Cognitive Heuristics Employed by Design Experts
A Case Study

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Abstract: Psychological research has shown that decision making and problem solving often rely on simplified cognitive heuristics. Heuristics are reasoning processes that do not guarantee the best solution, but often lead to potential solutions by providing a “short-cut” within cognitive processing [16]. It is proposed that designers utilize specific *design heuristics* to explore the problem space of potential designs, leading to the generation of novel and creative solutions. The intent of this research is to identify these heuristics through comprehensive analysis of an expert designer’s ideation process over several months as a case study. Fifty sequentially-generated concepts were examined; each represented as a labeled drawing, and a retrospective protocol of the designer discussing his generation process was collected. This case study uncovers over twenty design heuristics that promote variation in concepts and alter existing solutions, supporting the claim that expertise incorporates the use of heuristics to explore potential designs.

Key words: Design Heuristics, Creativity, Idea Generation, Design Expertise.

1. Expertise

What differentiates experts from novices? Several decades of research in cognitive science has defined expertise as the skilled execution of highly practiced sequences of procedures [2]. Many studies of expert design behavior suggest that designers move quickly to early solution conjectures, and use these conjectures as a way of exploring and defining the problem and solution together. Lloyd and Scott [15], using five experienced engineering designers’ protocols, found that this solution-focused approach appeared to be related to the level and nature of previous experience of the designers. Their analysis showed that more experienced designers used more „generative’ reasoning - bringing something new to the design situation, in contrast to „deductive’ reasoning - making the design problem in hand clearer. In particular, designers with specific experience with the problem type tended to approach the design task through problem/solution structuring using general discipline experience, rather than through problem analysis identifying needs of the specific problem.

The purpose of the idea generation phase in the design process is to conceive of as many creative solutions as is possible for the criteria defined by the design problem. Many researchers have investigated the cognitive processes that occur in the idea generation phase of design creation [1, 4, 6, 10, 14]. One such process is “problem framing,” where Schon [18] suggested, “In order to formulate a design problem, the designer must frame a problematic design situation: set its boundaries, select particular things and relations for attention, and impose on the situation a coherence that guides subsequent moves”. Designers explore the problem space from a particular perspective in order to frame the problem in a way that stimulates and pre-structures the emergence of design concepts. A designer decides what to do (and when) on the basis of a personally perceived and constructed design task, which includes the design problem, the design situation, the resources (time) available, as well as the designer's own design goals. Goel and Pirolli's [8] protocol studies demonstrated that problem framing occurs not just at the beginning of the design task, but also re-occurs periodically throughout the process. Dorst and Cross [6] confirmed through a series of protocol studies that creative design involves a period of exploration in which the problem and solution spaces are evolving, remaining unstable until (temporarily) fixed by an emergent bridge that identifies a problem-solution pairing.

Schon and Wiggins [20] found that when designers are creatively exploring designs, they proceed through cycles of seeing-moving-seeing, in which seeing concerns a process of (re)interpretation of shapes and relationships in a design, and moving concerns transformations of these (re)interpreted shapes. During these creative periods of conceptual design, expert designers alternate quickly in shifts of attention between different aspects of their task or between different modes of cognitive activity. For example, Park et al. [17] found that expert designers using generation, transformation, and external representation in performing a sketching task produced more creative alternatives than the ones who used perception, maintenance, and internal representation as defined by their visual reasoning model. This finding suggests that continuously exploring new solution spaces results in the designer considering a variety of options, activating the creativity stimuli.

Other studies have identified some design strategies employed by expert designers [5, 14]. For example, Kruger and Cross [14] developed an expertise model of the product design process to study four different cognitive strategies employed by the designers. They found that designers using a solution-driven design strategy, where the focus is on generating solutions, tended to produce the best results in terms of the balance of overall solution quality and creativity as compared to designers using a problem-driven strategy, which consists of gathering data and identifying constraints to define the problem. However, many questions remain surrounding the use of strategies. First, what are the basic strategies designers use to generate alternative designs? Which are the most effective? Does frequency of strategy use change among designers at varied levels of expertise?

2. Design Heuristics

Heuristics are not guaranteed to produce a high quality or innovative 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. Design heuristics move the designer into other ways of looking at the same elements, and provide the opportunity for a novel design to occur.

The use of heuristics in design has been previously explored in TRIZ [3], which provides a systematic method for finding and using analogies based on past designs (stored in a relatively abstract form). For example, in designing a soda can, a designer employing the TRIZ theory 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 "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 the durability. The Synectics [9] framework, on the other hand, combines different techniques to address needs at different phases of ideation. A designer utilizing Synectics may try to "animate" the can by applying human qualities, such as adding a smiley face to the same can. While TRIZ focuses on engineering parameters, and related conflicts and trade-offs, Synectics highly relies on the fusion of opposites, both focusing on the use of past experiences and analogies. As a result, the heuristics proposed tend to centralize on known, specific engineering mechanisms, or very general theme suggestions such as the one presented in the "animation" example.

Our related approach attempts to describe design heuristics at the level of transformations of form and function that can lead a designer to introduce systematic variation to their current concepts, producing a more varied set of candidate designs. Rather than generalized principles and triggering questions typical in brainstorming sessions, we propose focusing on those cognitive heuristics that offer a means of generating possible designs by guiding specific types of variations within a problem context.

For example, one cognitive heuristic that can be used to introduce changes in a familiar form is, "Flipping.". Consider the example of designing a desktop accessory (Figure 1 below). In a protocol from an expert industrial designer, she reported attempting to create a distinctive design. For inspiration, she looked through a magazine of artistic designs, and came across a flower vase that made use of circles with overlapping edges (Figure 1b). By expanding on this form, she created a drawing of circular shapes with one long end hanging from each circle, leading to the "J" shaped object in Figure 1c. Then, to add interest to the form, she "flipped" the larger, center piece to go in opposition to the aligned J shapes (Figure 1d). The resulting office accessory is striking in the novelty of its design. Where did the novelty come from? This designer followed a heuristic strategy to create innovation: Refine a form by "flipping" its design (or portions thereof) across an axis.

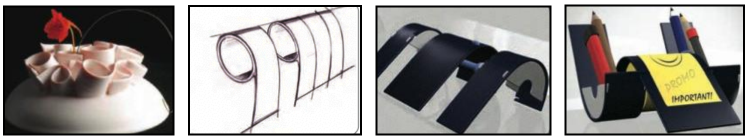

Figure 1a. Vase | Figure 1b. Exaggerated form | Figure 1c. Prototype | Figure 1d. "Flipped" final product

A heuristic may contradict other heuristics (e.g., when there is a conflict between decreasing complexity and increasing flexibility), and relevant heuristics may not be considered at times. However, the use of design heuristics may result in a more varied set of potential design solutions, and often, a more creative outcome.

The majority of studies analyzing expert designers' behaviors focus on differences in external activities, such as time spent gathering information, and problem solving activities, rather than the strategies employed in the concept generation phase, their effectiveness, and their selection according to the problem criteria at hand. Our approach is to learn from expert designers by following their intentional steps through a design process, and identifying specific strategies they use in design creation. It is this type of expertise – a very effortful, conscious process of attempting a variety of heuristics to generate new ideas – that is the target for our design heuristics approach. Research questions to address here include: What are the heuristics expert designers use throughout the ideation process? What are the procedural skills? How often do they use design heuristics? Do they prefer some heuristics over others? Koen [12] suggests that a single heuristic is seldom used in isolation in design, and that one can overrule the other within the given design problem. Are heuristics applied one at a time, or do multiple heuristics arise together? And, are sets of particular heuristics used together?

3. Method

To address these questions, the study reported here examines a sample of work from an expert industrial designer who has established a long and distinguished record for highly successful and innovative designs. The designer has worked as a professional product designer and taught a variety of design courses (including project-based studio courses) at a top design program for over a thirty-year period.

The design project selected for this study involves developing a bathroom that can serve Alzheimer's patients and their caregivers. An additional focus was a modular approach, with the self-contained product constructed and 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, transfer, and maintenance. 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. For this project, approximately three hundred sketches were collected from the scroll. The sketches were typically labeled with design features, and, using a three-color scheme, were highlighted to indicate areas of concepts that changed from prior concepts. For the purpose of data analysis, the first fifty of the three hundred drawings were studied.

Years after the project's completion, the designer was interviewed using the scroll record as an organizing structure. This taped interview solicited the designer's retrospective report about the design process, including his recall of his idea generation. For this interview, which lasted for approximately seventeen minutes, the designer was asked to talk about what he recalled about each concept sketch while examining each of the sketches in a sequence.

A set of potential heuristics was generated by the first author, a product designer. First, common changes to designs that add variety to the structure of a form were identified. Then, heuristics that address specific functions were listed, such as, "*Simplifying the already existing, standard solution*". These heuristics are devised to be (1) applicable to many different, and potentially all, design concepts, and (2) readily applicable to a given concept so as to potentially lead to a new concept. Each heuristic is designed to be considered independently, and so that its application may lead to a new, distinct concept. For example, the heuristic, "*Using a common element for multiple functions*," encourages the approach of attempting to keep the element constant while making minimal changes to incorporate other needed functions.

Next, two independent coders, both professionals with master's degrees in art and design, conducted an examination of the fifty design concepts on the scroll in the order that they appeared. The coders were uninformed about the nature of the study and its hypotheses. They were asked to identify which, if any, of the proposed heuristics listed in Table 1 appeared in the transition from one concept to the next. The printouts of the sketches were sequentially ordered, and each sketch was numbered. The visual data analysis started with identifying the changes among the sequence of concepts, recognized by studying the form, labels, and context provided in each of the drawings. Each concept design was examined for evidence of new elements, focusing on aspects of the form (i.e., changing the configuration, reversing, repeating, etc.) and aspects of function (i.e., changing how the user physically interacts with the system, adjustability according to different users' needs, etc.). In the coding, both the transition between the concepts and the transitions or changes depicted in each concept drawing were taken into consideration. For the coders, each heuristic was defined verbally, and the written descriptions were provided for them to review if needed. Each of the 21 heuristics in Table 1 was compared to fifty sketches individually, and the coders identified which sketches included the heuristics through this analysis.

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 coders were given half an hour to read the descriptions of the codes and briefly study the sketches before the coding process. After completing the coding, they were asked to go over the sketches a second time to confirm the codes. The entire process took approximately two hours. The agreement between the two coders (the percent of the observations where both coders positively scored a given sketch as containing a specific heuristic) was 91% overall. Only observations where both coders agreed were considered in the following analysis.

4. Results

4.1 Examples of Concept Sketches and Heuristic Use

The cognitive heuristics attempt to describe the designer's strategies evident in the elements altered in each of the concept sketches. To illustrate, we provide several examples of the concept sketches contained in the designer's scroll followed by the narrative the designer provided in the interview, and describe how the cognitive heuristics are identified within each sketch.

Figure 2A shows a labeled drawing where two bars are embedded in the sink wall, serving as controls for the faucets. The labels indicate that the user can turn on the hot and cold faucets by depressing the bars with their arms as they lean in towards the sink. In Figure 2B, 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 2A; as a result, the faucet control is more flexibly used (by either arm), requiring no coordination between hot and cold controls, and the design elements needed are fewer (one bar instead of two). This (arguably) improved design concept appears to have arisen from the application of the design heuristic, "*Simplifying the already existing, standard solution*". This heuristic includes a sense of an aesthetic 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.

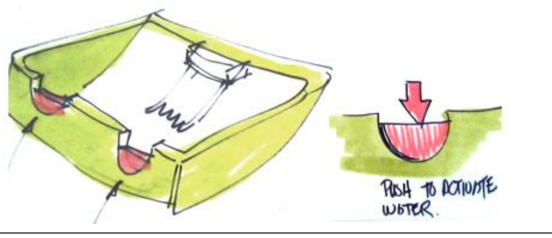

Figure 2A

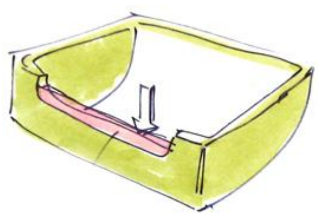

Figure 2B

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

> Figure 2A. & Figure 2B. "… 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 one bar, terribly simple."

In another, separate 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 2C and 2D 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, "*Adding on, taking out or folding away components when not in use*", the designer minimized the need for new materials, and created a system that integrated existing products with the newly defined elements. While this heuristic is quite general, its application to existing designs can be straightforward.

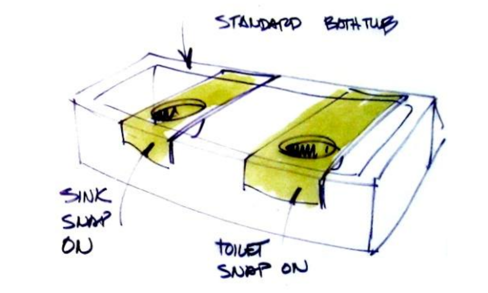

Figure 2C

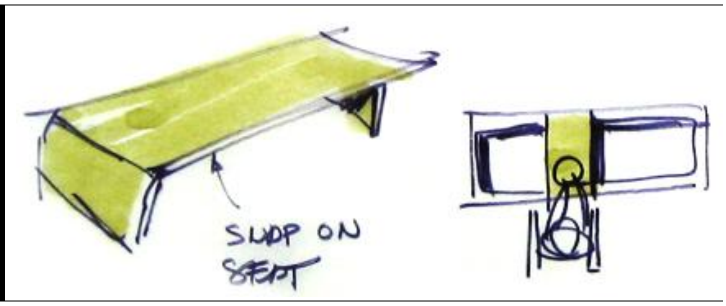

Figure 2D

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

> Figure 2C. & Figure 2D. "… 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 from the problem given the physical needs of the potential users. Using the heuristic, "*Changing how the user physically interacts with the system*" as a concept alteration technique, 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 2F. & Figure 2G. "… shower, toilet, it is one piece; one piece molded and put in place. But then I'm thinking about swiveling."

Whereas Figure 2F shows stable, mounted features, the next concept (Figure 2G) 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 to consider in a new direction.

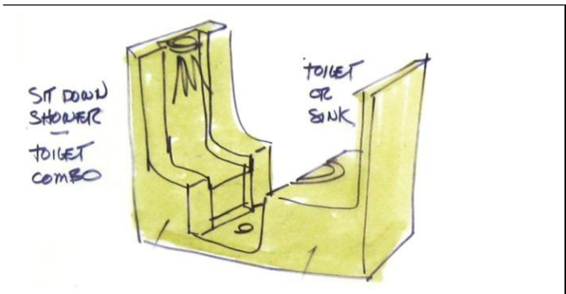

Figure 2F

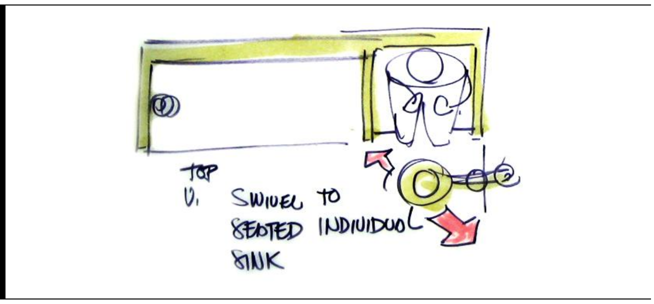

Figure 2G

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, "*Repeating 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 the same module is used for another function within the design. While using this strategy, in numerous cases, he also reversed the identical design elements around the same base structure by removing the directional boundaries, which is a related heuristic called, "*Reversing the repeated forms for various functions*". The integrated application of these two heuristics to the concept sketches can be seen in Figure 2H and Figure 2I. These principles of combined system design subsequently guided the designer's generation of the basic form and the detailed design features:

> Figure 2H. "I am trying to be as minimal and as spontaneous and as brief in my comments to myself as possible, so I know there is more detail, but I'm not going to stop and draw it. 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 2I. "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.

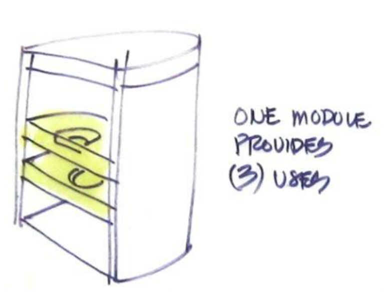

Figure 2H

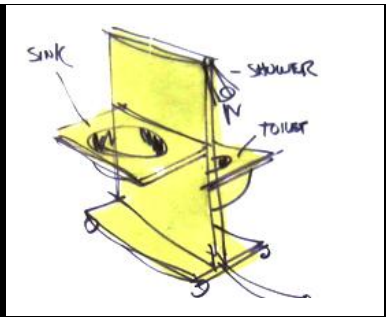

Figure 2 I

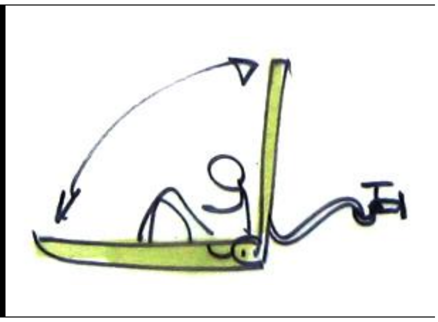

Figure 2J

As the concepts appear on the scroll, structural changes and new configurations become rather visible. In a considerable number of sketches, the designer used the heuristic: "*Adding-on, taking-out, or folding away components when not in use.*" An example of this heuristic can be seen in Figure 2J, where the designer considered a folding toilet. In the interview, for this concept, he commented:

> Figure 2J. "… 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 2J, using the folding heuristic in combination with repeated elements, the designer transformed the folding cover of a toilet into toilet that folds up and out of the way. This heuristic is then applied to the other functions within the design; applying the space-saving solution repeated to see if alternative concepts benefit from this heuristic.

The examples presented here are meant to illustrate in detail the specific aspects observable in the concept sketches, and the possibility for observing changes in designs. Next, we present a more formal analysis of the presence of heuristics identified in the design scroll.

4.2 Quantitative Analysis of Heuristic Use

By defining the exploration process of an expert designer according to a small set of heuristic rules, it is possible to quantitatively analyze this process. In particular, it is possible to determine which heuristics designers use when moving from one sketch to another in a sketch sequence, and then examine the patterns of heuristic use.

The observed counts of heuristics across the functional and structural categories are shown in Table 2. According to this tabulation, some heuristics were used more than others, perhaps depending on the nature of the design problem, the design elements, 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 (*"Changing the configuration using the same design elements," "Merging a variety of components,"* and *"Repeating the design elements"*) were frequently observed. The problem criteria also specified target consumers with physical challenges, and the heuristic focused on *"Adjustability according to different users' needs"* was also frequently observed. Finally, other problem criteria specified the portability and flexibility of the system. The designer utilized the heuristic, *"Changing how the user physically interacts with the system,"* as a means to increase flexibility.

Table 2. Design Heuristics identified in the sketch sequence through coder's observations

Functional Heuristics		n	%
F1. Adjustability according to different users' needs		38	19%
F2. Applying an existing mechanism in a new way		35	18%
F3. Changing how the user physically interacts with the system		33	17%
F4. Using a common element for multiple functions		24	12%
F5. Simplifying the already existing, standard solution		22	11%
F6. Putting more than one function on one continuous surface		19	10%
F7. Adding-on, taking-out, or folding away components when not in use		12	6%
F8. Applying portability to existing standard solutions		12	6%
	Total	195	100%
Structural Heuristics		n	%
S1. Changing the configuration using the same design elements		25	18%
S2. Merging a variety of components		24	17%
S3. Changing the direction of the orientation		16	11%
S4. Repeating the same form multiple times		15	11%
S5. Hollowing out space within a solid		12	8%
S6. Nesting one design element within another		12	8%
S7. Changing the scale of elements		11	8%
S8. Substituting one for another element		10	7%
S9. Reversing the repeated forms for various functions		9	6%
S10. Splitting a form into multiple, smaller elements		8	6%
S11. Folding forms around a pivot point		5	4%
S12. Flipping the direction of a form across an axis		4	3%
S13. Cutting edges into forms		2	1%
	Total	153	100%

A surprising result is that the average number of heuristics observed in the sketches is 7.16, with a range from 2 to 15, showing that multiple heuristics were observed in almost all sketches. 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 2G. 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, several specific heuristics worked together to implement the concepts, and were observed occurring together repeatedly.

The set of concept sketches examined (fifty in all) and the number of heuristics observed within each concept is shown in Figure 3. Eleven out of 50 sketches were scored as including ten or more heuristics, with 15 being the highest. Across the sequence of concept sketches, it appears that the majority included six or fewer heuristics; however, the sequence is punctuated by 11 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 [6]", and they were followed by numerous variations using them as the key concepts.

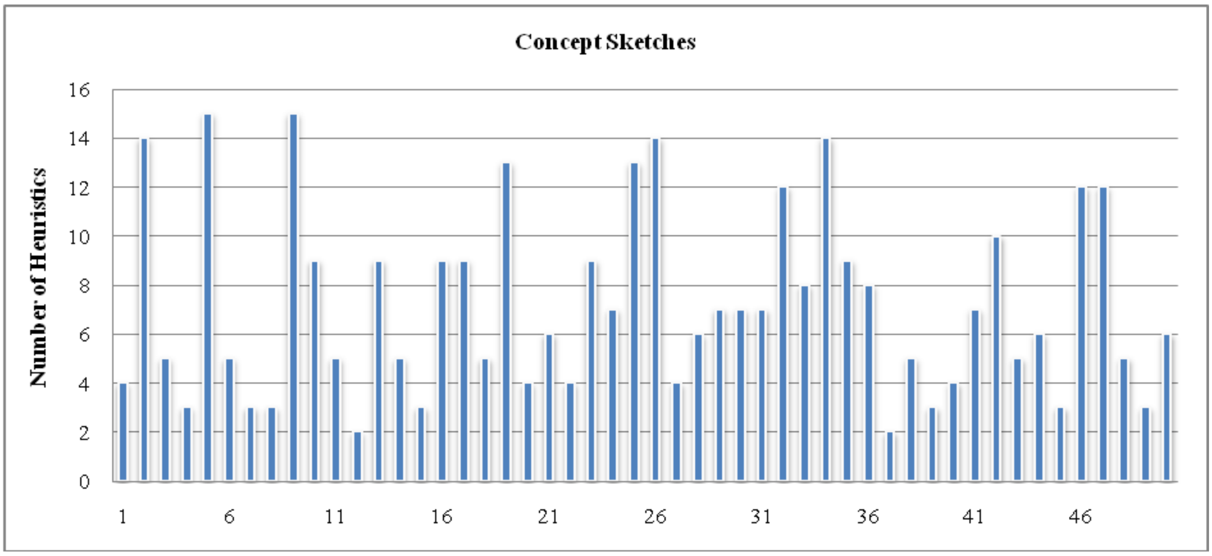

Figure 3. Frequency of differing heuristics used in each concept sketch.

Quantitative analysis of heuristic use provides an account of the expert's design process in terms of the transformations taking place on design elements. The design heuristics provide a specific description of how elements are changed, suggest which combinations of heuristics are important to the design process, and reveal 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 as representing disparate areas of the "problem space" of possible designs. The presumed goal of ideation is to generate as many varied concepts as possible in order to maximize the variety and novelty of candidates for selection and refinement. The success of this heuristic analysis method in characterizing differences among candidate designs may lead to schemes that assist in design evaluation. Further, the identification of heuristics and groups of heuristics may suggest ways for development of computational tools for design. For example, the frequency of the heuristics applied can be analyzed in order to understand which of the heuristics are most commonly used, for what kind of design problems that aroused, and which heuristics may be suggested as potentially relevant given the observed patterns. In particular, this approach may hold promise in instruction for novices as they build their experiences with heuristic use.

5. Discussion

From these results, it is clear that the expert's concept sketches reflected the systematic use of the proposed design heuristics. Many designs with obvious variations were created, and the source of the variation appeared to be the introduction of elements that follow design heuristics. By applying these well-known strategies, the expert was able to extend his creative thinking and consider specific aspects of innovative design represented by the heuristics. The sheer prevalence of heuristics use suggests their importance in exploring new problem-solution spaces. Another important finding is the role of design heuristic application in extending prior design ideas. From the sketches, it is clear that one important aspect of this design process was to remember functions and/or arrangements adopted previously, and to abstract them out of the particular contexts of previous sketches to apply them within a new design. This suggests a "generate and test" approach, where heuristics were used to explore potential variations of existing designs.

In addition, our results indicate that the expert designer generally used more than one heuristic when moving from one concept sketch to another, where multiple heuristics were considered simultaneously. This suggests that expertise may involve repeated experience with the simultaneous application of related heuristics. If these patterns of heuristic use are observed across design problems, they may reflect this designer's unique approach to concept generation based upon his experiences. Potentially, other experts may have developed different heuristic groupings, or perhaps the heuristics fall into natural categories that many designers would learn through trial and error experiences with design. In addition, true design expertise may follow from a sequence of learning individual heuristics, becoming skilled in their application, and eventually acquiring patterns of multiple heuristic applications. The patterns of heuristic use observed in this expert protocol suggest a trajectory for the development of heuristic use.

Of interest, the interview data suggests that while the expert recognized the use of specific heuristics, he was not articulate about the role of heuristic use within his design process, and did not readily name the variety of heuristics demonstrated by concept sketches. This pattern fits well with prior findings on the execution of procedural skills. The use of heuristics may be so naturally a part of the well-learned procedures for generating designs that any conscious access to their content and use is limited. For example, as with practice on procedural skills like riding a bike or solving algebraic equations, the performer has less and less conscious access to the cognitive processes organizing the execution of the skill. For the expert, looking at a video of his own bike riding might lead to recognition of skilled elements; however, there may be little conscious reflection on that process as it occurs. The interview provides a similar sense of detachment where the expert observed that his design protocol must indeed include the heuristics; however, there was a lack of conscious access to the heuristics and their use. This observation fits with results from Kavakli and Gero's [11] protocol analysis of an expert and a novice designer's works, suggesting that experienced designers use strategic knowledge, but do not identify or communicate what this strategic knowledge is.

The present study observed the sequence of ideas generated 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 analysis shows that heuristic use can be quantitatively documented using actual designs produced within a professional project based on the artifacts produced. 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 use of design problems and solutions created by experts without requiring a scientific study by using the archival data recorded by the designer as part of his own work process. This method allows the study of design process of professional designers taking place over extended periods of time.

6. Conclusions

Our findings demonstrate that the design protocols from an expert product designer show consistent use of cognitive heuristics that introduce interesting and valuable variation in the potential designs considered. Further, independent raters were able to readily identify the frequent and consistent use of heuristics across a sample of 50 concept sketches. While the pattern of use of multiple heuristics related to the degree of novelty within the sequence of designs, the expert had little conscious reflection about the use of these heuristics within his own cognitive process.

Future work will identify and refine the heuristics uncovered in this analysis, and compare them to prior proposals in the engineering design field. Then, access to heuristics as they occur during the design process will 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 and apply to create innovative designs, and what novice designers need to learn from them.

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