachable and detachable* (number 11) occurred more often than many others. In Figure 8a, the designer placed two identical elements for two different uses (sink and toilet) on opposite sides of a common base. This way, each function (sink and toilet) was located on the reverse direction of the other. The heuristic *Reverse direction or angle of component for each function* here was used as a local heuristic, as it defined the two components' relationship with each other within the same concept. In Figure 8b, on the other hand, the same heuristic was used as transitional heuristic between two concepts. In the first concept, the designer bent a continuous surface multiple times and assigned different functions to each of the bent surfaces. In the second concept, these bent surfaces were separated from each other and attached again from their pivot points. Using a pivot point gave the designer the flexibility of reversing the directions of each component according to the needs of the targeted users. Thus, the designer reversed the individual parts seen in the first figure to generate an alternative product concept.

The most common heuristics were *Attach independent functional components within the product* (8% of the heuristics observed in the set), *Change where or how product will be used* (7%), *Vary physical directions for product approach* (6%), and *Reverse direction or angle of component for each function* (6%). These choices reflect the context of the problem (fitting many specialized

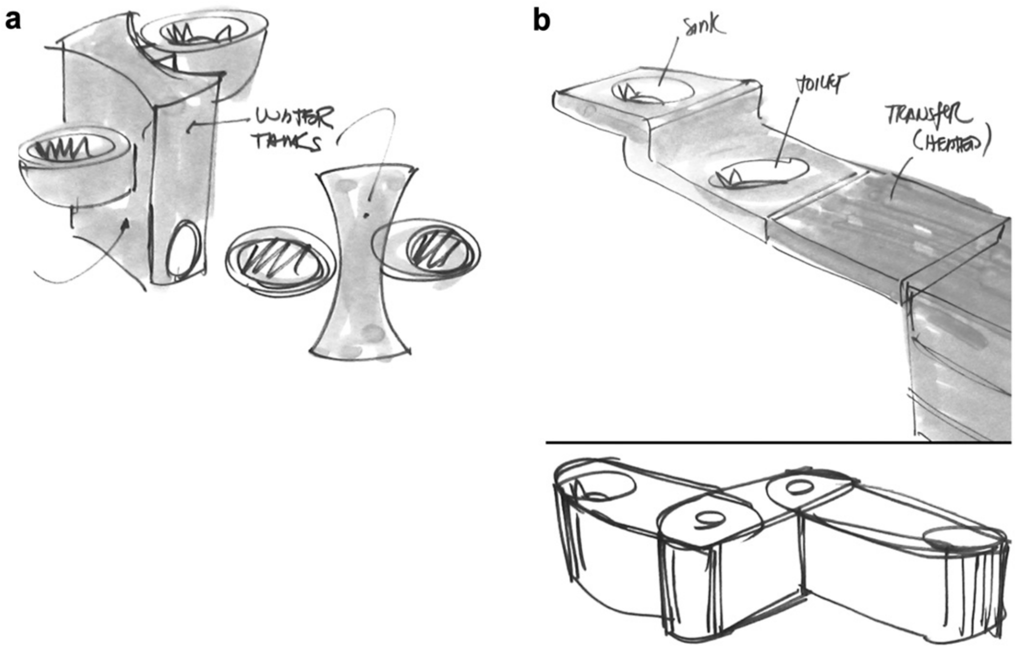


Figure 8 Example using Reverse direction or angle of component for each function (a) as a local heuristic, (b) as a transitional heuristic

functions into a small space (existing bathrooms) and the strategic emphasis of the designer (multipurpose and multiple approaches for functions). For example, the designer assigned forms to each of the functions in the system (sink, toilet, and tub), and then attached them in a variety of orientations to create alternatives, resulting in changes in how the product systems would be used. He also varied physical directions for approaching the products by reversing the units or sliding them over each other, adding flexibility for varied users.

4.4 Multiple heuristic Use

The total number of local heuristics per concept ranged from 1 to 18, and in almost all of the concepts (208 of 218), multiple heuristics were observed. This view of the ideation stage includes successively applying multiple heuristics to generate a large set of candidate designs. This suggests the constant application of *heuristic combinations*, rather than an approach where each sketch demonstrates the application of a single heuristic. This might arise from the heuristics' relationships to each other. For example, in designing a shared structural unit for the bathroom, the designer applied the notion of a 'swiveling' seat, seen in Figure 6b. This approach led to a combination of three structural heuristics: *Changing the configuration of the identical design elements* utilized in the previous concept in order to repeatedly use the swiveling motion around that *common base*, while *changing the physical interaction of the user with the system* and *adding multiple functionalities to the same component*. As a result, these specific heuristics were observed occurring together repeatedly.

Across the sequence of concept sketches, it appears that the majority included six or fewer heuristics; however, the sequence is punctuated by individual designs where 10 or more heuristics were applied. These sketches appeared quite distinguishable from the rest, representing novel concepts that show a 'creative leap' (Cross, 2004) in the design sequence. They were also followed by numerous design variations using them as key concepts. To illustrate this 'punctuated' use of multiple heuristics, a graph of just the first fifty concepts is presented in Figure 9.

This figure illustrates that most concepts involve more than one heuristic; however, occasionally, a very novel design occurred where many more changes, and consequently heuristics, were observed.

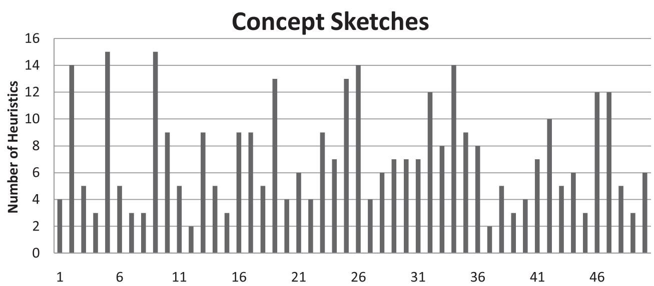


Figure 9 Frequency of differing heuristics used in each concept sketch

Out of all of the concepts, each concept that had an application of 15 or more heuristics used these three heuristics stated above. This may reveal that these heuristics were used by the designer in a combined manner, complementing each other. Concepts with fifteen or more diverse heuristics applied were also the ones with major changes in the concepts generated. For example, in Figure 10a, the designer used 17 diverse heuristics, such as *Elevate or lower product base*, and *Create modular units by repeating, substituting, or splitting*, in addition to the previous trio mentioned. This concept was also one of the distinct concepts used as a starting point for a different sequence of concepts that used the idea of two connecting cylindrical elements and further developed. This suggests that this concept indeed reflects a major change in the designer's thinking, as the heuristics used in generating the concept.

The concept seen in Figure 10b also used 17 diverse heuristics, and can be regarded as another major shift in the process. In this concept, the priority was given to identical components that are attachable and detachable to the existing products to accomplish different functions (sink and toilet). These findings suggest that there is a relationship between design heuristics and solutions' creativity due to the concepts using a large number of heuristics and being regarded as strong distinctions by the designer reflecting his decision about those being more creative than others.

The least frequently used heuristics were *Make the product expandable to fit various sizes*, and *Roll product around a pivot point*. The reason may lie in the choice of material for this project. The designer was highly concerned about the accessibility and practicality of the design solutions; he repeatedly sought alternative structural solutions. Because these heuristics suggest the use of flexible materials, they may not have been perceived as beneficial for

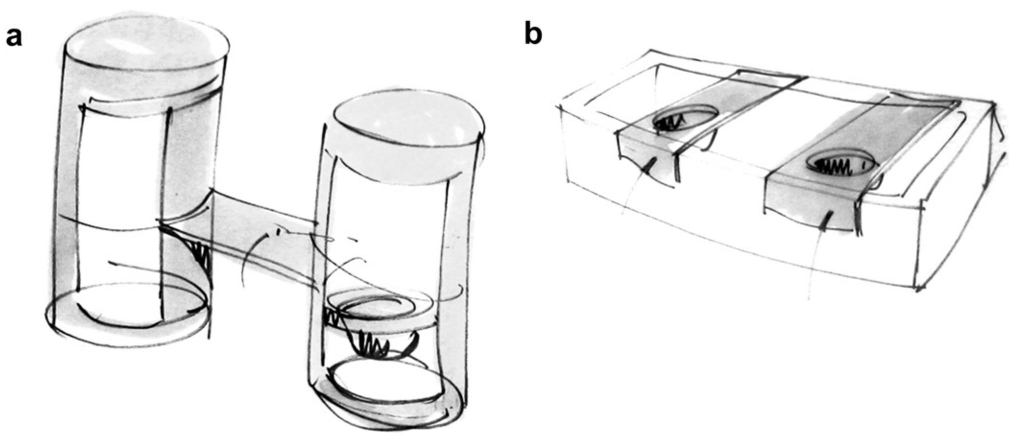


Figure 10 (a) Twin tower modules using the central component as a transferring unit between the two, (b) Snap-on components attached to standard bathtub and used for different functions the function of this design problem. Another rarely used heuristic was *Stack components*, which appears relevant to this problem. Applying this heuristic could have a notable impact in accommodating multiple functions; however, the designer did not utilize this heuristic as often as others. This might have resulted from the designer's focus on required functions, without evident thought towards building in extra features such as storage areas.

In total, another 13 heuristics taken from a previous study of consumer products (Yilmaz and Seifert, 2010b) were not observed in the present data. The heuristics not observed in this case study, but present in the consumer product study, were oriented toward the later stages of the design process. For example, one heuristic observed in the consumer products was, *Cover joints for safety and visual consistency*. This heuristic could potentially be applied to the current design problem, but it would likely be considered once a concept had been selected, and further design refinements were taking place. Other consumer product heuristics not observed in this case study may not be appropriate for the present design task (e.g., *Create a recycling system for returning to manufacturer*). At the same time, there was a great deal of overlap in the heuristics observed in the studies, as most (27 of 40) of the heuristics identified in the consumer product study were also observed in this case study. This suggests that heuristics may be suited to differing stages of the design process, may not be applicable to a given design task, and may depend upon the designer's personal preferences.

4.5 Diversity

Diversity in concept generation may be achieved through bringing a range of variables to the design task. Design heuristics, in that sense, assist the designers in the process of exploring and identifying new, unexpected variables and contexts that would alter the design criteria and the solutions in different ways, and eventually creating diverse concepts.

In this case study, the designer's main focus was creating diverse concepts in the first place. So the number of diverse concepts (210) generated was expected. He used a range of different combinations using the same design elements, which resulted in diverse solutions. For example, Figure 11a reveals that he incorporated a sliding shower unit, transferring the motion from the user to the product. This is achieved by applying a variety of design heuristics; such as, *Slide components across product surface*, and *Control/Change in function through movement*.

In another version of this idea (Figure 11b), the horizontal alignment of the components is converted into vertical, which requires the user to take a shower while standing. Heuristics observed in this concept were rather different; for example, the designer applied *Change the direction of orientation*, and *Use a common base or railing system to hold multiple components* in order to create

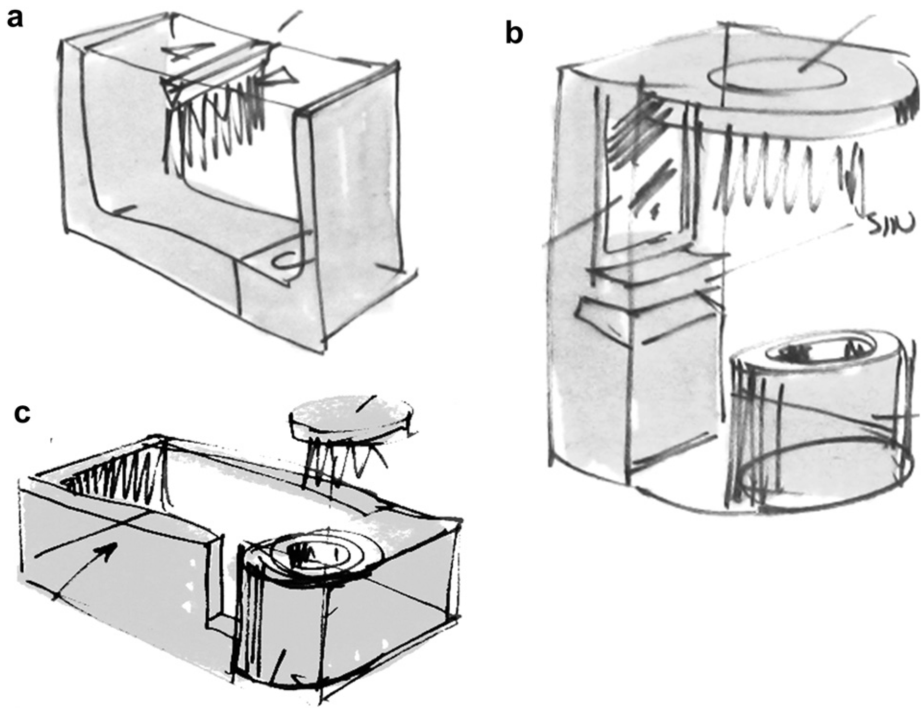


Figure 11 Example using (a) Slide components across product surface, and Control/Change in function through movement for a diverse solution, (b) Change the direction of orientation, and Use a common base or railing system to hold multiple components for a diverse solution, (c) Offer optional components and adjustable features, and Change product orientation for each function for a diverse solution

a structure using a vertical body and multiple functions attached to it with an additional separate seating element.

In a third variation (Figure 11c), the designer used design elements in a horizontal orientation once again, with a new corner unit for toilet and sink. This concept also allows the user to take a shower and a bath since the bathtub is included within the concept. Other heuristics observed in this concept include, *Offer optional components and adjustable features*, and *Change product orientation for each function*.

As seen in the examples, diverse design solutions did not depend on the use of specific local or transitional heuristic(s), but rather diverse use of heuristics when jumping from one concept to another. Carrying the same heuristic to the next concepts did not allow the designer to explore the problem space thoroughly. However, the expert designer seemed to be comfortable in bringing in different heuristics each time and even though all three concepts were formed by the same elements, they were diverse concepts with minor similarities.

4.6 *Process heuristics*

Some observed design changes appeared to be strategic choices the designer made repeatedly in order to force changes in a specified direction, such as, *Assign a context, or change it*. In this sense, *process strategies* are identified as those that direct the designer's overall approach through the solution space. The designer is most likely to be aware of these heuristics, and to consciously choose to use them for developing different approaches to the design problem. Some of the heuristics proposed in SCAMPER (Eberle, 1995) and Synectics (Gordon, 1961) are similar to these, along with more general strategies such as *Evaluate*.

For example, the designer used a *Brainwriting* strategy multiple times throughout the sketching process, suggesting he felt the need to expand his search for designs. In this strategy, the designer listed the potential constraints and the criteria that could direct his thinking, and then selected one or more of them, or combined them, to generate new concepts in a new direction. Thus, the process heuristics were used consciously when the designer appeared to be fixated in one area of the design space.

The commonly observed process heuristics are listed in Table 5 with their descriptions.

One process heuristic observed was *Redraw earlier concepts*. In order to remember where he left in the ideation phase, and/or to investigate the previously

Table 5 Process heuristics observed, and their descriptions

Process Heuristics	*Descriptions*
Assign form to each function	Giving form to each function separately, and creating a relationship between this forms (separate, attached or merged pieces)
Brain-write	Using brainstorming sessions and generating words describing the constraints and variables to suggest new concepts
Contextualize	Assigning a context or changing it if it exists
Evaluate	Placing value to the idea and then staying with or leaving it
Prioritize certain constraints	Selecting and prioritizing certain constraints and developing concepts satisfying those
Redraw earlier concepts	Redrawing the previously proposed concepts
Synthesize	Merging different concepts into one
Analyze morphology	Identifying different ways of achieving the same function and combining and substituting each way to generate a new concept
Switch level of focus	Change from a general system-level design focus to one on a specific concept element, and back
Propagate	Once a new concept element is identified, try to apply it to other existing concepts

generated concepts further, the designer sometimes drew the same ideas multiple times. The concepts that were redrawn reflected the major changes within the structure of the product systems. These concepts were evaluated and marked with stars by the designer indicating the need for further development. Surprisingly, even though the starting points (the initial proposed product concepts) were the same, the further development of these concepts differed remarkably. These differences in concept directions appear to have been accomplished by changes in the use of other (local) heuristics. For example, choosing alternate ways of defining the relationships of the design elements within the same concept, and the context of where and how the product will be used.

Throughout the process, the designer jumped from designing the overall system to designing the details of individual components within specific system concepts, and back again. This *Switch of focus* strategy as a process heuristic allowed him to think about both the depth and breadth of created concepts. At times, he also synthesized two concepts into a new one, and went back to previous concepts and improved them further. This process was very dynamic, flowing between new and revisited concepts. Another process heuristic is that when the designer found a new, noteworthy idea, he consistently tried to *Propagate* the new concept element to other objects in different concepts. For example, after developing a design to mount an element on the wall, he then also attempted to attach it on top of a cart, and attach it onto a standard bathtub.

One other strategic flexibility noted was that the designer appeared to switch between two major design concepts, one a stable bathroom unit pushed towards a wall, and the other a mobile bathroom located in the middle of the room for easy access. Going back and forth between these two approaches, rather than settling on just one to pursue, seemed to increase the designer's generation of novel ideas. Specifically, he thought about the entire system, and created different scenarios about how the user would interact with that system. For example, he thought that the person would utilize the components aligned around a full cylindrical module for the three different functions: shower, sink and toilet. For privacy, a curtain would give 360° coverage (Figure 12a). In another scenario, he considered a user with a wheelchair and his needs in the bathroom. For that purpose, he merged the three functions into one design component and assumed the user would use each side of the product for different features by simply going forwards and backwards on the same surface (Figure 12b).

The designer also seemed to go back and forth between the system level, and the individual components and their details, throughout the ideation process. A previous study by Cross (2003) emphasized three common design processes in expert designers: (1) experts took a broad 'system approach' to the problem as opposed to merely accepting narrow problem criteria; (2) experts framed the problem in a distinctive and personal manner; and (3) experts designed from

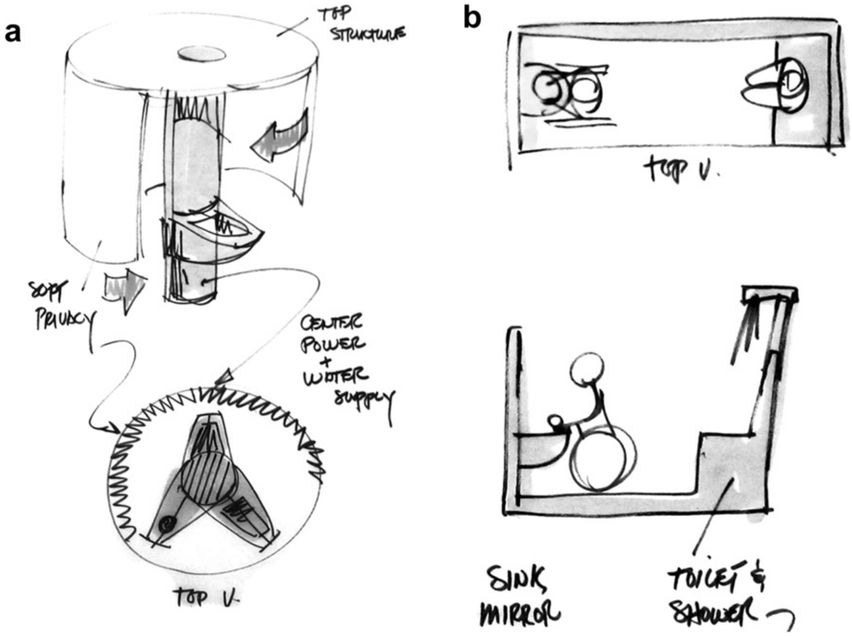


Figure 12 Example of a system (a) created by synthesizing concepts, (b) focusing on the needs of people with wheelchairs

'first principles'. The 'back and forth' thinking process between the system level and the individual concept level has not been reported before. In this case study, the designer appeared to use this thinking process as a way to overcome fixation, as well as to elaborate further details within the initial concepts he generated.

Process heuristics that direct the designer's approach over multiple concepts were difficult to localize to specific concepts, and so their occurrence was not scored quantitatively. Their more general nature, and their apparently optional or conscious invocation by the designer when the flow of ideas had reached a stopping point, suggests these process heuristics are important tools to learn. At the alternate end of the spectrum, there was little evidence of TRIZ heuristics (Altshuller, 1984) in this data set. This may be expected because the design task was clearly conceptual, and stopped short of the mechanical specifications that would give rise to the trade-offs solved by the application of TRIZ heuristics. The lack of overlap in these sets of heuristics suggests that the intermediate level of analysis described in Table 2 is an alternative and useful conception of the transformations made by the designer during conceptual product development.

4.7 Awareness of design heuristic use

Of interest, the interview data suggests that while the expert recognized the use of specific heuristics, he was not articulate about heuristic use within his process, and did not readily name the variety of heuristics observed in the concept sketches. However, when shown the analysis of concepts, he readily concurred that the heuristics captured the nature of the changes he created in his concept sequences.

This suggests this designer was not conscious of his use of heuristics, but appeared to implicitly invoke them as he worked through the design process. This pattern fits with prior findings on the execution of procedural skills (Anderson, 1982). The use of heuristics may be so well learned that conscious access to their content is limited. As with practice on procedural skills like riding a bike or solving algebraic equations, the experienced designer may have less conscious access to the cognitive processes organizing the execution of his skill. The expert looking at his own scroll may recognize the use of some elements; however, there may be little conscious reflection on them during the design process as it occurs. The interview provided a sense of conscious detachment, where the expert observed that his design protocol must indeed include the heuristics; however, there was a lack of conscious awareness of heuristic use. This observation fits with results from Kavakli and Gero's (2002) protocol analysis of an expert and a novice designer's works, suggesting that experienced designers use strategic knowledge, but do not identify or communicate their existing strategic knowledge.

This analysis of design heuristics provides a specific description of how design elements are changed, suggests which combinations of heuristics are important to the design process, and reveals the process of incremental vs. major changes across concept sketches. This provides an account of how the expert explored potential designs in the ideation process, and may potentially identify classes or categories of designs that are separable, representing disparate areas of the 'problem space' of possible designs.

5 Discussion

From these results, it is clear that the expert's concept sketches reflected the systematic use of design heuristics. Many designs with obvious variations were created, and the source of the variation appeared to be well captured by design heuristics. By applying these heuristics, the expert appeared to extend his creative thinking, and consider specific aspects of innovative design represented by the heuristics. The sheer prevalence of heuristic use suggests their importance in exploring new problem-solution spaces. Another important finding is the role of design heuristics in extending prior design ideas. From the sketches, the occurrence of heuristics as transitions between designs was observed as the designer revisited functions and/or arrangements adopted in previous concepts. Past research on approaches like case-based reasoning (Kolodner, 1993; Maher and Gomez de Silva Garza, 1997; Watson and Marir, 1994) emphasize the reuse of prior designs; however, the reuse observed here seemed to emphasize selected elements rather than complete design reuse. This suggests a more 'generate and test' approach, where heuristics were used to explore potential variations of existing designs, and those variations extended into further new concepts.

In addition, the results indicate that the expert designer generally used multiple heuristics simultaneously when moving from one concept sketch to another.

This suggests expertise may involve repeated experience with the simultaneous application of related heuristics. The patterns of heuristic use observed across designs may reflect this designer's unique style in concept generation. Potentially, other experts may have developed different patterns of heuristic groups. Alternatively, perhaps design heuristics fall into natural categories that many designers learn through experiences with design domains. Design expertise may follow a developmental sequence, from learning individual heuristics and becoming skilled in their application, to eventually developing patterns of multiple heuristic applications. The patterns of heuristic use observed in this expert protocol suggest such a trajectory for the development of heuristic use.

Most importantly, this study provides the first empirical evidence of the use of heuristics in design creation. Alternative theories such as SCAMPER (Eberle, 1995), Synectics (Gordon, 1961), and TRIZ (Altshuller, 1984), have proposed specific heuristics to be used by designers in the conceptual design phase. However, no studies demonstrating their use are available. The findings show strong evidence of the use of design heuristics in a large conceptual design project, giving a naturalistic validity to the approach. Further, there is some suggestion that the use of these design heuristics may lead to more creative designs. In an experiment, we investigated the role of simple form heuristics in a redesign task with novice designers. Undergraduate students were asked to redesign salt and pepper shakers beginning with simple three-dimensional shapes. Some participants were instructed about six different design heuristics, including *Change the scale of elements*, *Change the geometrical form (circle, triangle, cylinder),* and *Nest* (Hide/Collapse/Flatten) elements within each other. Those given heuristics to help in creating concepts produced designs that were rated as significantly more creative than those of control subjects (Yilmaz et al., 2010c). These findings suggest that using design heuristics can be related to more creative outcomes.

The findings from the present study are limited to the observation of concept generation by a single expert designer; as a result, the question of heuristic use by experts in general, and its effects on other design tasks, is not addressed. However, the findings show that heuristic use can be quantitatively documented using actual design sketches produced within a professional project taking place over an extended period of time. The results suggest expert designers may use numerous heuristics in an integrated fashion to generate alternative design solutions. The analysis method developed here allows the analysis of design concepts created by experts without requiring a protocol study (c.f. Goel and Pirolli, 1992; Suwa and Tversky, 1997) through the use of archival data. This data is the work product recorded by the designer as part of his own creative process. This method allows the study of the design process of professional designers taking place natural settings.

The design heuristic approach was successful in characterizing the expertise demonstrated in this design task. This suggests the approach may hold promise in instruction for novices as they build their own experience with heuristic use and design in general. A previous study showed that novices produced concepts judged more creative when they made use of design heuristics (Yilmaz et al., 2010c). The success of this heuristic analysis method in characterizing differences among candidate designs may lead to a defined set of heuristics encompassing some of the expertise acquired through experience and training. Then, a pedagogical method could be developed to support novices by presenting practice with heuristics, demonstrating their use in generating multiple concepts, and varying the types of design problems where they are applied. As a result, the development of expertise may be facilitated by providing explicit instruction in design heuristics in the early stages of training. This may lead more quickly to designers with the skills to maximize the variety and novelty of their candidate concepts, leading to innovative designs.

Future work will identify and refine the design heuristics uncovered in this analysis. Ongoing work is directly comparing the variety of design heuristics evident in specific domains such as product design (Yilmaz and Seifert, 2010b). It is possible that different domains of design (e.g., industrial design, mechanical engineering, software engineering, landscape architecture) will require differing sets of design heuristics to assist in ideation. Another direction for future work is to examine multiple expert designers as they approach the same design problem, allowing the comparison of individual differences in the use of design heuristics. It is important to develop methods to directly compare individuals at varying levels of expertise in order to examine the trajectory development for design heuristic use in ideation. Then, access to heuristics as they occur during the design process can be examined, along with the ways of training novice designers to use heuristics. By understanding how design heuristics are used to introduce variation in concepts, we will learn what experts know about concept generation, and how to apply these design heuristics to create innovative designs. Most importantly, this research promises to uncover what novice designers need to learn, and how to design effective pedagogy across design domains.

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