DESIGN HEURISTICS

BY

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To Mom and Dad whose support has been felt even from thousands of miles away.

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ABSTRACT

This thesis describes research carried to investigate the evidence of design heuristics and their role in the design ideation process. Design heuristics are guidelines that help the designer to consider areas of possible designs that may not otherwise come to mind during the idea generation stage. The research is cross-disciplinary bringing findings, methods, and perspectives from cognitive psychology to product design domain. The exploratory research work undertaken has produced a list of design heuristics that are commonly used by designers in generating diverse concepts, inspiring design ideas that in turn affect the design outputs produced through the creative design process.

By combining content analysis of real-world examples of expert designs and investigation of expert and novice designers' decision processes through case studies using designers' sketching processes, a set of design heuristics was constructed as an aid for designers. A short list of heuristics was selected and validated through experimental studies with novices. It was shown that designers employed cognitive heuristics in order to enhance the variety, quality, and creativity of potential designs they generate during the ideation stage. Specific design heuristics helped the designer to explore the problem space of potential designs, leading to the generation of creative solutions. The effectiveness of instruction on design heuristics in solving design problems was also shown since, even for novice designers, a few minutes of text and illustration on heuristics led to designs reliably judged as more creative and diverse. The evidence suggested that research on design heuristics used in design problem solving can contribute to our understanding of cognitive processes in design and the assessment of design ability, help identify more effective instructional and computational tools to support designers at any level of expertise, and improve pedagogical approaches to teaching design.

CHAPTER 1

INTRODUCTION

"TO MAKE THIS PAINTING TOOK ME 10 MINUTES AND 80 YEARS."

SENGAI (JAPANESE MASTER-PAINTER)

OVERVIEW

It has become widely accepted that business survival and prosperity is strongly linked to the ability to innovate (Prahalad & Ramaswamy, 2003; Soosay & Hyland, 2004; Taghavi, Hghiasi, Ranjan, Raje, & Sarrafzadeh, 2004). The increased market demands for new and creative products, and the elevated levels of competition, require the ideation phase of the design process to be shorter and more effective than ever. The need for increased quality of ideas is compromised by the ever-shortening time in which they are to be produced. Thus creative tools are required to aid designers in producing more 'creative' and 'diverse' ideas in shorter periods of time.

In recent years, many studies have taken place with the aim of identifying and understanding aspects of creativity in design (Candy & Edmonds, 1996; Christiaans & Dorst, 1992; Goldschmidt & Tatsa, 2005). These studies suggest that creative design involves movement from one 'solution space' (Newell & Simon, 1972) to another. According to Cross (1997), this is what characterizes creative design as exploration, rather than search of a well-defined solution space. This thesis presents a new model that addresses the cognitive processes involved in design exploration. It aims to identify and enhance designers' abilities to explore designs through design heuristic use.

This research was initiated as an exploratory project focusing on the integration of the two domains, psychology and design, to address the question of how designers create novel designs. The methods include analyzing successful designs and sketching processes of expert designers, and conducting laboratory studies with non-designers. This diverse approach elicited commonalities and differences in design cognition while examining a wide range of expertise. The results led to the development of a theory of "design heuristics" to account for creativity in design, and provide a foundation for pedagogical innovations in design instruction.

This chapter provides the context of relevant literature examining issues such as design creativity, design education, cognitive strategies, and design expertise. Design heuristics are also described, and their differences from the other strategy tools are discussed. Finally, the questions addressed in this research and the organization of the thesis is specified.

1.1. BACKGROUND

In order to understand the process of designing, designers' strategies, and the potential application of the theory to design education, data is gathered and relevant variables are identified. The approach in this thesis is cognitive, intending to reveal heuristics that are selected and applied, and how their use adds variation to the design concepts generated. The work described within this thesis crosses disciplinary lines between the domains of cognitive psychology and industrial design. There are distinct knowledge contributions from research in both communities, and this section is structured to make the research more accessible from both perspectives: (1) the practice and education of industrial design, and (2) the cognitive science of creativity and problem solving.

Previous research using protocol studies (Atman, Chimka, Bursic, & Nachtman, 1999; Benami & Jin, 2002; Cross, 1997) has proposed cognitive activity models of conceptual design. However, these experiments either focused only on one attribute, such as visual analogy, or they proposed a very general perspective. My approach is a combination of these two viewpoints to improve our understanding of how creative cognitive processes and design heuristics result in innovative products and effective design processes that are more effective.

1.1.1. Processes of design generation and exploration

Designers appear to generate questions and choose directions during a session while maintaining an internal dialogue. Understanding this process requires understanding the mental activities of the designer in relation to their design process. Jin and Chusilp (2005) claimed that design concepts are created through mental iterations of idea generation and evaluation. They defined these iterations as the repetition of cognitive activities occurring in designers' thinking processes. Adams and Atman (1999) argued that these processes take place as designers attempt to gather and filter information about a design problem, and result in the revision, improvement, or modification of possible solutions. Even though these processes are believed to lead to better quality solutions at a faster pace, there is little research that identifies which processes may contribute to designers' performance, creativity, and expertise.

This thesis concerns how designs are generated and solutions are explored by means of concept representations. It makes references to the cognitive processes evident during design, but it is not an enquiry into the mechanisms of the mind. The goal is to identify how designers create and transform concepts using heuristic rules.

1.1.2. The Domain of Industrial Design

Despite numerous studies on industrial design, very few operational definitions are proposed. For industrial design, one of the definitions used by ICSID (International Council of Societies of Industrial Design, 1964) is:

"Industrial design is a creative activity whose aim is to determine the formal qualities of objects produced by industry. These formal qualities include external features but are principally those structural and functional relationships which convert a system to a coherent unity both from the point of view of the producer and the user. Industrial design extends to embrace all aspects of human environment which are conditioned by industrial production."

At least two aspects of this definition are of importance. The first is the concept of creativity, which is apparently an important criterion as to the quality of the design; and the second is related to the multidisciplinarity of industrial designing, ranging from the applied arts to engineering. In reviewing studies of design, Cross (1990) described what designers do, and what their abilities are:

- Resolve ill-defined problems
- Adopt solution-focusing strategies
- Employ abductive/productive/appositional thinking
- Use non-verbal, graphic/spatial modeling media

Products created by designers elicit specific emotions from consumers, such as happy or angry, secure or anxious. Products create bonds with users. For example, a watch may display a variety of personalities, such as playful, sporty, and elegant, and all aspects of the design (both functional and aesthetic) will be part of its engagement for the user.

Given these intangible characteristics of design, industrial design can be seen somewhere between the disciplines of engineering and art (Gotzsch, 1999). While in engineering, the form of the product is highly driven by the functional constraints, in art, the form is emotional, and influenced by aesthetic values. Depending on the type of product, however, one discipline becomes more applicable and relevant than the other. Gotzsch asserts that during the design process, industrial designers switch back and forth between functional aspects of design (related to engineering) and emotional aspects of design (related to art) depending on the type of product and stage of the design process. This suggests that designers are able to attend to functional and emotional aspects of designs separately. The question is, therefore, “How do successful industrial designers learn to design?”

1.1.3. Design Education

Design is exploratory. It is emergent, opportunistic, rhetorical, reflective, risky, and an important human endeavor (Cross, 1999). This statement also reflects the intuitive, experienced-based nature of the field. Designers think in a specific way that is both ubiquitous and unique, often referred to as "design thinking" or "design cognition". Acquiring design thinking, for a number of reasons, is a very intricate activity.

First, in order to design a product, designers need to understand concepts and procedures from several different domains, emphasizing the interdisciplinary character of the field. Second, the design activity itself is usually thought to be a valuable teaching tool – ‘learning by doing’ (Anzai & Simon, 1979) – in that, students experience not only the problem and the information needed, but also the cognitive strategies or *heuristics*. Third, because of the complexity of design problems, it is almost impossible to give design students clear and detailed working methods to consistently attain a good design result.

The typical paradigm underlying design education is the experiential learning approach (Tynjälä, 1998). The curriculum of experiential learning activities usually takes the form of complex projects consisting of generally structured, guided experiential activities (Tynjälä, 1998). While project-based learning has also been adopted as the key teaching-learning strategy in most design schools, questions about the effectiveness of this approach remain unanswered. It assumes that students will have their curiosity aroused with an increased motivation to learn, and that when in a novel design situation, students will transfer the meaningful insights they learned in school into other design tasks (Pietersen, 2002). However, in these later activities, students are often faced with unstructured, ambiguous design problems, for which they may not have acquired strategies to assist them in developing new solutions. Indeed, with a critique-based evaluation of student projects, the set of design knowledge and strategies acquired may not be apparent even to the successful student.

Many design undergraduates are provided with general instructions about concept generation, and the importance of creativity in this stage of the design process. But it is less common to teach specific cognitive strategies that may lead to generating more creative ideas. Design students need *heuristics* to take them out of the fixated thought process (Jansson & Smith, 1991), as much as they need the technical skills to further develop functional ideas.

Prescriptive models are often used as a basis for current design methods (Cross, 2000; Pahl & Beitz, 1996), which claim to offer systematic methods concerning the execution of design. However, these models are not based on firmly validated theories. Moreover, they mostly offer rather general recommendations; for example, a prescribed sequence of design phases (concept generation, evaluation, concept selection, etc.). Thus, they are not validated methods for training individuals to design.

1.1.4. DESIGN CREATIVITY

Creativity is an integral and essential part of the industrial design process. As Boden (1995) notes, creativity is the ability to conceive or recognize novel and valuable ideas. Creative designs provide feasible solutions to relevant problems in new ways. Without creativity, there is no potential for innovation, which is where creative ideas are actually implemented (Mumford & Gustafson, 1988) and transformed into commercial value (Thompson & Lordan, 1999). A broad definition of creativity is that it concerns with the production of novel ideas that are in some sense useful, or an advance beyond previous conceptions (Eysenck & Keane, 2000). However, there are a wide variety of definitions, over 200 in the current literature alone (Goldenberg & Mazursky, 2002). But what is a creative product idea? In one study by Goldenberg and Mazursky (2002), a short of list of products' creativity characteristics was defined: "original", "simple", "surprising", "elegant", and "changing conventions". Jackson and Messick (1965) used "unusualness, appropriateness, transformational power and condensation of meaning" as a definition.

From an engineering perspective, organizations must enhance innovation (Bharadwaj & Menon, 2000), so the creative process of individuals must be considered within the design process. While there is a large number of engineering design process models, none of them suggests innovation tools; instead, it is commonly assumed that creativity is something that occurs somewhere within a "conceptual design" stage of the engineering process (Gero, 1990; Hybs & Gero, 1992). In most models, there is no account of the process of developing ideas, (Howard, Culley, & Dekoninck, 2008). Most authors take the view that the ‘illumination’ stage is really a sudden perception of an idea (Cross, 1990; Lawson, 2006).

The main interest in creativity is in methods like Synectics, where the goal is explicitly to remove mental blocks inhibiting creativity. Several techniques have been developed to assist people in manipulate their knowledge to aid creativity. Brainstorming, for example, involves the manipulation of ideas based on different interpretations based on past experiences (Osborn, 1957). Another technique, TRIZ (Altshuller, 1984), provide paths to solutions based on past innovative patents and inventions. These method-based techniques suggest it is possible to enhance designers' creativity.

Although these methods indeed encourage people to generate more ideas, it is not yet known whether they are effective in bringing about exceptionally creative design solutions. Over the last three decades, several authors stressed the general correspondence between the structure of creative process and the structure of problem-solving (Newell & Simon, 1972; Weisberg, 1988). Anderson (1982) described problem solving as a goal-directed sequence of cognitive operations, and differentiated creative problem solving from routine problem solving by emphasizing the involvement of learning or acquisition of new procedures compared to using existing procedures. Newell and Simon (1972) proposed that a "problem space" consists of knowledge states and the operators (sequence of operations) that transform the current state into a state closer to the goal. This view suggests that operations or "heuristics" can be used to guide movement through a "design space" to uncover new designs. Psychological studies suggest the processes involved in the manipulation of knowledge are the fundamental means by which people form creative ideas (Ward & Finke, 1995). And studies of creativity in design suggest that creative solutions are more likely if several alternatives are explored (Cross, 1997).

This conception of design as moving through a space of possibilities using heuristic guides is the central theme in my approach. Within this research study, the solution of a design problem is viewed as a search through a "problem space" of possible designs that satisfy multiple constraints (Goel & Pirolli, 1992). In most design problems, this space of possible designs is never fully defined, and may include new features not previously applied to the problem, and not already identified as relevant. The key to creative solutions is characterized as the strategies that assist the designer in exploring new parts of this potential design space. What kinds of strategies lead to designs that are original, differing from past designs? How do these strategies influence the efficiency of the process and the quality of the solutions?

1.1.5. Designers' Cognitive Processes

What are the processes that lead successful designers to creative products? According to Boden (1990), three general types of creativity in design have been identified:

- *Combinational creativity*, in which new ideas arise from the unusual combination or association of familiar ideas.
- *Exploratory creativity*, which consists of applying search procedures within a defined conceptual space, as with scientific discovery models.
- *Transformational creativity*, where models are based on evolutionary techniques and include procedures for modifying parts of defined solutions.

Design researchers and cognitive scientists have further developed a variety of process models to account for creativity in design. These models are often based on observations of design processes in verbal protocols of experts solving design problems. Cross (2000) described a four-stage model of exploration, generation, evaluation, and communication. Benami and Jin (2002) introduced a cognitive model to capture interactions between cognitive processes, design entities, and design operations. French (1985) proposed a model that includes analysis of the problem, conceptual design, embodiment of schemes, and detailing (**Figure 1.1**).

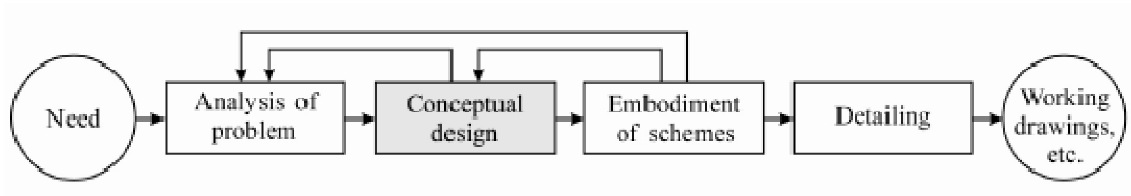


FIGURE 1.1. Model of the design process (French, 1985)

The first task in the design process is generally ‘analysis of the problem’, or clarification of the task. In order to analyze a problem, it is often necessary to go one step forward and generate design solutions as this will allow the designer to be engaged in the process further and redefine the problem according to his/her preferences. This indicates that designers learn about the problem as they generate solutions. Akin (2001) found that designers continue searching for alternative solutions through feedback loops even when they have already developed satisfactory design solutions.

In the a second stage, namely the ‘conceptual design stage’, designers generate broad solutions and, according to French (1985), it is at this point where many significant decisions are taken. This stage can be broken down into: (i) generate an idea, (ii) record the idea − e.g. through visual representations − and (iii) decide whether to continue to generate more ideas or explore the existing ones (Kolli & Pasman, 1993). It is estimated that 70% of a product’s cost is defined during conceptual design (Pahl & Beitz, 1996). Perhaps as a result, much research has investigated the cognitive processes that occur in the *idea generation* phase of design creation (Adams & Atman, 1999; Chan, 1990; Christiaans & Dorst, 1992; Dorst & Cross, 2001; Hybs & Gero, 1992; Kruger & Cross, 2001). The purpose of the concept generation phase is to conceive as many creative solutions as possible that fit the requirements defined by the design problem. By generating multiple alternatives, the designer can then select the best prospects for further development.

During the conceptual stage, past knowledge, described a “reproductive thinking” by Wertheimer (1959), often leads the designer down familiar paths. Rarely, creative ideas are begun from scratch, but they are often a mixture of old and new ideas (Ward & Finke, 1995). In some cases, the process leads to "functional fixedness," where familiar patterns block the generation of new ideas (Duncker, 1945). In studies with design students and professional designers, Jansson and Smith (1991) found that designers are sometimes trapped by the characteristics of a possible solution that has been developed, or by existing precedents. On the positive side, analogies to past experiences in design can also be sources for design solutions (Dahl & Moreau, 2002). Most engineering designs are adaptations or variations of existing design, or creations of new designs on the pattern of previous designs (Eckert, Stacey, & Clarkson, 2000). The case-based design approach (Kolodner, 1993; Schank, 1982) reminds designers of their previous experiences (also called "design precedents" (Pasman, 2003) and uses them as building blocks to modify for new situations (Ball, Ormerod, & Morley, 2004; Klein, 1998; Maher & Gomez de Silva Garza, 1997; Scott, Lonergan, & Mumford, 2005). Such tools can assist designers in making use of previously created designs in new problems (Cross & Cross, 1998).

There have been some descriptions of the varieties of ways that new ideas are generated. Finke et al. (1992) divided these creative processes into *generative* (analogical transfer, association, retrieval, and synthesis) and *exploratory* (contextual shifting, functional inference, and hypothesis testing). Shah et al. (2001) proposed a model of Design Thought Process involving brainstorming to describe generation and interpretation of ideas. Linsey et al. (2007; 2008) suggested a method for identifying analogies as part of the ideation process, and showed that memory representations influence the ability to use analogy to solve a design problem. Christensen and Schunn (2009) suggested studying the cues designers are using within creative cognitive processes to understand what leads to creative outcomes. They propose that, as a cue promotes one type of generative process, it may constrain another exploratory one. Alternatively, a cue might aid the cognitive process within the design domain, while hindering the information processing between domains. Therefore, a more detailed understanding of cognitive processes and their functions is needed.

The stage that follows conceptual design is the ‘embodiment of schemes ‘where selected design solutions are developed in greater detail. French points out that in most cases there is a great deal of feedback from this stage to the conceptual design stage making sometimes the boundaries between both stages not very clear. Once a concept design is generated and perceived, designers try to improve it by transforming the concept. According to Goel (1995), in the idea exploratory stages, two types of transformations can be identified: (1) lateral transformations that manipulate one idea into another one as a result of interpreting the first idea differently, and (2) vertical transformations that clarify lines and add detail to an idea. Finally, Jin and Chusilp (2005) identified repeated mental iterations of idea generation, followed by evaluation, as important features of cognitive processes during design. In these cognitive process models, the focus is on clarifying more general stages of thinking involved in the design process rather than identifying specific information involved in these steps.

The last stage of the design process is the ‘detailing stage’ in which more subtle, but no less important, changes such as shape features, as well as colors and textures of the product, are laid down.

1.1.6. Design Expertise

What differentiates experts from novices? Several decades of research in cognitive science have defined *expertise* as the skilled execution of highly practiced sequences of procedures (Ericsson, Charness, Feltovich, & Hoffman, 2006). For example, a violinist may use a variety of exercises to learn the vibrato technique, requiring extensive repetition, over many pieces of music and performances, until it can be executed automatically. By contrast, expert musical *composition* requires very different cognitive processes, including conscious reflection and introduction of variation that leads to unique, creative music. Because each composition is intentionally novel, there is no highly practiced skill that allows seamless composition in the same way as mastering the vibrato technique. Design expertise appears more similar to composition: While a skill like sketching may be automatic, the process of creating a new design is unlike executing a well-learned procedure. Instead, it is the intentional, deliberately considered introduction of variation, sometimes resulting in a creative solution.

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. Akin and Akin (1996) in their study with an experienced architect and a non-architect, found that the experiences architect possessed procedural knowledge to reduce fixation, where the novice did not, and was not able to generate anything other than a very conventional solution. They suggested that realizing a creative solution depends on simultaneously specifying a new set of frame of references that restructure the problem in such a way that the creative process is enhanced. Experts have better strategies, tend to use strategies that are better overall more often, are better able to select the circumstances to which a strategy best applies, and are better able to execute a given strategy (Schunn, McGregor, & Saner, 2005).

In studies of design, Ahmed et al. (2003) found clear differences between the behavior of novice and experienced engineers. They found that novices (graduates) used 'trial and error' techniques by 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 their multiple tentative proposed solutions before implementing them and making a final evaluation. Thus, unlike the novice designers, they generated multiple possible solutions to be considered as a group before moving on to more detailed design phases. Lloyd and Scott (1994) studied experienced engineering designers' protocols, and 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. So, becoming an expert is not just a matter of getting faster or more accurate. It is a matter of finding alternative ways of doing things in order to transform the way one operates. One of the key principles behind the development of high levels of skill seems to be the change from a conscious struggle to effortless, even automatic, performance (Lawson & Dorst, 2009).

Dorst and Cross (2001) 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 (1992) 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. (2008) 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.

In this research, my approach arises from the intuition that designers appear to generate questions and choose directions from within an internal dialogue, choosing to follow known strategies with or without conscious reflection. Observational studies of designers at various levels have demonstrated the use of such cognitive strategies (e.g. Adams & Atman, 1999). Other studies have identified some design strategies employed by expert designers in the product design process (e.g. Cross 2004; Kruger & Cross, 2006). For example, Kruger and Cross (2001) 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 as compared to designers using a problem-driven strategy, which consists of gathering data and identifying constraints to define the problem. However, little is known about these cognitive strategies, and whether their use leads to innovative designs. 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? How can such strategies be effectively taught in engineering design courses?

1.2. HEURISTICS

In **psychology**, research in decision making has shown that judgment applied under uncertainty often depends on simplified heuristics (Kahneman, Slovic, & Tversky, 1982). "Heuristic" here refers to experimental and especially trial-and-error methods serving as an aid to learning, discovery, or problem-solving. The modern scientific name "Heuristic" was coined by French philosopher Rene Descartes (1596-1650), and is based on the Greek word "heurisko", which roughly means "a discovery aid". A heuristic method is particularly used to rapidly arrive at a solution that is reasonably close to the best possible answer or 'optimal solution'. Thus, heuristics are also considered "rules of thumb" (Nisbett & Ross, 1982), educated guesses, intuitive judgments, or simply common sense. Cox (1987) defines heuristic competencies as reasoning processes that do not guarantee a solution or a useful transformation, but derive their validity from the usefulness of their results. These rules work well under most circumstances, but in certain cases lead to systematic cognitive biases. Heuristics identified by Tversky, Slovic, and Kahneman (1982) include:

- *Representativeness:* People tend to judge the probability of an event by finding a 'comparable known' event, and assume that the probabilities will be similar.
- *Availability:* People make a judgment based on what they can remember, rather than complete data. In particular, they use this for judging frequency or likelihood of events.
- *Anchoring and Adjustment:* People tend to rely heavily on, or "anchor" on one trait or piece of information when making decisions, and adjust from there.

Psychologists further identified *general purpose* (affect, availability, causality, fluency, similarity, and surprise) and *special purpose* (attribution substitution, outrage, prototype, recognition, choosing by liking, and choosing by default) heuristics (Gilovich, Griffin, & Kahneman, 2002).

In **computer science**, a heuristic is considered a technique designed to solve a problem that ignores whether the solution can be proven correct, and usually produces a good solution or solves a simpler problem that contains or intersects with the solution of the more complex problem. Heuristics are intended to gain computational performance or conceptual simplicity, potentially at the cost of accuracy or precision. Riel's (1996) "Object-Oriented Design Heuristics" describes 61 heuristics used by program developers includes this example:

> All data should be hidden within its class.
>
> - When a developer says "I need to make this piece of data public because…"
> - They should ask themselves "What is it that I'm trying to do with the data, and why doesn't the class perform that operation for me?"
>
> Users of a class must be dependent on its public interface, but a class should not be dependent on its users.

In **human-computer interaction**, heuristic evaluation is a usability-testing technique that identifies a design's usability problems so that they can be addressed in iterative design process. In heuristic evaluation, experts review the user interface, assessing its compliance to usability heuristics (broadly stated characteristics of a good user interface), and recording violating aspects. Some of the heuristics Nielsen (1993) listed in his book "Usability Engineering" are:

- *Speak the user's language* (Match between system and the real world)
- *Minimize user memory load* (Recognition rather than recall)
- *Consistency* (Consistency and standards)
- *Feedback* (Visibility of system status)
- *Clearly-marked exits* (User control and freedom)
- *Shortcuts* (Flexibility and efficiency of use)

In **engineering**, a heuristic is an experience-based method that can be an aid in solving process design problems, varying from size of equipment to operating conditions. Employing such heuristics can reduce the time it takes to solve problems, which may be very valuable. Because heuristics are fallible, it is important to understand their limitations. They are intended to work as aids to make quick estimates in preliminary process designs. Altshuller (1984) found that technical problems could be solved by utilizing principles previously used to solve similar problems in other inventive situations. For example, a “wearing problem” in the manufacture of an abrasive product and a “wearing problem” with the cutting edge of a back hoe bucket were both solved utilizing the principle of “segmentation”, which is summarized as dividing an object into independent parts and increasing the degree of an object’s sections. Some engineering heuristics (Altshuller, 1984) include:

- *Extraction:* extract the “disturbing” part or property from an object.
- *Universality:* an object can perform several different functions; therefore, other elements can be removed.
- *Pneumatic or Hydraulic Construction:* replace solid parts of an object with a gas or liquid. These parts can now use air or water for inflation, or use pneumatic cushions.

Across these disciplines, heuristics share a common definition: they are effective means for generating possible solutions when the end product cannot be formally derived, but requires a leap across problem dimensions, referred to by Newell and Simon (1972) as the "problem space" consisting of all potential solutions. This standard view of heuristics proposes that they constrain search (Kaplan & Simon, 1990), facilitating navigation by selecting operators to move within an existing problem space. Thus, heuristics are more general than operators because they serve as strategies for selection among operators, or "short cuts" to move to an acceptable solution.

1.2.1. Design Heuristics

Following Newell and Simon (1972), my approach is to consider the design process as occurring within a “design space” consisting of all possible designs. Some of these potential designs are easy to generate because they involve simple combinations of known features, or involve already-known elements. But a designer may never consider some features within this space, missing the opportunity to consider some solutions that don't come to mind during the idea generation process. An alternative process to assist in exploring the design space is the application of *design heuristics*. Specific design heuristics help the designer to explore the problem space of potential designs, leading to the generation of creative solutions. These cognitive strategies are applied to a design problem to take the designer to a different part of this space of potential design solutions. The key to generating innovative solutions, then, is successively applying different design heuristics that assist in generating novel candidate designs from within this potential design space.

I propose that designers employ cognitive heuristics in order to enhance the variety, quality, and creativity of potential designs they generate during the ideation stage. Design heuristics are transformational strategies that take a concept, and introduce intentional, systematic variation to produce a candidate design. 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. 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 by applying a heuristic. Each heuristic provides a starting point for transforming an existing concept, altering it to introduce variation, or defines variations among individual design elements. This view of the ideation stage involves applying multiple heuristics successively to identify a large set of candidate designs.

The broad objective of this research study is the development of design heuristics for idea generation that will increase the variety, creativity, and quality of designs. I attempt to identify and describe useful design heuristics at the level of transformations of form and function that can lead to systematic variation in current concepts, producing a more varied set of candidate designs. Rather than generalized principles and triggering questions typical in brainstorming sessions, this approach proposes heuristics that guide specific types of variations within a problem context. As a result, which heuristic may be useful depends upon the immediate problem context, so that there is no determinate heuristic that will lead to a definitive solution. A single heuristic can produce alternative designs depending on how it is applied, so that the same heuristic can be applied repeatedly.

For example, one design heuristic that can be used to introduce changes in a familiar form is, *Flipping*. Consider the example of designing a desktop accessory (**FIGURE 1.2** below). In a past design experience, I looked through a magazine of artistic designs for inspiration, and came across a flower vase that made use of circles with overlapping edges (**FIGURE 1.2B**). By expanding on this form, I created a drawing of circular shapes with one long end hanging from each circle, leading to the "J" shaped object in **FIGURE 1.2C**. Then, to add interest to the form, I "flipped" the larger, center piece to go in opposition to the aligned J shapes (**FIGURE 1.2D**).

The resulting office accessory is striking in the novelty of its design. Where did the novelty come from? In this experience, I identified a heuristic strategy to create innovation: Refine a form by "flipping" its design (or portions thereof) across an axis.

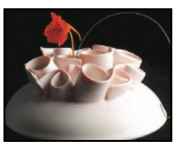


FIGURE 1.2A

Vase

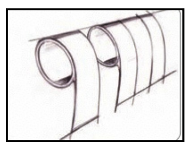


FIGURE 1.2B

Exaggerated form

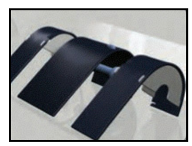


FIGURE 1.2C

Prototype

FIGURE 1.2D

"Flipped" final product

In this example, the innovation in design came from identifying a new area of the design space based on the transformation proposed by the heuristic.

How is a design heuristic applied to a candidate concept? The cognitive process occurs through the use of heuristics as "idea prompts," avoiding fixation on combinations of current design features by proposing alternative transformations to existing ideas (e.g., von Oech, 2003). Each heuristic varies according to the specified features required for its application, and in its potential adaptiveness for particular problems. Heuristic application is context-dependent in that there will be more than one way to apply a specific heuristic to a candidate form (for example, flipping upside down or from side to side). An even more challenging question is how the application of design heuristics is organized. There may be no general prioritized ordering of heuristics; instead, designers may recall and use heuristics based on specific cues or factors within the problem, such as needs of the user, or a specific functional requirement, such as needing a secure closure. For each problem, some heuristics are better than others, and some are not appropriate for a given design problem. Heuristics may contradict with each other (e.g., when there is a conflict between decreasing complexity and increasing flexibility), and relevant heuristics will often fail to be considered. However, following these cognitive strategies can prevent lingering in recombinations of already-considered elements. Instead, the design heuristics allow the designer to "jump" to a new part of a very broad problem space of potential solutions that may never have been considered without the use of design heuristics.

The power of design heuristics is that they result in a more varied set of potential design solutions. Though design heuristics do not guarantee the best solution, they help to reduce search time, and may guide the designer toward discovering more creative solutions. Design heuristics help to propose alternative designs not yet envisioned, and set up a new design space to search with new features to consider.

1.2.2. How Design Heuristics Differ From Other Methods

Although the importance of design heuristics is well recognized (Finke, et al., 1992), little is known about whether designers apply them, what the specific heuristics are, and how they affect the quality and creativity of the resulting design. Design heuristics differ from previous approaches to idea generation in design, but share the goal of providing "idea triggers" that can assist in creating concepts using simple prompts. Several competing heuristic theories, SCAMPER (Eberle, 1995), Synectics (Gordon, 1961), and TRIZ (Altshuller, 1984), include specific transformations such as substitution, rearranging, iterating, and eliminating. These three approaches appear to drastically differ, but upon closer evaluation, it can be seen that there are similarities among them. These proposed heuristics include a wide variety of methods and processes, and may be applied based on form, function, and context for the intended design.

Comparing these three heuristic approaches (SCAMPER, Synectics, and TRIZ), there are some clear differences and similarities. The SCAMPER approach defines seven general heuristics (substitute, combine, adapt, modify, put to other uses, eliminate, and rearrange/reverse). No specifics are given to guide the designer about how or when to apply them to a problem. For example, given a design problem like redesigning a hand soap dispenser, applying the heuristic, "modify," provides little direction for exploring potential redesigns. The Synectics framework combines more and different heuristics to address needs at different phases of ideation. The heuristics proposed in Synectics provide very general theme suggestions, including "parody, prevaricate, metamorphose, and mythologize." A designer utilizing Synectics may try to “animate” the can by applying human qualities, such as adding a smiley face to the same can. 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 mechanisms. These heuristics also focus on the in-context setting or meaning of the product, comparing it to markets and other similar products it may compete with.

Some of Synectics' idea "triggers" are very specific and concrete, while others offer broader, even very general theme suggestions in a style more similar 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. SCAMPER and Synectics both provide very broad heuristics at an abstract level, without much guidance about their application.

At the opposite extreme, the TRIZ heuristics were designed to address specific mechanical trade-offs in engineering design (Altshuller, 1984), and apply to very specified features of mechanical designs. The TRIZ heuristics were identified by examining successful U.S. Patent awards for common mechanical device improvements. 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 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 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 engineering mechanisms, the majority of the TRIZ heuristics do not overlap with Synectics or SCAMPER. They are focused on specific engineering mechanisms (such as pneumatics), parameters and related conflicts and trade-offs.

In contrast to these very general (SCAMPER and Synectics) and very specific (TRIZ) heuristics, perhaps there are more useful heuristics for creating new designs 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, but provide greater applicability than the specific alternations of TRIZ. One goal of the present study is to identify the heuristics employed by experienced industrial designers, and determine an appropriate level of description to characterize the usefulness of these heuristics.

Most importantly, there is no empirical evidence assessing the success of these three past approaches to the use of heuristics in design creation. A second goal of the present study is to demonstrate the natural occurrence of heuristics in design, and to test whether the intentional use of design heuristics does in fact lead to more, and more creative, designs.

1.3. RESEARCH AIMS

This research introduces a new approach to concept generation in industrial design. By examining successful, creative product concepts and sequences of sketches in experts' design process, I aim to identify useful design heuristics, and explore how their use might impact design pedagogy. The objective of the present research is thus: (1) to identify whether expert designers use design heuristics in the development of concept ideas, (2) to test whether design heuristics can provide more varied and creative designs, and (3) to provide directions for the use of design heuristics in education.

Design heuristics may prove to be useful in conceptual ideation by generating and exploring designs through a trial and error process. These research studies identify common heuristics among expert designers, and examine how heuristic use differ with the criteria defined in the design problem. In further studies, design heuristics are tested and validated with novice designers through controlled experiments. The aim is to show that design heuristics can be successfully taught, and that they do then result in more creative designs. Although design exploration is performed in many stages of the design process, this research focuses on the early stages where the exploration of ideas is central.

1.3.1. Study Motivation

This research seeks to impact the education and training of product designers. What process does a designer go through to result in a successful design? Little is known about how designers accomplish cognitive activities in this process, and which processes lead to more innovative designs. Learning to apply specific design heuristics during the design generation process may be a key feature of successful design. If so, it is a candidate for education and training for students in product design. This research on design heuristics can contribute to our understanding of the cognitive processes in design, and to the assessment of design ability. Ideally, the results will help to identify more effective instructional and computational tools to support designers at every level of expertise, and improve pedagogical approaches to teaching design.

1.3.2. Research Questions

The major question of this research is, "What are the cognitive heuristics used by designers in generating concepts?" Recognizing that the concept of design cognition is fairly broad, a specific focus has been selected for further investigation. The particular questions are:

> **Q1.** Do designers use cognitive heuristics in generating diverse concepts within the concept generation phase of product design process?
>
> **Q2.** Can heuristics be extracted from successful product designs and expert designers' design ideation processes?

Q3. How do heuristics vary with the context of the design problem?

Q4. Which design heuristics are most frequently used?

Q5. Do design heuristics lead to more successful and creative designs?

Q6. How can design heuristics be implemented as pedagogy, and how can they be effectively taught to novices?

Following these research questions, four main hypotheses will be tested:

H1. Designers access specific heuristics as part of generation process for creative solutions ***(Chapter 2, Chapter 3, and Chapter 4)***

H2. The usefulness of these heuristics depends on the nature of the design problems ***(Chapter 4, and Chapter 5)***

H3. More frequent and more diverse use of design heuristics leads to more creative designs ***(Chapter 3, Chapter 4, and Chapter 5)***

H4. Design heuristics can be taught to novices through simple instructional sessions ***(Chapter 5)***

1.3.3. THESIS OVERVIEW

This thesis is presented in three parts. Part One examines the heuristic use in the creative process of exploring designs, and then identifies the design heuristics extracted from three studies. Part Two presents the validation of a selected set of heuristics proposed in Part One in developing novel product concepts. Finally, in Part Three, the list of design heuristics is presented with their implications in design education and practice.

In order to tackle the research questions addressed, a variety of research methods are used in the studies. These studies are largely qualitative since the aim of the research is to gather an in-depth understanding of designers' behaviors and the heuristics that govern such behavior.

The thesis is organized as follows:

Part One

Evidence of Design Heuristics Use in Professional Practice

Chapter 2 examines the role of heuristics in design and presents a descriptive visual content analysis as the research methodology for studying a set of successful, award-winning products. Heuristics extraction methodology is discussed, a set of forty heuristics are identified, and how each criterion influences the heuristic use is explored.

Chapter 3 presents an empirical study resulting from a case study using an expert designer's design sketches for an entire project to investigate how an expert industrial designer approaches to a design problem and generate and explore designs. This case study provides insight into design heuristics employed during design exploration, and offers how design heuristics can be used as an interchangeable and combined method. This study improves the findings in the first study: heuristics extracted in Chapter 2 are used as the basis for the analysis, and another thirty heuristics are added from observations. This case study also reflects the concept generation phase in the real-world setting of a long term design project.

Chapter 4 focuses on heuristic use in two types of design problems: a novel and a redesign problem. The empirical studies included in this chapter explain the functioning of heuristics use in different contexts further. In addition to the design heuristics extracted from the first two studies, more heuristics are observed and they are classified according how they fit to each design task.

Part Two

Validation of Design Heuristics Use in Instruction

Chapter 5 includes a comprehensive study where the validation of heuristics was explored and qualitative and quantitative data were collected. While qualitative data gives insight about how novices utilize heuristics, strengthening the interpretation and illustrating findings, quantitative data helps generalizing and clarifying these findings. This study is designed as a prescriptive study testing the effects of heuristics on creativity, diversity and practicality of design concepts in twelve experimental conditions, and proposes a model of heuristic use in design pedagogy.

PART THREE

DESIGN HEURISTICS AND THEIR APPLICATION

CHAPTER 6 explains the design heuristics identified in detail, providing examples of how they are used, and proposing how they serve to generate alternative concepts in the design process. This chapter also shows how design spaces can be expanded, contracted, or displaced as design exploration advances through the use of design heuristics.

CHAPTER 7 includes general conclusions and outlines the contributions presented in the thesis. In addition, the implications for design pedagogy for heuristics are provided.

CHAPTER 2

HEURISTIC USE IN PRODUCT DESIGN

"WE CAN'T SOLVE PROBLEMS BY USING THE SAME KIND OF THINKING WE USED WHEN WE CREATED THEM."

ALBERT EINSTEIN

OVERVIEW

This chapter explores the use of design heuristics as cognitive strategies in the creation of innovative products. Design heuristics are extracted from award-winning, successful products using content analysis method, and a design heuristic methodology is proposed for the idea generation phase of the design process. This methodology provides designers with a set of heuristic principles demonstrated by designers and a process for applying them to create new designs.

2.1. INTRODUCTION

Designers want to satisfy consumer needs by integrating marketing, appearance, functionality, and engineering requirements into a product solution (Tovey, 1989). In order to meet these requirements, designers explore the design space from within a particular perspective that frames the problem, and stimulates 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, a ‘hierarchy of consumer needs’ (Jordan, 2000), the design setting, the resources (time) available, and the designer’s own goals. According to Goldschmidt (1995), the expert designer is able to structure a design problem through transformations, make long interrelated chains of moves (retrieve larger knowledge chunks from memory), and identify "clues" to good designs.

The aim of this chapter is to introduce a new approach to the creation of novel designs, that of successively applying different *design heuristics* that assist in generating novel candidate designs from within the potential design space. Current design theory lacks a systematic methodology to identify the strategies used in the creation of innovative products. This chapter presents the hypothesis that innovative products often reflect the application of design heuristics in the creative process. The study examines the designs of 400 award-winning products to identify heuristics through a content analysis of key features and functional elements. These heuristics are defined according to their perceived role in transforming each product idea into a novel design. This methodology generates both a set of heuristic principles demonstrated to be useful to designers and proposes a process by which they can be applied to create new designs.

The focus of this chapter is the ideation involved in generating innovative products: How do designers "play" within the space of possible designs to come up with novel ideas? The content analysis attempts to describe design heuristics at the level of transformations of form and function in the ideation phase that can introduce systematic variation in the set of candidate concepts. To investigate this hypothesis, I set out to identify how the designer might transform concepts in award-winning products. The resulting heuristics offer a means of generating possible designs by guiding specific types of variations within a problem context. But what are the heuristics that lead to creative designs? The heuristics evident in product designs that are judged to be successful by award competitions are investigated, and their content is analyzed to determine how the designers must have transformed initial ideas into their final, innovative concepts.

2.1.1. Extracting Heuristics from Products

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. The source of the example designs analyzed for this study includes:

- International Design Excellence Awards, 2009 (www.idsa.org) IDSA has been honoring design excellence via the IDEA Awards since 1980. The illustrations can be found in the http://www.idsa.org/IDEA_Awards/gallery/
- Red-Dot Product Design Awards, 2009 (www.red-dot.de) With more than 12,000 submissions from more than 60 countries, the international "red dot design award" is the largest and most renowned design competition in the world.
- iF Product Design Awards, 2008, (www.ifdesign.de) Since their introduction in the year 1953, the iF design awards, with an international expert jury, have been a reliable indicator of outstanding quality in design.
- Good Design Awards, 2008-2009 (http://www.g-mark.org/english/) Awarded by jury through the Japan Industrial Design Promotion Organization.
- National Design Awards, 2009, (www.nationaldesignawards.org) U.S. national awards initiated by the Smithsonian's Cooper-Hewitt, National Design Museum.
- Deconstructing Product Design: Exploring the Form, Function, Usability, Sustainability, and Commercial Success of 100 Amazing Products, by William Lidwell and Gerry Manacsa, Rockport Publishers (November 1, 2009)
- Design Secrets: Products, by Industrial Designers Society of America, Rockport Publishers (September 1, 2003)
- Design Secrets: Products 2: 50 Real-Life Product Design Projects Uncovered (v. 2), by Lynn Haller and Cheryl Dangel Cullen, Rockport Publishers (October 1, 2006)
- Process: 50 Product Designs from Concept to Manufacture, by Jennifer Hudson, Laurence King Publishers (May 1, 2008)

- 1000 New Eco Designs and Where to Find Them, by Rebecca Proctor, Laurence King Publishers (June 10, 2009)

The initial database of innovative product designs included hundreds of products from these sources. A detailed investigation was performed on approximately 400 products providing a variety of distinct designs. Major elements and key features of the products were scored for functionality, form, user-interaction, and physical state. 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. The descriptions of each heuristic were then defined. This heuristic extraction process is illustrated in **FIGURE 2.1**.

Select an award-winning product from the source list.	
Define its functions and key features of the product.	With a simple swivel, the chair turns from a highchair to an under-table chair. In its high position, it fits under the kitchen counter. In its low position, it lets toddlers sit at any standard-height table without a booster seat. While meeting the needs of secure seating for youngsters aged six months to six years, it also serves as a small desk chair for children aged four to six.
Hypothesize potential heuristic applications.	The designers possibly recognized consumer needs in flexibility of children's chair heights. They decided to double the function by using both the top and the bottom of the product for varying needs of different age groups. This double-functionality is accomplished by flipping the product on the Y axis. Adding the tray on one of the seats also increased the potential flexibility of the overall product.
Derive context-dependent design heuristic(s), as well as potential context-independent design heuristics.	<u>Design Heuristic 1</u>: Adjust the functions according to different demographic needs <u>Design Heuristic 2</u>: Provide multiple functions by using each side for only one function

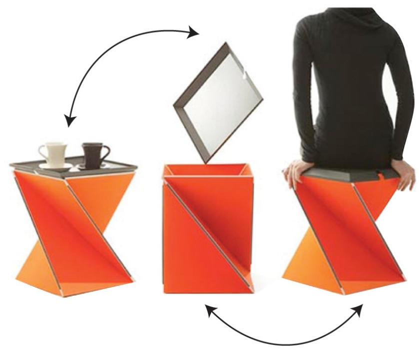
	Context-independent Design Heuristics: 1. "Flipping" around a pivot 2. Repeating design elements for different functions	
Identify design criteria used in the product.	Secure, comfortable, adjustable, multi-functional, and practical	
Select another product that shares the same criteria and uses the same heuristic(s)		
Describe how each similar product used the heuristic to identify different ways of implementation.	A secondary design element (the tabletop) is chosen for the durability of the form. Two different functions are assigned to this secondary element, and the functions differ when the component is "flipped" and placed back over the main structure to form a seating unit.	The form is split into four different functions (hammer, crow bar, board bender and splitter), which can be accessed by "flipping" the product from one direction to another.

FIGURE 2.1. Heuristic Extraction Process

Clearly, subjective interpretation is necessary to derive a potential heuristic from the description of a finished product. The data provided no intermediate steps from the design process, no competing concepts that were considered, and no process trace of the designer's work. However, the success of this extraction approach is not determined by whether the derived heuristic was in fact part of the process. 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.

2.1.2. DEFINING DESIGN HEURISTICS

The analysis of the 400 products resulted in 40 heuristics that facilitate the design process. At a general level, they can be organized as "content-independent heuristics," including *addition, removal, distortion, orientation*, and *substitution*. This list is similar to the general heuristics in previous approaches like Synectics and SCAMPER. However, heuristics described at this general level are problematic because they give little indication of whether they can be applied to a specific design problem, and how to apply them to an existing concept.

Through the content analysis, a more specific description of heuristics was identified -- "context-dependent heuristics" -- that provides a motivation for applying them, and may consequently make the heuristics more specialized and valuable as aids to design. For example, *Twisting forms to create a playful look* refers to distortion of the form. However, the reason for applying this heuristic is directly related to the design criteria in hand, which is the intended audience of children (in the product analyzed, designing a stool for a playground). The design heuristics vary in that as some add functionality, suggest use of fewer resources, save space, provide ideas about visual consistency, and form relationships among the design elements. These more specific heuristics go beyond general transformations to identify why a particular heuristic might be advantageous.

Consider these examples of the extraction of heuristics from the set of innovative products in the study:

HEURISTIC EXAMPLE A.

CONVERTING TWO-DIMENSIONAL MATERIALS INTO THREE-DIMENSIONAL PRODUCTS

Change an object's dimensions with a change in boundary conditions to produce different functional outcomes: Create an object by manipulating two-dimensional geometrical surfaces around an axis, or twisting in various directions in order to generate a three-dimensional product; changing or creating a curvature, or creating an inner surface by using sheet materials.

For example, **Figure 2.2A** shows a concept for a trash can that is made out of a recycled sheet plastic rolled around its center. Since it can be entirely flat, it also enhances the efficiency of transportation and storage. **Figure 2.2B** shows a light made out of sheet metal twisted around to give directional options for controlling light intensity.

Figure 2.2A & 2.2B. Example designs for heuristic example A

Heuristic Example B.

Using packaging as a functional component within the product

Embed the packaging within the product to perform a different function: Create a shell or cover for a component or the entire product using the package, and uncover it when it's used. In **Figure 2.3A**, a set of colored pencils is located inside a package that also serves as a stand during use. In **Figure 2.3B**, the lighting unit is packed so it is enclosed inside a wrapped form made out of the same material. When opened, the package supports the structure, and functions as a necessary shade component.

Figure 2.3A & 2.3B. Example designs for heuristic example B

Heuristic Example C.

Hiding / Collapsing / Flattening design elements when not in use by nesting elements inside each other

Place an object inside another entirely or partially, where the internal geometry of the one is similar to the other: One object is placed inside the other or one object passes through a cavity or interfaces with a cavity in another object. In **Figure 2.4A**, the lighting unit collapses when not in use on the cavity that is defined by the bottom support of the product. In **Figure 2.4B**, the container has several layers that are nested inside each other for storage when the product is not in use.

Figure 2.4A & 2.4B. Example designs for heuristic example C

Heuristic Example D.

Convert into modular units by repeating or splitting elements

Divide single continuous parts into two or more elements, or repeat the same design element multiple times, in order to generate modular units: The separation of continuous components creates independent parts that can then be reconfigured, and the repetition of a component can also assist in generating reconfigurations.

Product modules are distinct building blocks that combine to form machines, assemblies, or components that accomplish an overall function. In **Figure 2.5A**, the modules allow several combinations, offering flexibility and rapid adaptation to varying user needs. According to how the modules are set up, the product can be converted to a shelf, a table, or a closet. In **Figure 2.5B**, the user configures the gaming tower. Splitting the functions into independent modules also allows for an open structure where they are visible, and air flow is improved.

FIGURE 2.5A & 2.5B. Example designs for Heuristic Example D

HEURISTIC EXAMPLE E.

VISUALLY SEPARATE THE PRIMARY FUNCTIONS FROM THE SECONDARY FUNCTIONS

Create visual, hierarchical relationships among the functions within the product by changing the elements' dimensions, locations, colors, and materials: Visually emphasize which functions are most important to facilitate the ease of use by improving the interface.

In **FIGURE 2.6A**, even though the two attached forms look alike for visual consistency (similar form and color), the size differs to communicate the two different functions: medicine and drink container. In **FIGURE 2.6B**, the form and color again suggests two similar functions; however, the size difference in the forms emphasizes the different functions used in water flushing.

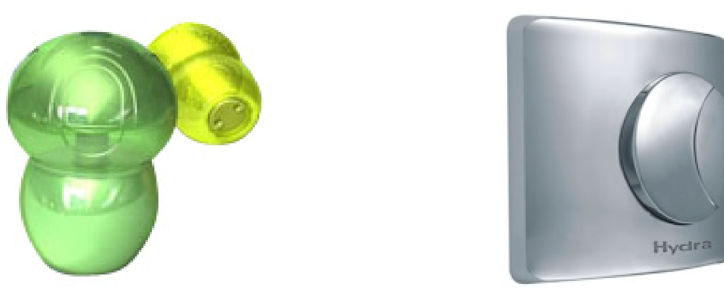


FIGURE 2.6A & 2.6B. Example designs for heuristic example E

Following these methods, a total of 40 distinct design heuristics were demonstrated and validated by observing multiple instances within the set of 400 products analyzed.

2.2. RESULTS

The results of the product design analysis include the following:

- Demonstration of a proposed methodology for identifying design heuristics
- A set of design heuristics used in innovative products
- Identification of their relationships with the criteria defined in the design problem
- Comparisons of multiple applications of these heuristics
- Demonstration of applying identified heuristics to new problems

2.2.1. DESIGN HEURISTICS IDENTIFIED

Each of the forty identified heuristics was identified in at least four different products of the 400 in the database. In some of the products, multiple heuristics were observed (this aspect of the research is not further reported here). **TABLE 2.1** presents the forty extracted design heuristics, and how many times each was observed within the 400 award-winning designs analyzed for the study. These heuristics differ based on the design problem, the context defined in the problem definition, and designers' preferences. Each heuristic requires specific features within the design problem in order to be applicable, and produces a changed concept altered in a specific fashion. As a result, which heuristic to use highly depends upon the immediate problem context? As implied by the use of "heuristic," there is no determinate heuristic that will lead to a definitive solution.

TABLE 2.1. Context-dependent heuristics identified in the product analysis

Design Heuristics	**Products Where Observed**
1) Remove the moving parts to minimize potential breakdowns.	24
2) Adjust functions according to different demographic needs.	23
3) Refocus on the core function of the product.	22
4) Apply an existing mechanism in a new way.	21
5) Adjust functions by moving the product's parts.	17
6) Reduce the amount of material needed for the same function.	16
7) Animate product using human features for an approachable look.	16
8) Change the context of where and how the product will be used.	14
9) Convert into modular units by repeating or splitting elements.	14
10) Implement characteristics from nature within the product.	14
11) Replace materials with recycled ones.	14
12) Change physical approaches to the system (from front to side)	13
13) Hide / Collapse / Flatten elements not in use by nesting elements.	13
14) Merge the functions that can use the same energy source.	13
15) Use human-power as the energy source.	13
16) Attach the product to an existing item as an additional component.	12
17) Make the individual parts attachable and detachable.	11
18) Minimize steps in use by creating a hierarchy of the features.	11
19) Convert two-dimensional materials into three-dimensional.	9
20) Visually separate primary functions from secondary functions.	9
21) Provide multiple functions by using different surfaces for each.	8
22) Replace limited-use parts with ones that can be used multiple times.	8

23) Replace solid material with flexible material for compactness.	8
24) Use an extension of the product surface for the handling function.	8
25) Provide sensory feedback to the user (tactile, verbal, visual, etc.).	7
26) Use same design element, color, graphics for visual consistency.	7
27) Use the outer surface space of the product for different functions.	7
28) Convert the packaging into a game after the product is removed.	6
29) Create systems for returning to manufacturer after life cycle ends.	6
30) Make the product expandable in order to fit various sizes.	6
31) Visually separate similar functions using size and color.	6
32) Add a portability feature to existing solutions.	5
33) Use a common base or the same surface for multiple functions.	5
34) Use packaging as a functional component within the product.	5
35) Express cultural values in the product.	5
36) Add motion to the product as a playful attribute (push/pull, etc.).	4
37) Cover the joints for visual consistency.	4
38) Design communal activities for users to unite as a community.	4
39) Include users in customizing or assembling the product.	4
40) Twist forms to create a more playful look.	4

According to IDSA (Industrial Designers Society of America), the judging process for the successful products is based on the following criteria:

(http://www.idsa.org/absolutenm/templates/?a=3917#JudgingCriteria)

1. Innovation (design, experience, manufacturing)
2. Benefit to the user (performance, comfort, safety, ease of use, user interface, ergonomics, universal function and access, quality of life, affordability)

3. Benefit to society and natural ecology (improves education, meets basic needs of low income populations, reduces disease, energy efficient, durable, uses materials and processes with low ecological impact throughout lifecycle, designed to be repaired/reused/recycled, addresses toxicity, source and waste reduction)
4. Benefit to the client (profitability, increased sales, brand reputation, employee morale)
5. Visual appeal and appropriate aesthetics
6. Usability testing, rigor, reliability
7. Internal factors and methods, implementation

Since creativity is a critical component of innovation, products selected were considered to be highly-creative, and the heuristics that were observed in those products were regarded as guiding principles leading designers to creative solutions. In the content analysis of the 400 products, designers seemed to use *Removing the moving parts to minimize potential breakdowns* and *Adjusting functions according to different demographic needs* most-commonly as heuristics to explore new solution spaces, suggesting that they were also effective in generating creative solutions. Removing the moving parts yielded simplified solutions which required the designers to think about different ways of keeping the function without using components that would suggest the additional feature. For example, in **FIGURE 2.7A**, the waste bin solves the problems seen in many other bins with a simple design without using any mechanisms for connecting the lid to the bin, yet keeping them connected.

For the product, Peter Haythornthwaite, IDSA, Principal, Creativelab comments:

> "Surprisingly simple, delightfully ingenious. This handsome, everyday product will cause users to pause, smile and ask 'Why didn't someone do this before?' Ease of use, purposefulness and well-considered form embodied in a minimal and original design."
>
> (http://www.idsa.org/IDEA_Awards/gallery/2008/award_details.asp?ID=649)

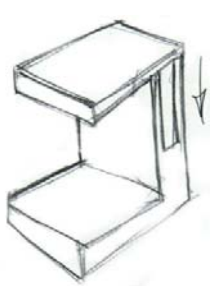
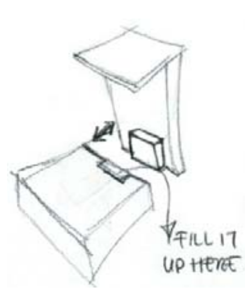
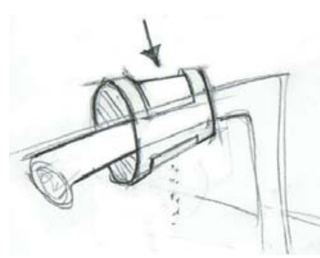
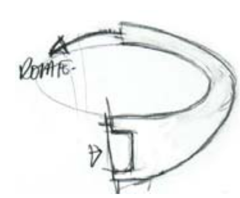
Figure 2.7A. Eva Solo Bin, with a lid balancing on the top edge of the bin without hinges or other mechanisms

Figure 2.7B. Copco Chopping Bowl, with a rocker knife and knob handle

In **Figure 2.7B**, the chopping knife is designed to act like a handle to fit any hand, while the blade of the rocker knife fits the interior curve of the bowl. Both of the products suggest a different approach to an existing problem defined by the designer which lead them apply specific heuristics, which eventually resulted in successful products.

2.2.2. A PROPOSED METHOD FOR USING DESIGN HEURISTICS

The purpose of identifying the heuristics in **Table 2.1** is to take advantage of them in the generation of new design concepts. In **Figure 2.8**, an example is presented to illustrate how a set of three different heuristics can affect the direction of the concepts generated.

Initial Concept	**H17:** Make the individual parts attachable-detachable	**H16:** Attach the product to an existing item as an additional component	**H1:** Remove the moving parts
			

Top part is nested inside the main structure which holds the soap. Soap is dispensed by a push-motion from the top. The central open space is used for hand placement.	The two parts are separated easily with a snap-on motion. The location for connecting the parts is also used as the opening to fill it with soap.	The product can be attached to the faucet through a sliding motion. This way the soap dispenser does not occupy additional surface space on the countertop. Soap comes out from the channels on the sides, and the product can be filled with soap from the top part, which also serves as the part users push to receive soap.	Soap is dispensed through the top of the tubing component by rotating the entire product around its center. The cavity on the bottom of the product is used for filling it with soap.

FIGURE 2.8. Illustration of three separate heuristics' application in generating concepts

This illustrated problem is to design a container that can dispense a specific volume of liquid hand soap. Beginning with the initial concept in the first column, three separate heuristics were selected from **TABLE 2.1** at random, and each was applied to the design, resulting in the concepts illustrated in **FIGURE 2.8**.

As the example in **FIGURE 2.8** demonstrates, each heuristic brings the designer to a new area in the space of possible designs. With each heuristic implementation, additional features are explored beyond the basic criteria defined in the problem. For example, in the above illustration, attaching the product on the faucet allowed the designer to consider alternate ways of using the space around the faucet. The criterion was redefined as the user interaction with the product was changed. On the other hand, this change brought up new questions to tackle, such as how it will be mounted, how the size will differ according to the varying types and sizes of faucets, how the faucet will be cleaned with the product attached, etc. The application of these three different heuristics produced three varied concepts for further consideration.

The presumed goal of the ideation stage in design is to generate as many varied concepts as possible in order to maximize the variety and novelty of candidate concepts for selection and refinement. The success of this heuristic analysis method in characterizing differences among candidate designs may assist designers by identifying heuristics that can be used to add to their concept sets. Further, the identification of heuristics and groups of heuristics may suggest ways for development of computational tools to assist in design. For example, the frequency of the heuristics applied could be analyzed in order to understand which of the heuristics are most commonly used, what kind of design problems they were applied to, what kind of new design spaces they generated, 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 experience with heuristic use and design in general.

2.3. Discussion

Which design heuristics can be shown to enhance innovation most effectively? And how can design strategies be effectively taught in engineering design courses? Pedagogy for enhancing design creativity is essential because most engineering problems demand innovative approaches in the design of products, equipments, and systems. Many design undergraduates are provided with general instructions about concept generation, and the importance of creativity in this stage of the design process. However, it is less common to teach specific cognitive strategies that may lead to generating more creative ideas. Rather than getting stuck in one concept, a designer can choose a heuristic, apply it to the current problem, and see where the resulting transformation leads. Using heuristics in design adds to one's ability to generate multiple creative concepts to consider.

Exposure to a variety of heuristics, and experience in applying them on many different problems, may lead to the development of expertise in innovation. For many design students, simply having an arsenal of design heuristics to try might lead to improvement in concepts generated. In fact, one factor may be motivational: it is possible that demonstrating the effectiveness of heuristics for creative tasks may, through feelings of efficacy, motivate creative efforts,. Improvement in the use of heuristics might be indicated by a growing level of complexity in the representations of the concepts proposed, indicating an understanding of the design heuristics and their application as idea-triggering strategies.

This study suggests that in design problems, making use of specific design heuristics may lead to more varied and creative solutions. Normally, when faced with a design problem, an appropriate heuristic is not obvious; rather, one is applied only if it can be accessed from memory. As an alternative, it is possible to learn a variety of design heuristics through engaging in instruction, providing a medium for learning when and how to apply them. Increasing sophistication of integrating and implementing these heuristics in design creation may demonstrate the gradual acquisition of knowledge about design heuristics and creative outcomes. The award-winning designs analyzed in this study, and further analyses, may reveal the design heuristics developed by innovative designers that may be useful to all practitioners of design.

The present study examined designs by over 400 different designers, and covering a very wide range of products. Will the use of design heuristics be as evident in the work of a single designer, working overtime on a set of product concepts, as design is more traditionally practiced? To examine this question, Chapter 3 presents a case study of an expert industrial designer by examining the series of concepts generated while working on a project for over a year. The goal is to explore how heuristics are used by this expert designer in generating a variety of conceptual designs for the same set of products, and to determine whether heuristics can be extracted from these concept sketches as well. The differences between the heuristics used for the wide variety of design problems seen in this study, as opposed to the heuristics preferred for a single project by a single designer over time, provides an opportunity to compare the use of design heuristics in these extreme cases.

CHAPTER 3

HEURISTICS USE IN CONCEPTUAL DESIGN

"NO AMOUNT OF RULES AND FACTS CAN CAPTURE THE KNOWLEDGE AN EXPERT HAS WHEN HE OR SHE HAS STORED EXPERIENCE OF THE ACTUAL OUTCOMES OF TENS OF THOUSANDS OF SITUATIONS."

DREYFUS AND DREYFUS

OVERVIEW

Chapter 2 identified design heuristics extracted from award-winning products. In this chapter, the role of heuristic use in the early stages of product design is examined through a case study of an expert industrial designer working on a single project over time. Sequences of exploratory concept sketches are analyzed in terms of the design heuristics using the same methodology established earlier. The variety of heuristics are validated, and expanded, by examining how they influence the mechanisms used to generate and explore concept designs.

3.1 INTRODUCTION

The result of the design activity is often expected to be original, adding value to the base of existing designs by solving technical problems in new ways. Diversity in concept generation provides multiple pathways that designers can pursue as they progress in design tasks, and thus concept generation can be considered successful if designers produce multiple pathways for exploration in later design phases.

Understanding both successful and unsuccessful concept generation is the key to developing strategies for improving design education and practice. Many studies in this research field have attempted to understand designers' reasoning. Some studies have simply interviewed designers and asked them to explain their design thinking (Cross, 2003; Lawson, 1994). In others, researchers have studied design thinking from case studies (Candy & Edmonds, 1996; Neiman, Do, & Gross, 1999). A more popular approach has been to observe designers while conducting a design task in a lab while recording their comments (Goel & Pirolli, 1992; Suwa & Tversky, 1997). While none of these techniques alone is able to reveal designer's reasoning, the sum of them contributes towards constructing a more accurate picture of the processes used in design exploration.

The majority of studies analyzing expert designers' behaviors focus on differences in external activities, such as the 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. Expertise consists of many different cognitive abilities. Lemaire and Siegler (1995) have proposed a four-layered account of expertise from a strategies perspective, which they've termed 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). This approach fits to design heuristics, but leaves open the main question: What heuristics do expert designers use to generate multiple, diverse design concepts? What heuristics are evident in their concepts? How do the heuristics impact design outcomes?

To investigate these questions, the process of a single expert designer was followed through his intentional steps in the design process, and specific strategies he used in design creation were identified. 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 this study. Koen (1991) suggests that a single heuristic is seldom used in isolation in design, and that one can overrule another within the given design problem. Are heuristics applied one at a time, or do multiple heuristics arise together? And do designers have a conscious awareness about the use these heuristics within their own thinking? Understanding these cognitive processes is not easy, but examining their external representations (e.g. sketches) during their design process may reveal aspects of their thinking processes.

In this thesis, I propose that designers utilize specific design heuristics to explore the space of potential designs, leading to the generation of novel and creative solutions. A drawback of relying on heuristics, however, is that they are considered to limit the scope of creativity. Design heuristics, in some sense, may be understood as design "rules," a recipe rather than a means to systemize and bring order to a design task. Uncovering how designers employ guiding principles as points of departure will help to explain the mechanisms used to generate and explore designs. While the guiding principles used in architecture are normally straightforward to identify, they are difficult to find in product design. This does not mean that the design process is less systematic and logical than in architecture, but it may suggest that product designers use different types of principles. One effective way to gain an understanding of how product designers use guiding principles to generate and explore designs is by examining their sequence of sketches.

The intent of this chapter is to identify design heuristics through a comprehensive analysis of an expert designer's ideation process over several months as a case study. Two hundred and eighteen sequentially-generated concepts were examined. Each concept was represented as a labeled drawing, and a retrospective protocol of the designer discussing his generation process for the first fifty sketches was collected. Three hypotheses are tested in this case study:

H1. Designers access specific heuristics as part of their process in order to generate creative solutions.

H2. More, and more diverse, use of design heuristics leads to more creative concepts.

H3. Designers have some conscious reflection about their use of design heuristics.

3.2. 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 design program 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, two hundred and eighteen 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.

Years after the project's completion, the designer was interviewed using the scroll record as an organizing structure. For the purpose of the interview, 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, which lasted approximately seventeen minutes, the designer was asked to talk about what he recalled about each of the fifty concept sketches while examining each of the sketches in sequence.

A set of potential heuristics were generated, shown in **TABLE 3.1**, following the method in Chapter 2. 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, *Adjust / Control functions by moving the product's parts*. 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, *Use a common element for a variety of functionalities*, encourages the approach of attempting to keep the element constant while making minimal changes to incorporate additional functions.

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 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 3.1** appeared in the transition from one concept to the next. Printouts of the sketches were provided, 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., 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.). In the coding, both the transition between the concepts and the transitions or changes depicted within each concept drawing were taken into consideration. For the coders, each heuristic was defined verbally, and written descriptions were provided for them to review as needed. Each of the 21 heuristics in **TABLE 3.1** was compared to each of the fifty sketches individually, and the coders identified which sketches included the heuristics through this method.

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 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.

3.3. Results of the First 50 Sketches

3.3.1. Examples of Local and Transitional 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, several examples of the concept sketches are provided from the designer's scroll, followed by the narrative the designer provided in the interview, and a description of how the cognitive heuristics appear within each sketch.

Figure 3.1A 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 3.1B**, 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 3.1A**; 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.

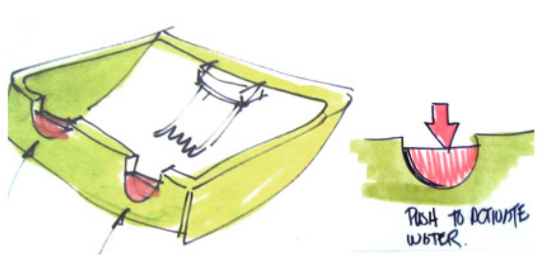


Figure 3.1A. Initial 'sink' concept

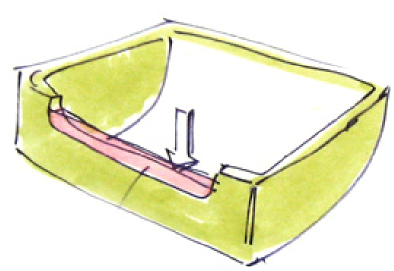


Figure 3.1B. Example using the heuristic *Simplifying the already existing, standard solution*

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

> **FIGURE 3.1A** and **3.1B** "… 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 3.2A** and **FIGURE 3.2B** 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.

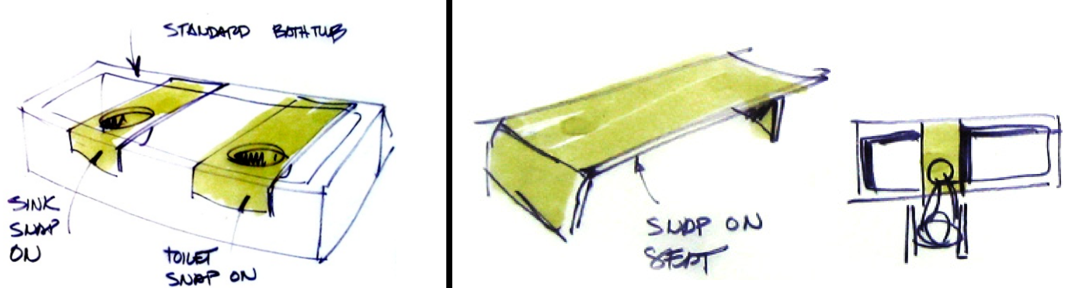


FIGURE 3.2A & 3.2B. Examples using the heuristic *Adding on, taking out, or folding away components when not in use*

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

> **FIGURE 3.2A & 3.2B** "… 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 3.3A** and **3.3B** "… shower, toilet, it is one piece; one piece molded and put in place. But then I'm thinking about swiveling."

Whereas **FIGURE 3.3A** shows stable, mounted features, the next concept **(FIGURE 3.3B)** 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.

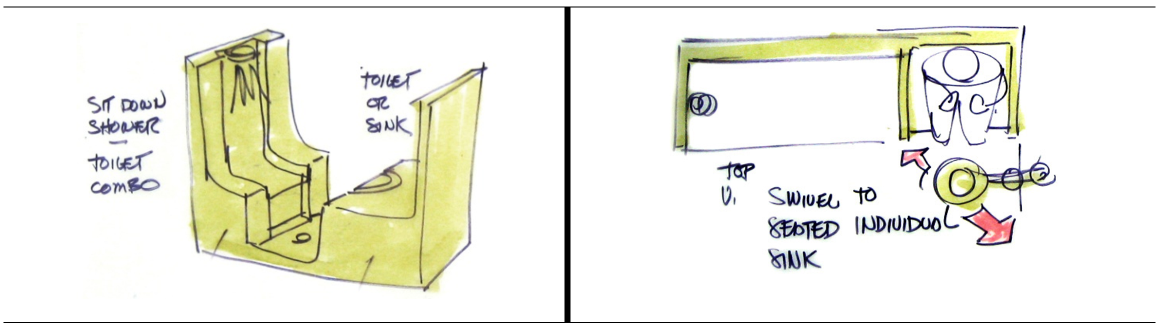


FIGURE 3.3A & 3.3B. Examples using the heuristic *Changing how the user physically interacts with the system*

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 3.4A** and **FIGURE 3.4B**. These principles of combined system design subsequently guided the designer's generation of the basic form and the detailed design features:

> **FIGURE 3.4A.** "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 3.4B.** "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.

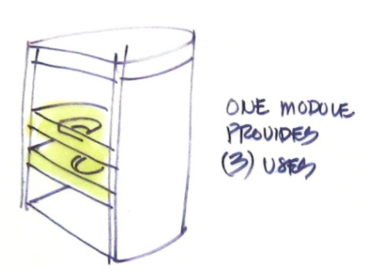


FIGURE 3.4A. Example using the heuristics *Repeating the same form multiple times*, and *Reversing the repeated forms for various functions*

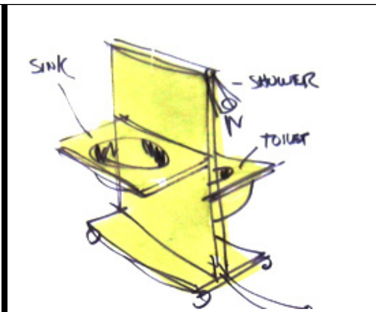


FIGURE 3.4B. Example using the heuristics *Repeating the same form multiple times*, and *Reversing the repeated forms for various functions*

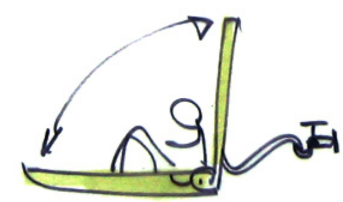


FIGURE 3.4C. Example using the heuristics *Repeating the same form multiple times*, and *Adding-on, taking-out, or folding away components when not in use*

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 3.4C**, where the designer considered a folding toilet. In the interview, for this concept, he commented:

> **FIGURE 3.4C.** "… 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 3.4C**, 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 the specific aspects observable in the concept sketches, and the clarity of observed changes in the design concepts. Next, a more formal analysis of the presence of heuristics identified in the design scroll is presented.

3.3.2. 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 this designer uses most when moving from one sketch to another in a sketch sequence, and to examine the patterns of heuristic use.

The observed counts of heuristics across the functional and structural categories are shown in **TABLE 3.1**. 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 related heuristic, *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 in his designs.

TABLE 3.1. Design Heuristics identified in sketches by coders

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 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 7.2, with a range from 2 to 15, showing that multiple heuristics were observed in almost all of the 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 3.3B**. 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 worked together to implement the concepts, and were observed occurring together repeatedly.

The set of concept sketches examined (50 in all) and the number of heuristics observed within each concept is shown in **FIGURE 3.5**. Eleven out of 50 sketches were scored as including ten or more heuristics, with 15 being the highest number observed within one sketch. 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" (Cross, 2004), and they were followed by numerous variations using them as the key concepts.

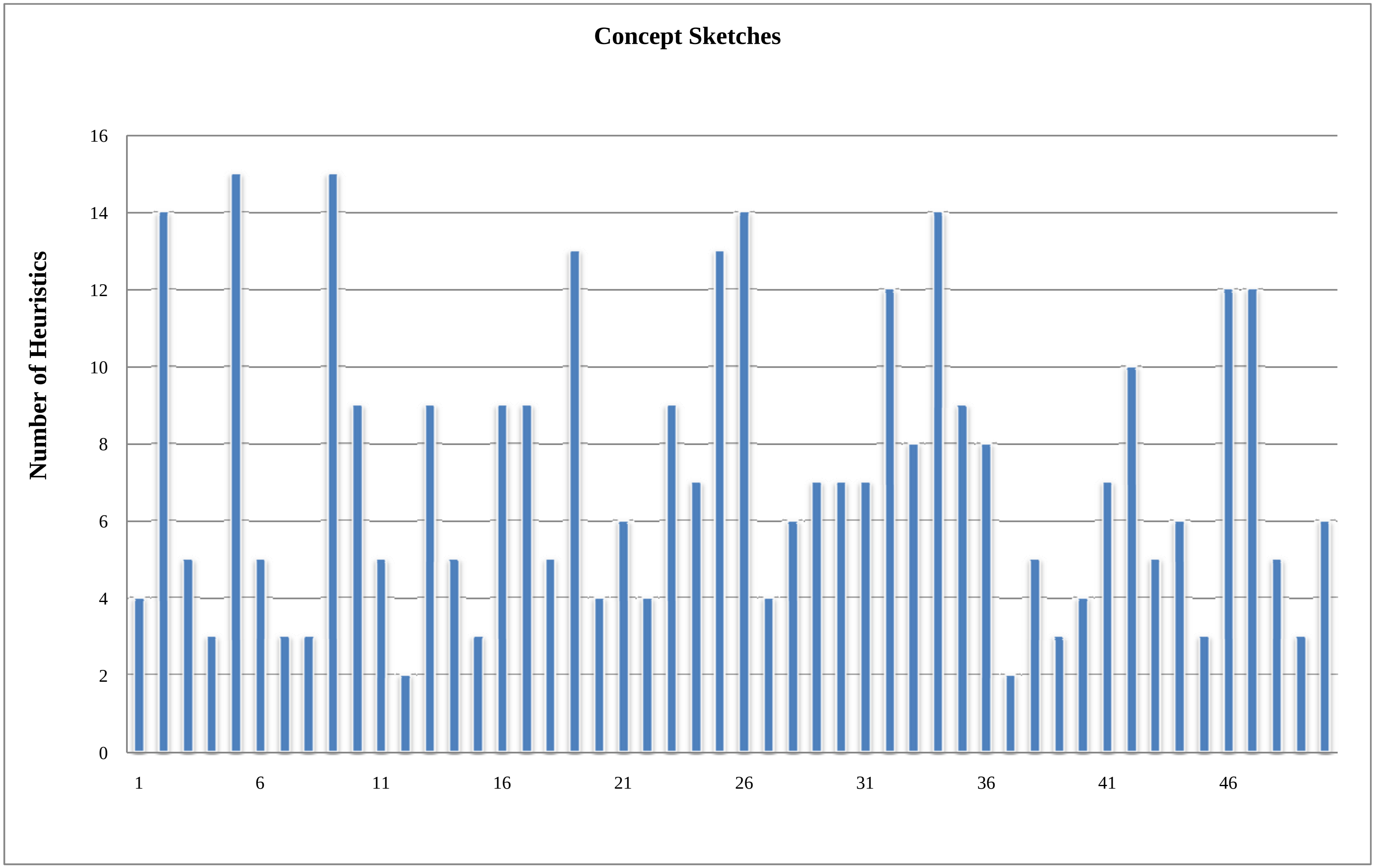


FIGURE 3.5. Frequency of differing heuristics used in each concept sketch

Quantitative analysis of heuristic use provides an account of the expert's design process in terms of the transformations taking place with 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, representing disparate areas of the "problem space" of possible designs. The success of this heuristic analysis method in characterizing differences among candidate designs may lead to schemes that assist in design evaluation, demonstrating when large variations in concepts occurred, and allowing the selection of concepts that may maximize the variety and novelty of candidates for further refinement.

3.4. Results of the Entire Set (210) of Sketches

After the outcome of the first fifty concepts showed evidence of heuristic use and relationships with creative design concepts, a second analysis was conducted including the entire set of concepts recorded on the same scroll. This larger set consisted of two hundred and eighteen sequential concepts and required an analysis taking place over multiple sessions. Since my own coding of heuristics within the first fifty concepts demonstrated extremely high reliability with the other two blind coders (IRR = .91), I personally coded the entire set of concepts individually. This method is selected due to the amount of time and effort required for coders given the size of the entire set.

3.4.1. 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. These solutions would be considered distinct in the design space. Criteria used to classify the content of designs are presented in **TABLE 3.2**.

TABLE 3.2. Types of solutions generated for the design problem

Diversity Criteria	**Examples**
Method of implementing multifunctionality	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

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 3.6A**). 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 3.6B**). These concepts achieve similar criteria (portability) 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 were not counted because they either repeated a previously drawn idea once again, or they had only minor changes to those ideas. In the analysis, the "entire set" of concepts refers to the total number of different concepts (210).

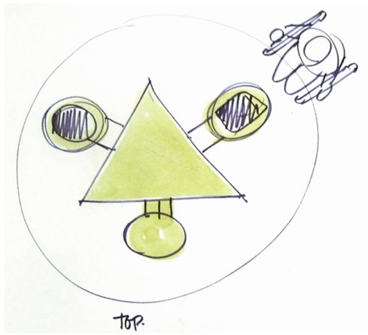


FIGURE 3.6A. Example of using a central base for aligning components

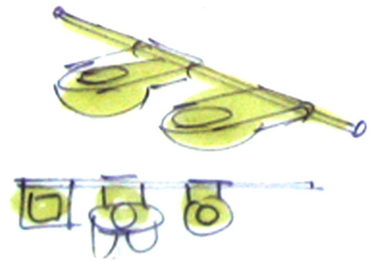


FIGURE 3.6B. Example of using a railing system for aligning components

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 transform 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.

Heuristics extracted from the first fifty concepts, along with and the forty heuristics observed from the product analysis (Chapter 2), were merged as the initial coding set for the entire set of concepts. Some of the heuristics coming from these two different sources were identical, some were similar, and some were considerably different. The goal of this analysis was to refine the design heuristics extracted from the two sources, code the two hundred and ten sketches according to the refined version, extract more heuristics observed in this larger set, and identify the patterns of heuristic use in the sequential concepts generated.

Analysis of the entire set of concepts revealed more than just additional heuristics. They also depicted the designer’s overall design practice in a broader sense. This analysis led to a further distinction of heuristics according to whether they were used throughout the process, within a concept, or for improving and building upon previous sketches. Three different heuristic types were identified in this content analysis:

1. *Process Heuristics:* These represent a designer's general approach throughout the idea generation process, and are used to initially propose ideas by directing the designer's overall approach through the solutions space; for example, "Changing the context to give rise to new aspects of the product."
2. *Local Heuristics:* These assist the designer in initiating a concept by defining relationships of design elements within each concept. They provide and characterize detail within a concept; for example, "Adjusting function by moving the product's parts."
3. *Transitional Heuristics:* These introduce intentional, systematic variation to produce a candidate design from a previous idea. They provide a way to transform an existing concept into a new concept; for example, "Substituting an alternate form."

The results of the content analysis are presented based on these three types of heuristic categories.

3.4.2. PROCESS HEURISTICS

Some observed design heuristics appeared to be strategic choices the designer made repeatedly in order to force changes in direction, such as, *Assigning a context, or changing it*. In this sense, *process heuristics* 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 to develop different approaches to the design problem.

Process heuristics were not clearly identified within the analysis of the first fifty concepts of the designer's scroll; however, when the complete set was analyzed, they represented a recurring pattern. For example, the designer used the *Brainwriting* heuristic 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 3.3** with their descriptions.

TABLE 3.3. 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

Another process heuristic observed was *Redrawing earlier concepts.* In order to remember where he left in the ideation phase, and/or to investigate the previously 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 *Switching 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 bath tub.

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, and when he needed the privacy, he could use the privacy curtain that would give an entire 360 degree coverage (**FIGURE 3.7A**). 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 the different features by simply going forwards and backwards on the same surface (**FIGURE 3.7B)**.

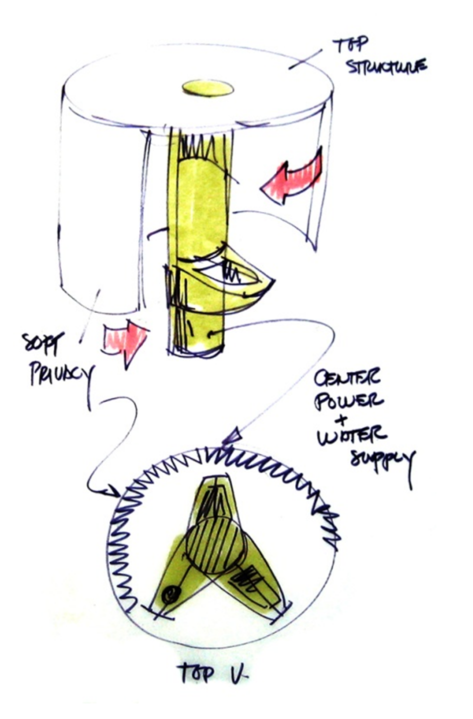


FIGURE 3.7A. Example of a system created by synthesizing concepts

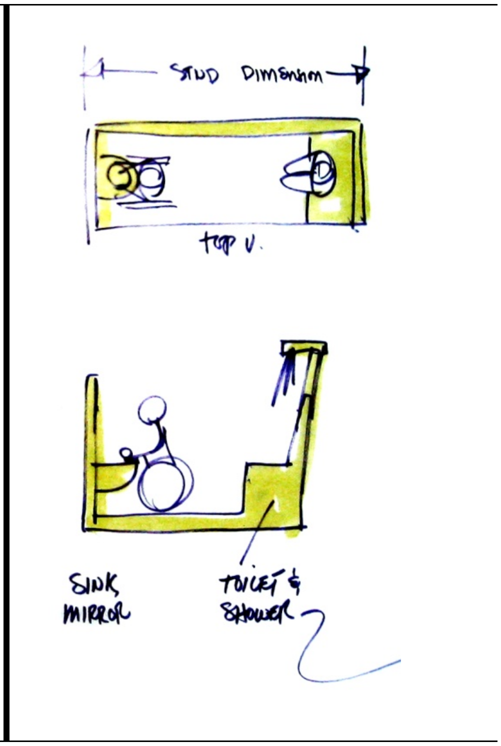


FIGURE 3.7B. Example of a system focusing on the needs of people with wheelchairs

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 '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 concept locations, 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 session heuristics are ones that are important tools to learn. It may be that these occur more often in highly expert design sessions.

3.4.3. Local and Transitional Heuristics

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. A second type of design heuristic observed is called a *local heuristic*, 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 related concepts. With the application of local and transitional heuristics, one is actively and dynamically constructing new solutions. A transitional heuristic provides a starting point for transforming an existing concept, and a local heuristic has the potential to produce a variety of designs within a single concept. This view of the ideation stage includes successively applying multiple heuristics to generate a large set of candidate designs.

Table 3.4. Local (LH) and Transitional (TH) Heuristics identified in the content analysis of the entire set of 210 sequential sketches generated by the designer

Local and Transitional Design Heuristics Observed		LH	TH
1	Attach independent functional components within the product	145	6
2	Change where or how product will be used	135	7
3	Vary physical directions for product approach	118	6
4	Reverse direction or angle of component for each function	93	30
5	Control / change in function through movement	76	2
6	Use a common base or railing to hold multiple components	73	8
7	Apply an existing mechanism in a new way	64	2
8	Create modular units by using repeat, substitute, or split	64	6
9	Redesign components to add on, fold in, take out	57	0
10	Use the same surface area for multiple functions	56	7

11	Make components attachable and detachable	54	13
12	Use a common component for multiple functions	54	1
13	Adjust functions to needs of differing demographic	50	2
14	Attach the product to an existing item as an additional component	49	7
15	Add portability	40	2
16	Refocus on the core function of the product	37	2
17	Nest (Hide / Collapse / Flatten) elements within each other	32	0
18	Elevate or lower product base	31	0
19	Hollow out inner space for added component placement	31	1
20	Split or divide surfaces into components	31	7
21	Unify elements, color, and graphics for cost and consistency	31	1
22	Flip the direction of orientation (e.g., vertical to horizontal)	28	13
23	Extend surface area for more functions	28	7
24	Rotate on a pivot axis	26	6
25	Fold product parts with hinges, bends, or creases to condense size	25	4
26	Offer optional components and adjustable features	25	2
27	Align components around a central, main function	22	2
28	Use the same material all throughout the product	22	0
29	Scale size up or down	21	7
30	Cover / Form Shell / Wrap surface for other use	18	5
31	Return sensory feedback to the user (tactile, audio, visual)	18	1
32	Bend into angular or rounded curves	16	0
33	Visually separate similar functions using size and/or color	16	1
34	Remove product parts to increase fit during use	16	3
35	Slide components across product surface	14	4

36	Change the geometrical form (circle, triangle, cylinder, etc.)	12	12
37	Compartmentalize functions into distinct parts	12	1
38	Replace solid material with flexible material	12	3
39	Substitute / Swap an old component with a new design	10	3
40	Reduce the amount of material needed for the same function	9	0
41	Change the surface material at points of human contact	8	3
42	Compress product surface to create controller	8	1
43	Convert two-dimensional materials into three-dimensional	8	1
44	Transfer or convert to another function	8	0
45	Use an environmental feature as part of the product	8	0
46	Mirror shapes for symmetry	7	0
47	Merge functions that can use the same energy source	6	0
48	Visually separate primary functions from secondary functions	6	0
49	Replace materials with recycled and/or recyclable ones	5	0
50	Replace limited-use parts with multiple use ones	4	1
51	Use the same surface area of the product for different functions	4	0
52	Flatten product surface	3	1
53	Add gradations or transitions to use	3	3
54	Stack components	2	0
55	Make the product expandable to fit various sizes	1	0
56	Roll product around a pivot point	1	0
	TOTAL	**1752**	**194**

TABLE 3.4 presents the local and transitional heuristics evident in the concepts generated by the expert designer, and how many times they were observed across the 210 concepts. 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.

In sum, local and transitional heuristics were identified 1946 times (local heuristics=1752, and transitional heuristics=194) in the 210 different concepts on the scroll. This case study certainly demonstrates that design heuristics (both local and transitional) do occur, in great numbers, in the work of an expert industrial designer. The total number of local heuristics per concept ranged from 1 to 18, and in most of the concepts (208 of 210), multiple heuristics were observed.

Some heuristics were observed very frequently, and as both transitional and local heuristics. For example, *Reverse direction or angle of component for each function* (number 4), and *Make components attachable and detachable* (number 11) occurred frequently across concepts. In **FIGURE 3.8A,** 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) were located on the reverse direction of each 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 3.8B**, 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.

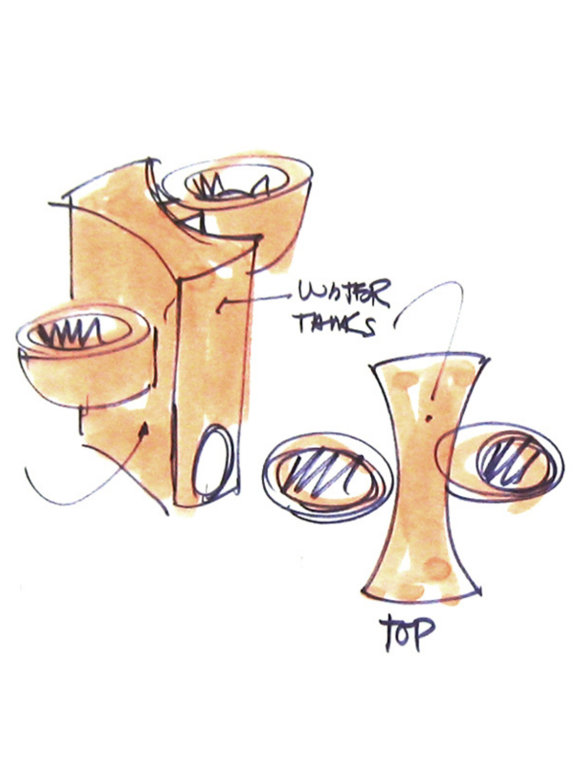


FIGURE 3.8A. Example using *Reverse direction or angle of component for each function* as a local heuristic

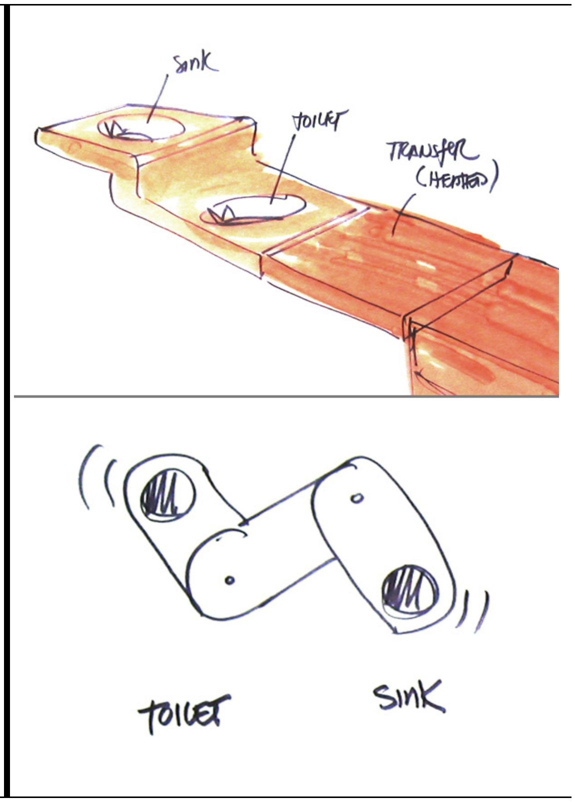


FIGURE 3.8B. Example using *Reverse direction or angle of component for each function* as a transitional heuristic

The most common heuristics were *Attach independent functional components within the product* (69% of the concepts in the set), *Change where or how product will be used* (64% of the set), and *Vary physical directions for product approach* (56% of the set). These choices reflect the context of the problem (fitting many specialized 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.

When looked at the overall coding of heuristics, each concept that had an application of 15 or more heuristics used these three heuristics. This may tell that these heuristics were used by the designer in a combined manner, complimenting each other for the success of same concept. Concepts with fifteen or more diverse heuristics applied were also the ones with major changes in the concepts generated. For example, in **FIGURE 3.9A**, the designer used 17 diverse heuristics, such as *Elevating or lowering product base*, and *Creating 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 this concept 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 3.9B** also used 17 diverse heuristics and regarded as another major shift in the concept generation as there were another set of concepts further developed this idea and generated new concepts. 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.

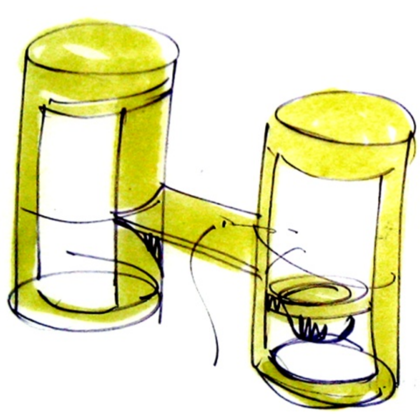


FIGURE 3.9A. Twin tower modules using the central component as a transferring unit between the two

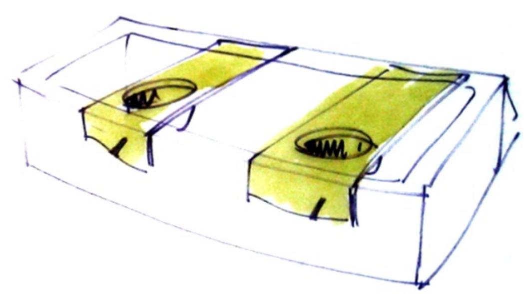


FIGURE 3.9B. Snap-on components attached to standard bathtub and used for different functions

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 installation compared to the portable products in Chapter 2. 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 the function of this design problem. Another rarely used 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 these heuristics 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.

Diversity in concept generation phase of the design process is mostly achieved by bringing a range of variables to the design task and redefining the problem with each variable. 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 3.10A** reveals that he incorporated a sliding shower; 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 3.10B**), 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 a structure using a vertical body and multiple functions attached to it with an additional separate seating element.

In a third variation (**FIGURE 3.10C**), 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. Heuristics observed in this concept also changes, for example, *Offer optional components and adjustable features*, and *Change product orientation for each function* were the heuristics defining the concept.

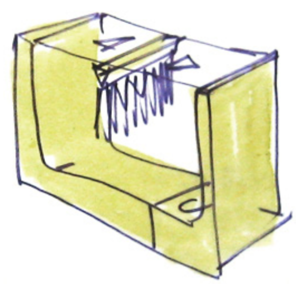


FIGURE 3.10A. Example using *Slide components across product surface*, and *Control / Change in function through movement* for a diverse solution

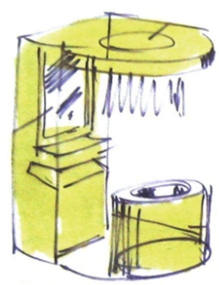


FIGURE 3.10B. Example using *Change the direction of orientation*, and *Use a common base or railing system to hold multiple components* for a diverse solution

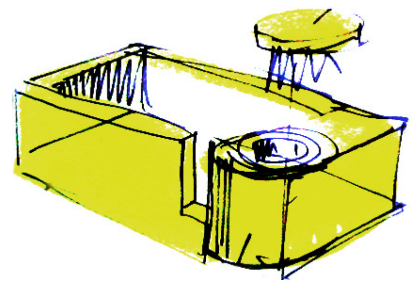


FIGURE 3.10C. Example using *Offer optional components and adjustable features*, and *Change product orientation for each function* for a diverse solution

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.

The local and transitional heuristics identified in this study were fairly consistent with engineers' and industrial designers' heuristic use in a different design task (Yilmaz, Daly, Seifert, & Gonzalez, 2010). Similarly, there was a great deal of overlap in the heuristics observed in this study and those identified in the product analysis in Chapter 2. Most (27 of 40) heuristics identified in the study described in Chapter 2 were also observed in this case study. This suggests that the types of heuristics used may not differ based on the design problem; however, the frequency of their use, and which ones are primarily observed, may depend upon the design problem, and the specific designer. Heuristics from the product study that were not observed in this case study were ones more useful in the later stages of the design process, such as, *Covering joints for safety and visual consistency.* Other ones not observed may not fit the present design task (e.g., *Creating a recycling system for returning to manufacturer*). Heuristics from Chapter 2 that were not observed in this case study are shown in **TABLE 3.5**.

TABLE 3.5. Local Heuristics not observed in the entire set of 210 sequential sketches

1	Add features from nature to the product
2	Animate look by using human features
3	Convert leftover packaging for another use
4	Cover joints for safety and visual consistency
5	Create a hierarchy of features to minimize steps
6	Create recycling system for returning to manufacturer
7	Design user activities to unite as a community
8	Expose / Uncover internal components
9	Express users' cultural values in the product
10	Include users in customizing or assembling the product
11	Telescope long components to reduce size when not in use
12	Twist geometric forms to add variation
13	Use human-generated power as energy

3.5 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 as described 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, called *transitional heuristic* use. From the sketches, it is clear that one important aspect of this design process was to revisit functions and/or arrangements adopted in previous concepts, and to abstract them out of the particular contexts of previous sketches to apply them within a new design. Past research on approaches like case-based reasoning (Kolodner, 1993; Maher & Gomez de Silva Garza, 1997; Watson & Marir, 1994) emphasize the reuse of prior designs; however, the reuse observed here seemed to emphasize selected elements rather than more complete design reuse. This suggests a "generate and test" approach, where heuristics were used to explore potential variations of existing designs, and those variations extended into further 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. If these patterns of heuristic use are observed across designs by this expert, they may reflect this designer's unique pattern in concept generation. Potentially, other experts observed may have developed different patterns of heuristic groupings. Alternatively, perhaps the heuristics fall into natural categories that many designers learn through experiences with design. Design expertise may follow a developmental sequence, from learning individual heuristics, becoming skilled in their application, to eventually developing 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 process, and did not readily name the variety of heuristics demonstrated in the concept sketches. 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. For the expert, looking at the scroll of his own designs might lead to recognition of skilled elements; however, there may be little conscious reflection on that 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.

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 design sketches produced within a professional project taking place over a long 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 use of design problems and solutions created by experts without requiring a controlled scientific study through the use of archival data recorded by the designer as part of his own work process. This method allows the study of the design process of professional designers taking place natural settings.

CHAPTER 4

HEURISTICS USE IN DIFFERENT DESIGN TASKS

"I HAVE YET TO SEE ANY PROBLEM, HOWEVER, COMPLICATED, WHICH, WHEN YOU LOOKED AT IT IN THE RIGHT WAY DID NOT BECOME STILL MORE COMPLICATED."

PAUL ANDERSON

OVERVIEW

Chapter 2 and Chapter 3 identified a set of design heuristics that were demonstrated to be useful in creating innovative products and novel concepts. In this chapter, sequences of exploratory design sketches produced by industrial designers, against two different task specifications, are analyzed for the design heuristics previously identified. The results show that the heuristic set used in varied design tasks do not differ considerably, suggesting that the heuristic use may not be context-dependent.

4.1. INTRODUCTION

Most design tasks include a mixture of problems to solve. For example, a design task might call for a new consumer product that will toast, butter, and serve a slice of bread on a plate. Since this is a new product, there will be a lot of conceptual design work upfront. However, it will also be necessary to configure the various parts, convert conceptual ideas into design elements, analyze heat conduction for toasting, (which will require parametric design), select a heating element, and select various fasteners to hold the components together. Furthermore, it may be possible to redesign existing products to fit some needs for this new product. In addition, styling for the individual components and the overall look of the product is required. Each of these subtasks can be considered a different type of design problem.

Throughout design research, categorizing the different tasks within design has proven to be useful for both analysis and the construction of tools, methods and techniques. Numerous researchers from the field of engineering design have identified different design outputs (Gero, 2001; Ullman, 1992). For example, Pahl and Beitz (1996) detailed three primary classes of design:

- *Original Design:* An original solution principle for a system with the same, a similar or a new task.
- *Adaptive Design:* Adapting a known solution principle to satisfy a new or changed task.
- *Variant Design:* Varying the certain aspects of the system, leaving the function and solution principle unchanged.

Ottosson (2001) states that for a product to be new, it must have 60% of new or redesigned technical parts, and from a marketing point of view, it needs to be considered new to the market. Design outputs can be defined based upon the initial problem or activity perspective (Ullman, 1992). This suggests that the designers begin their work with a notion that the eventual product will be either innovative, adaptive, or to order, and thus, perform the appropriate activity to accomplish these tasks. While these different design types appear to vary in their levels of creativity, they do not explicitly distinguish what is a creative or novel design from what is a routine or redesign. That is, a "variant design" could also be considered among the most innovative.

"Routine (redesign) design," according Gero (2001), is defined as having the necessary knowledge available for the design problem. In addition, routine design operates within a context that constrains the available ranges of the values for the variables through good design practice. Non-routine (novel) design, on the other hand, brings unexpected values to the design process and the artifacts designed because the problem specifics are not limiting, and allow designers to explore the criteria further.

How is the use of design heuristics affected by the level of constraints provided within a design task? Would a new design problem result in more use of design heuristics than the redesign of a familiar product? If the use of design heuristics relates to the creativity of the set of concepts generated, does the task definition play any role? In order to discover how designers' preferences in using heuristics may change between Redesign and Novel Design problems, two empirical studies were conducted. This chapter presents six designers' sequences of sketches generated in two differing design tasks. The goal is to examine whether and how the design problem affects the heuristics used to generate novel concepts and transform one concept into another in the design exploration process.

4.2. Experimental Design

One of the most-commonly used methods in studying designers' cognitive activities is think-aloud protocols, where designers are observed while completing a design task and talking aloud throughout their work, conducted in a controlled setting (Goel, 1995; Suwa & Tversky, 1997). The think-aloud method (Ericsson & Simon, 1993) was selected for this study because of the advantage of the sequence of information that can be revealed without altering cognitive processes. Lloyd et al. (1995) point out that the disadvantages with this technique: It can result in verbalization that is not a reflection of design behavior, and verbalization may affect the designing task. In fact, Lloyd et al. add that if designers could say what they were attempting to do, they wouldn't have to sketch it. In order to minimize these disadvantages, researchers have employed methods of retrospective reporting where participants, while watching a tape recording of their own sketching session, are asked to remember and report what they were thinking as they worked (e.g. Suwa & Tversky, 1997). This method also requires the designers to work in controlled conditions, such as having restricted access to external sources and limited time.

Atman and Bursic (1998) noted that researchers have effectively used verbal protocol studies to identify how designers introduce information or knowledge into the design process. These studies demonstrated that participants who verbalized concurrently with a task could provide information that did not change the nature of their thinking. Thus, it is assumed that mental processes such as retrieval from memory, computations, logical conclusions, summarization, etc., were not altered when the subjects were asked to verbalize their thinking as they worked on the design task. Consequently, this talk-aloud while sketching, controlled task procedure was selected to study the role of heuristics in two different types of design tasks.

In the present study, six industrial designers with professional experience ranging between two and five years participated. All of the designers' protocols were recorded, and analyzed for their heuristic use. Three of the designers generated concepts for a Redesign Task, and three other designers worked on a Novel Design Task for a novel product. Another difference between the two groups was the time constraint: Participants in the first group were given ten minutes, whereas participants in the second group had thirty minutes. This time difference was reasonable because more time was required for the novel task, since the constraints were left vague for the problem. The purpose of this study is not comparing the number or quality of concepts generated, but to compare the use of design heuristics in these two, intentionally varied design tasks, as might occur in real-life experiences of designers given differing time frames.

Therefore, for both groups of designers, the hypothesis was that the application of design heuristics in the creative process would enhance the diversity, quality, and creativity of potential designs generated during the ideation stage. It is proposed that specific design heuristics would help designers explore the problem space of potential designs, leading to the generation of creative solutions. The candidate set of heuristics included those identified in the product analysis (Chapter 2) and expert scroll analysis (Chapter 3). These six new participants were expected to have learned how to generate concepts for vaguely defined design problems, and should exhibit creative and diverse design behavior due to their training and experience in industrial design. The questions addressed in this chapter are: What heuristics lead designers to novel concepts? Do they differ between the two types (novel vs. redesign) of design problems? And if so, how can these heuristics be transferred between the tasks?

4.2.1. THE TASKS

The first data set (Park, Yilmaz, & Kim, 2008) utilized a Redesign Task. The data included three designers' sketching processes on the same task for approximately ten minutes. The design problem statement is presented in **FIGURE 4.1**.

In this task you are asked to devise a design for a new lemon squeezer. Your 'client' is a kitchen appliances manufacturer who wants to introduce a lemon squeezer into their range of products. The company has a reputation for manufacturing simple and effective designs. The outcome from the meeting between the design and management departments was the lemon squeezer concept shown below. As this is only a conceptual design it needs to be completed. You are asked to use this concept design and make it a real design proposal. Since the lemon squeezer only works manually you should not consider using any electrical motors in the design. In order to make an effective design, the new gadget should separate pips and pulp from the juice.

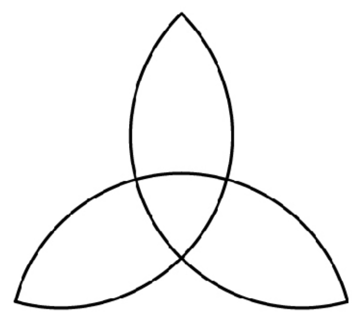


FIGURE 4.1. Redesign task

Three industrial designers were introduced to the triquetra figure as a concept design for a lemon squeezer, and asked to make it a real design proposal in ten minutes for a company that has a reputation for simple and effective designs. The main constraints for the final concept were "manual control" and "separation of pips and pulp from the juice." The design task performed by the participants was recorded on video. While sketching, designers made use of an A4 paper-based digital notepad, and this gave the dual advantage of resembling a traditional pencil-and-paper environment while facilitating the recording of pen strokes via screen capture software. A snapshot example of one of the participants' videos can be seen in **FIGURE 4.2**. The extended version of this data set, subsequently, was used in a different study with a broader perspective concerning how design shapes are generated and explored by means of sketching (Prats, Lim, Jowers, Garner, & Chase, 2009).

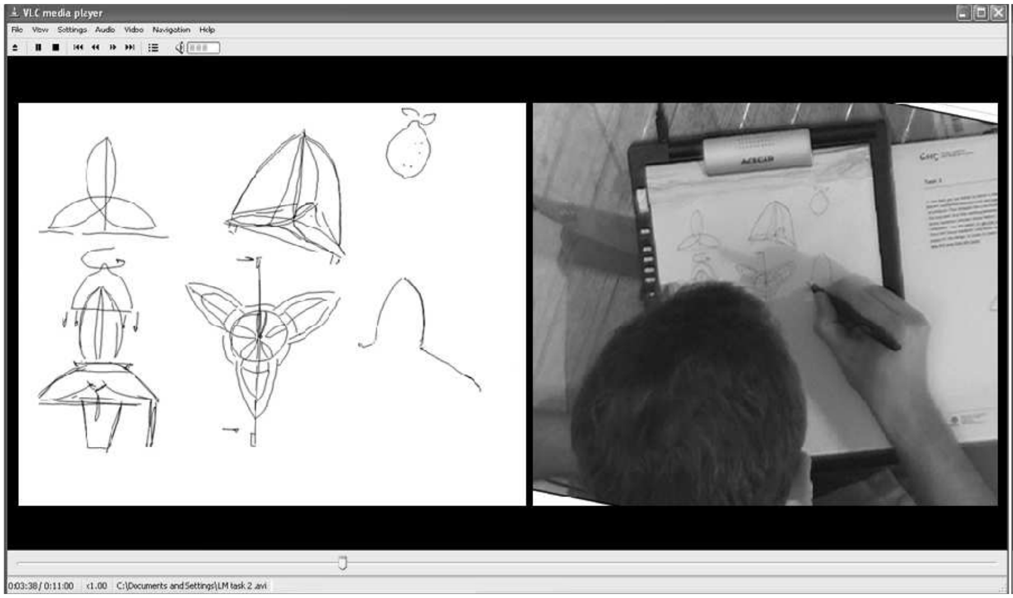


FIGURE 4.2. Synchronized video example of one of the participants

The analysis utilized all three outputs: the sketches on paper, the video data, and the sketches recorded via the digital notepad. At the end of each session, participants were shown their sketches and asked to review their design movements and what they were considering while generating each concept.

The second task used a think-aloud protocol to document and describe designers' approaches to generating concepts in a Novel Design Task. The problem involved designing "a solar-powered cooking device that was inexpensive, portable, and suitable for family use". The design problem statement, presented in **FIGURE 4.3**, also specified design criteria and constraints, and prompted participants to generate a variety of creative ideas for the solutions.

> Sunlight can be a practical source of alternative energy for everyday jobs, such as cooking. Simple reflection and absorption of sunlight can generate adequate heat for this purpose. Your challenge is to develop products that utilize sunlight for heating and cooking food. The products should be portable and made of inexpensive materials. It should be able to be used by individual families, and should be practical for adults to set up in a sunny spot.
>
> Note: Specific materials for a targeted temperature can be postponed to a later stage. Do not worry about the specific quantity of heat that can be generated. Please focus on conceptual designs. Please consider both the ways of capturing the light, and the structural variety of the

concepts.

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

FIGURE 4.3. Novel design task

Participants were given thirty minutes for the task, and they were provided a paragraph of additional information about transferring solar energy into thermal energy after the first ten minutes, in case participants did not feel they had the technical knowledge to generate ideas. This information was provided to encourage designers to move past the need for specific technical information for their solutions. Participants were also asked to keep talking if they became silent at any point during the session.

The designers' drawings were captured in real time, along with their verbal comments, using an electronic pen. After the task was over, participants were asked to verbally describe the concepts they had generated, how they moved from one concept to another, and their approaches to ideation. Finally, they were asked to provide demographic information about themselves, and rate their design performance.

4.2.2. ANALYSIS PROCESS

Verbal data from the experimental sessions were transcribed to supplement the audio and visual sketching data, and all data was analyzed for evidence of heuristic use by two evaluators, both with master degrees in art and design. The results of the analysis of two researchers were comparable, with an initial agreement of approximately 82% across the protocols. The goal of the analysis was to characterize the various design heuristics evident in participants' performance on the task. Thus, the analysis included determining the number and diversity of the concepts generated, and specific design heuristic use. These were considered for each concept, between concepts, and over the experimental session. The coders worked independently, and then discussed any disagreements.

Because the tasks involved just the initial stage of both the design process -- the idea generation phase -- it is difficult to know how concepts might be transformed as the process continued. For example, an idea that may seem impractical or unfeasible in the designers' sketches may become viable with further development in the design process. The focus of this analysis was on how heuristics helped designers explore varieties of designs within the design space. However, subjective coding (Amabile, 1982) of two criteria was also conducted: creativity and practicality. First, questions that would characterize creativity and practicality for the given design task were identified, and then each concept was coded for both criteria individually. Evaluators worked together to define the questions, but coded separately. Some of the questions considered for rating creativity were: Does it address a design criterion unique from the other designers' concepts? Is it considerably different from an existing well-known product? Does it use unexpected materials? For practicality, some of the questions were: Is it easy to use? Is it going to work?

4.3. RESULTS

The results reported here include a discussion of the heuristics identified within and among the concepts generated by designers from the two tasks, participants' heuristic use, and the relationship of heuristics used with the diversity of the concepts, as well as the solutions' rated for creativity and practicality. In each of these analyses, emphasis was given to differences between the two sets of designers working on two different design tasks.

How is the use of heuristics throughout the sessions related to the number and the variety of designs produced by each individual designer? The number of concepts was defined, in part, through the use of cues from participants as they indicated the beginning and ending to a given concept. New concepts were also evident in drawings when moving to a new illustration of an idea. However, the number of concepts generated alone does not necessarily reflect the diversity of the concepts, as similar concepts or evolution of one concept could appear at any point within the session. When looked at the total number of diverse concepts generated in each of the design task, it was clear that the ratio of number of diverse concepts/number of concepts for the Novel Design Task is considerable higher (Redesign Task=47%; Novel Design Task=93%).

Participants produced a total of 31 sketches (Redesign Task=17; Novel Design Task=14). The number of distinct concepts generated by participants in this study ranged from a low of 1, where the same design concept was considered repeatedly in close variations, to a high of 6 distinct concepts. The categorization according to the design task, the participant and the diversity of the concepts is shown in **TABLE 4.1**.

TABLE 4.1. Number of concepts generated by each participant

		Number of concepts	Number of diverse concepts
Redesign Task	Designer 1	6	2
	Designer 2	6	5
	Designer 3	5	1
Novel Design Task	Designer 4	6	6
	Designer 5	4	4
	Designer 6	4	3
Total		31	21

The key features defined in the concepts were identified in terms of user-interaction, form and function, and used as the criteria for describing the diversity of the concepts. For example, for the first task, design solutions could be either held in hand or placed on the table to achieve the function of squeezing the lemon. For the second task, solutions could direct the sunlight using mirrors, maintain heat by creating a closed product with a clear lid (so the sunlight could get in), use a magnifying glass to direct the sunlight, use an insulated box to maintain the heat. Other solution types added straps so the product could be carried by the user, or made a foldable container for easy transport. Each of these listed solutions would be counted as distinct concepts in the design space.

The Redesign Task was more constrained in that less time given to the participants, and an initial visual representation of the form was provided to designers. The designers started generating concepts with the given form, which resulted in less diverse and less detailed concepts. The Novel Design Task, on the other hand, was limited in the technical information provided, which may have limited the range of options to achieve the functions defined in the design problem. For example, in most cases, the designers preferred a hot surface as the preferred method of cooking rather than examining other concepts for heat production.

4.3.1. HEURISTIC USE

The main focus of this study is to document how designers used heuristics to move through design concepts; that is, how they created the transitions through concepts in the ideation stage, and how they create relationships among the design elements in each concept. Heuristics found in the previous chapters (Chapter 2 and 3) are used as a starting point in identifying the heuristics used in formulating ideas for these two tasks. **TABLE 4.2** presents the local and transitional design heuristics evident in the concepts generated by the six participants, and how many times they were observed.

TABLE 4.2. Local (LH) heuristics identified in the content analysis of concepts generated by industrial designers

Local Design Heuristics Observed in Design Concepts		Redesign Task	Novel Design Task
1	Attach independent functional components within the product	14	4
2	Align components around a central, main function	11	0
3	Refocus on the core function of the product	9	2
4	Create modular units by repeating, substituting, or splitting components	7	3
5	Elevate or lower product base	8	2
6	Split or divide surfaces into components	6	2
7	Hollow out inner space for added component placement	7	0
8	Change where or how product will be used	4	2
9	Cover / Form Shell / Wrap surface for other use	2	3

10	Fold product parts with hinges, bends, or creases to condense size	1	4
11	Nest (Hide / Collapse / Flatten) elements within each other	3	2
12	Use a common component for multiple functions	2	3
13	Use the same surface area of the product for different functions	4	0
14	Apply an existing mechanism in a new way	0	3
15	Bend into angular or rounded curves	1	2
16	Integrate or attach the product to an existing item as an additional component	0	3
17	Make components attachable and detachable	1	2
18	Mirror shapes for symmetry	3	0
19	Scale size up or down	2	1
20	Unify design elements, color, and graphics for lower cost and visual consistency	3	0
21	Use an environmental feature as part of the product	3	0
22	Use the same material all throughout the product	1	2
23	Add features from nature to the product	2	0
24	Change the direction of orientation (flip vertical to horizontal)	0	2
25	Control / change in function through movement	2	0
26	Replace solid material with flexible material	0	2
27	Add portability	0	1
28	Attaching the product to the user	0	1
29	Compartmentalize functions into distinct parts	0	1
30	Convert leftover packaging for another use	0	1
31	Design user activities to unite as a community	0	1
32	Extend surface area for more functions	1	0
33	Return sensory feedback to the user (tactile, audio, visual)	0	1

34	Roll product around a pivot point	0	1
35	Rotate on a pivot axis	0	1
36	Stack components	0	1
37	Transfer or convert to another function	0	1
38	Use the outer surface area for of the product for a different function	0	1
	TOTAL	**97**	**55**

The protocols demonstrate that the different heuristics were used 187 times in total (local heuristics=152, transitional heuristics=29, and process heuristics=6). The total number of local heuristics per concept ranged from 1 to 6, and in almost all concepts (30 out of 31), combinations of heuristics were observed.

Concepts in the Redesign Task made more use of heuristics (n = 97) than the concepts generated in the Novel Design Task (n = 55). This difference may be due to the nature of the two tasks. Designers seemed to use more heuristics when they were faced with the Redesign Task, possibly because their thinking process was restricted by the constraints provided in the task, along with the initial triquetra figure they started with. On the other hand, designers who worked on the Novel Design Task generated concepts that were very different from each other, and from existing products in the market. They used fewer heuristics; however the heuristics they preferred were more diverse (29 different heuristics in Novel Design Task vs. 23 in the Redesign Task). This suggests that the heuristics used in Redesign Tasks are more focused, specific, and applied. In contrast, heuristic use in Novel Design Task shows a different pattern. It appeared that the designers tackling the Novel Design Task used more diverse heuristics, suggesting that they were exploring different parts of the design space, and used a variety of heuristics to do so.

For both types of design tasks, *Attaching independent functional components within the product* was the most commonly applied heuristic. For example, in **FIGURE 4.4A**, Designer 2 attached the top components (used for squeezing the lemon) to the bottom component (container for the lemon juice) after he decided on the two functions and defined the forms for both functions separately. Designer 6, using the same heuristic, attached small solar panels in a row to the handle of the product, and attached the handle to the part where food would be cooked.

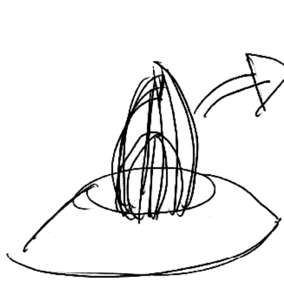


FIGURE 4.4A. Example from Redesign Task using *Attaching independent functional components within the product* heuristic

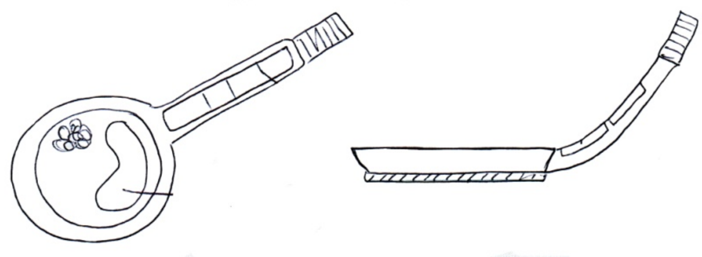


FIGURE 4.4B. Example from Novel Design Task using *Attaching independent functional components within the product* heuristic

Other common heuristics included within the Redesign Task were, *Aligning components around a central, main function*, and *Hollowing out inner space for added component placement*. Based on the context of the problem, these choices of heuristics were expected, as the function in existing product examples suggested aligning the design components at the centre and shaping a container with a bottom hollowed out. In the Novel Design Task, the other most commonly used heuristic was, *Folding product parts with hinges, bends, or creases to condense size*. Since the problem statement required the design solutions to be portable, this was to be expected as well. All the designers in this task applied this heuristic to provide multi-functionality within the concepts by attaching solar panels to one surface (for example, the cover) and / or unfolding it when the other surface would be used for cooking. For example, in **FIGURE 4.5A**, Designer 4 used the outer surface of the cover as the component to capture and store light, and used the inner surface as an additional cooking area by unfolding. In the second figure (**FIGURE 4.5B)**, Designer 5 used the outer surface as a sunlight collector when folded, and the inner surface for cooking (as a grill) when unfolded.

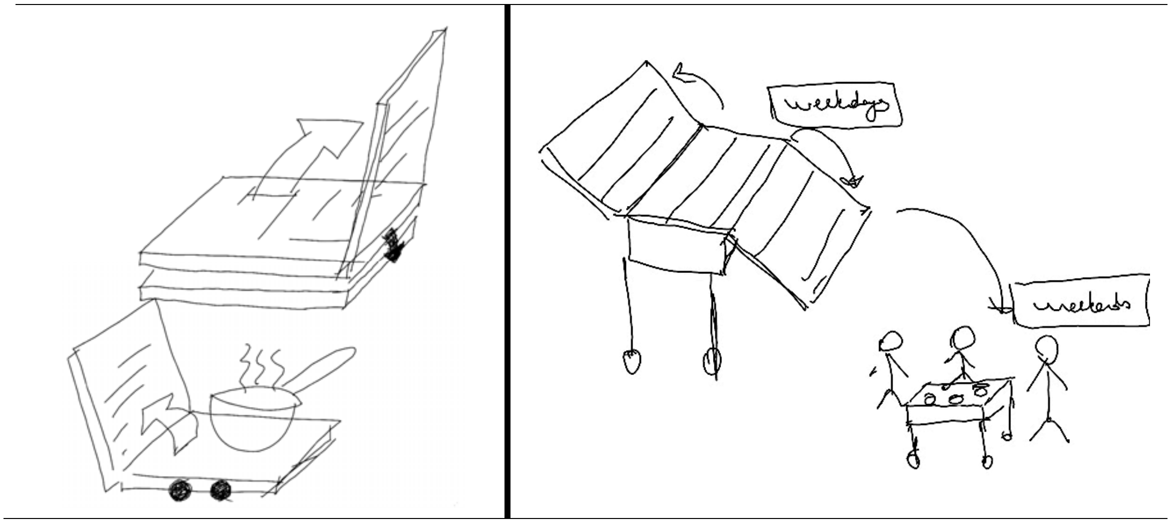


FIGURE 4.5A & 4.5B. Examples from Novel Design Task using *Folding product parts with hinges, bends, or creases to condense size*

There were large differences in the total number of heuristics used by each group of designers, and differences in the heuristic type used in each task; only 16 out of 38 heuristics were used in both tasks. Designers in the Redesign Task more often used, *Refocusing on the core function of the product* (9 vs. 2) as a heuristic, in this case a squeezer and a container. Since there were more variables and constraints in the Novel Design Task, designers visited this heuristic rarely; instead, they focused on the possible ways of capturing sunlight, and how to connect that to the cooking function. Designers working on the Redesign Task also more commonly used, *Elevating or lowering product base* (8 vs. 2) as a heuristic. The reason for this difference seems to be related to the tendency to use an existing cup or glass to collect the lemon juice in the Redesign Task. This decision required the concepts to be elevated from the table surface to create a gap underneath the product for another collection container.

Designers in the Novel Design Task, on the other hand, used, *Integrating or attaching the product to an existing item as an additional component* as one of the main heuristics in their concept generation process. This may be due to the nature of the problem as well, as some of the designers may not have had technical knowledge or confidence to feel comfortable generating a concept from first principles to generate adequate cooking heat.

Two of the 3 designers working on the Redesign Task continued to develop their initial ideas in further concepts, whereas all three designers working on the Novel Design Task generated multiple concepts from scratch. This made the transitional use of heuristics more evident in the concepts generated for the Redesign Task. For example, Designer 1 started with the triquetra figure provided in the design task, and used it as the top view of the first concept he generated. Then, he developed his sequential concepts by repeating elements, elevating the product, and adding further details, as seen in **FIGURE 4.6**.

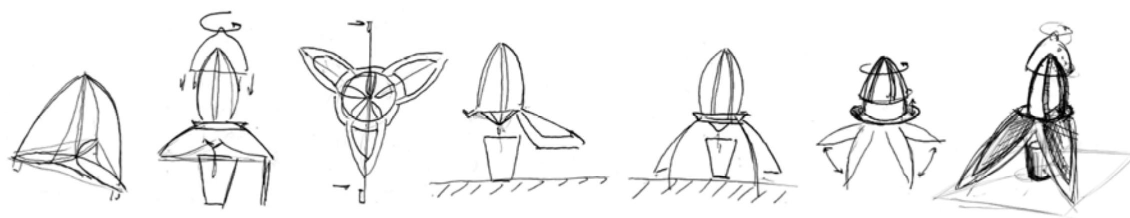


FIGURE 4.6. Sequential concepts generated by Designer 1

Certain heuristics appeared more often transitionally than locally; for example, *Adding details to the previous concepts* and *Scale size up or down*. Both of these heuristics require an initial concept, so this result could be expected. **TABLE 4.3** presents the transitional heuristics evident in the concepts generated by the six participants, and how many times they were observed.

TABLE 4.3. Transitional (TH) heuristics identified in the content analysis of concepts generated by industrial designers

Transitional (TH) Design Heuristics Observed		**Redesign Task**	**Novel Design Task**
1	Adding details to the previous concepts	3	0
2	Attaching the product to an existing item or a previous concept as an additional component	1	2
3	Scale size up or down	2	1
4	Split or divide surfaces into components	3	0
5	Attach independent functional components within the product	2	0
6	Change where or how product will be used	2	0

7	Elevate or lower product base	2	0
8	Fold product parts with hinges, bends, or creases to condense size	1	1
9	Refocus on the core function of the product	2	0
10	Add features from nature to the product	1	0
11	Cover / Form Shell / Wrap surface for other use	1	0
12	Extend surface area for more functions	1	0
13	Making a continuous surface out of multiple components by merging them	1	0
14	Nest (Hide / Collapse / Flatten) elements within each other	1	0
15	Replace solid material with flexible material	0	1
16	Reverse direction or angle of component for alternate function	1	0
	TOTAL	**24**	**5**

These observances of transitional use of heuristics are impressive given that these two tasks took place in a much shorter time frame (10 and 20 minutes) than the task observed in Chapter 3, and generated far fewer concepts. Though there were fewer opportunities to view the use of heuristics as transitions between concepts (n = 29), more of them occurred in the shorter, Redesign Task.

Finally, some use of process-based heuristics was observed for some of the designers despite the limited work time allotted. For example, one designer strategically chose different contextual uses for the product (cooking different types of food), resulting in generating several new design concepts. In the Redesign Task, *Evaluating*, *Simplifying*, and *Continuing the modification of the foundational concept* were the primary process heuristics selected by the designers. For designers working on the Novel Design Task, *Evaluating*, *Problem refining*, *Contextualizing*, and *Constraint prioritizing* heuristics were observed. However, only six process heuristics were observed in these short design sessions.

To understand the results further, it is helpful to follow individual designers through their session, and see how each type of heuristic was applied during their work. The following paragraphs provide a sample of one designer's work from each of the two design tasks. The use of local, transitional, and process heuristics are highlighted in these examples, and then the trends in heuristic use are discussed following the examples.

In the Redesign Task, Designer 3 generated only one concept; however, he worked through 5 iterations of that concept (see **FIGURE 4.7**). The designer interpreted the form provided in the task as a cross-section of the lemon squeezer, and began by attaching two independently functioning components to create a product: a squeezer, and a container for collecting the juice. In a second concept, he created a solution that would use a continuous surface, and he split this surface into two pieces to distinguish the two functions from each other, and added another component to keep the pulp of the lemon. In the next concept, he covered the top part of the product to explore alternate ways of squeezing the lemon, such as using a secondary component. In a forth concept, he extended the top part all the way to the bottom of the product, and in the final concept, he used the same material throughout the product by creating a continuous surface out of the multiple components.

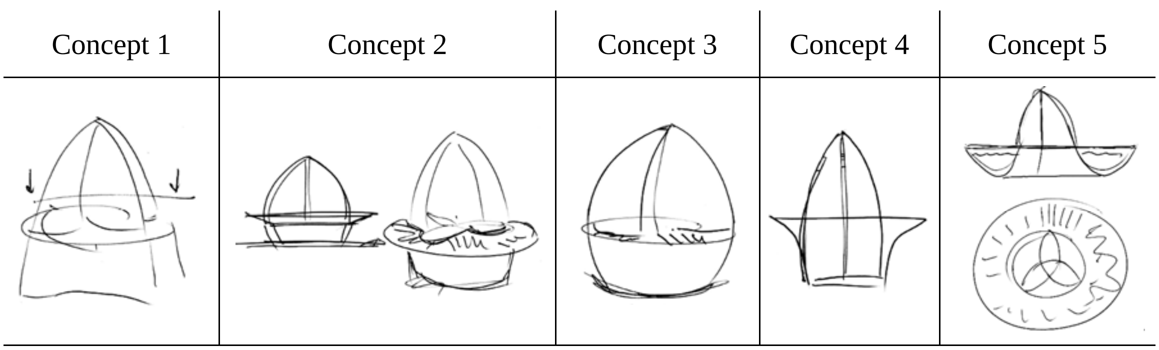


FIGURE 4.7. Sequential concepts generated by Designer 3

Though his concepts were not diverse, Designer 3 did use *Evaluating*, *Simplifying*, *Prioritizing constraints* and *Continuing the modification of the foundational concept* were as process heuristics to explore the design space. In the retrospective interview, he said, "… it can be manufactured in a single piece, and I thought maybe it will be cheaper…", and added "… and there is no need to add a spout because the piece, as it is, can be used to serve the juice," suggesting he was prioritizing cost and simplicity as criteria. He also said, "…I thought: I don't want to carry on with this one. It's too big…," suggesting he was evaluating his ideas while creating them.

The designer demonstrated successful use of transitional heuristics to move and explore within a single concept. For example, from concept 2 to concept 3, he used a transitional heuristic, *Covering / Forming Shell / Wrapping surface for other use*, and from concept 2 to concept 4, he used the transitional heuristic, *Making a continuous surface out of multiple components by merging them*, as he combined the squeezer and the container into one product. While the set of resulting concepts show commonality, they also reflect the iteration of design through the repeated application of design heuristics.

In the Novel Design Task, fewer different concepts were generated, and fewer heuristics were observed even though twice as much work time was provided. On this task, Designer 5 generated four concepts; all were considered diverse (see **FIGURE 4.8**). In the first concept, he described a context in which the user was a hiker, and designed an integrated backpack with a heat pot attached to it. The second concept was a barbeque using solar panels on one side, and a cooking surface on the other. Solar energy was captured when the panels are unfolded fully, and the product was used with the panels folded. The next concept used multiple mirrors to direct sunlight onto one piece of the product that could be attached to another piece for cooking. The location of those components would be switched; that is, the heat unit was on top of the pot for collecting sunlight, and switched below it for providing heat from the bottom when cooking. His final concept was a set of small black cubes that could be utilized to absorb heat, and their orientation could be changed according to cooking needs.

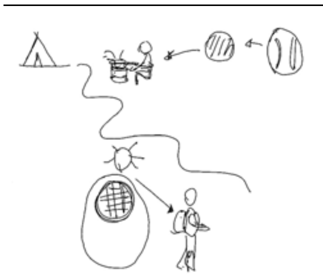
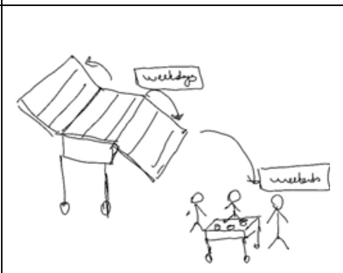
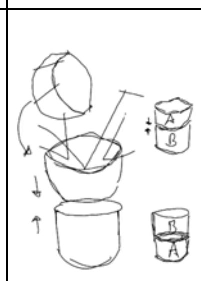
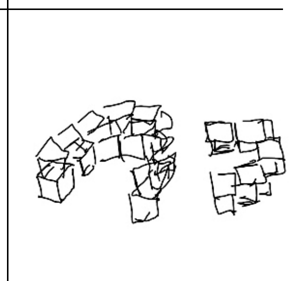
Concept 1	Concept 2	Concept 3	Concept 4
			

FIGURE 4.8. Sequential concepts generated by Designer 5

In his ideation process, the local heuristic, *Change the direction of orientation* was evident in his third concept, where two components of the product were switched from top to bottom depending on the function to be achieved (cooking or trapping heat). Consistent with the fact that there was no evidence of transitional heuristics, he seemed to use an approach of sampling from very different areas in the problem space. The only consistency among his design concepts was the idea of capturing the heat during one time period and utilizing it at a different time. He also used *Contextualizing* as a process heuristic throughout his ideation process, using this heuristic to generate diverse ideas for using the product in different settings.

4.3.2. THE RELATIONSHIP BETWEEN DESIGN HEURISTICS AND CREATIVITY

Creativity scores demonstrated a similar pattern between the two tasks: Six concepts generated in both the Redesign and the Novel Design Tasks had average creativity scores over 4 (with "7" as the "most creative design"). Compared to the number of concepts created in each task though, these result showed that creativity scores were higher in the Novel Design Task (43% vs. 33%).

However, when looked at the entire data, there were no mean differences between industrial designers working on the two design tasks on either creativity (Redesign: 3.41 vs. Novel: 3.64) scores ($t < 1$) or on Practicality (Redesign: 3.82 vs. Novel: 3.00). This is not surprising because there is little statistical power (three subjects in each group). However, across the sample, the average creativity (r=.54) and practicality (r=.53) scores correlate highly with the number of heuristics used by each designer ($p<.01$ for both criteria) (see **TABLE 4.4**)

TABLE 4.4. Average ratings and local heuristics observed for each participant

		Number of local heuristics	Average creativity	Average practicality
Redesign Task	Designer 1	42	4.08	3.58
	Designer 2	32	3.08	3.42

	Designer 3	23	3.00	4.6
Novel Design Task	Designer 4	19	3.17	3.25
	Designer 5	22	4.50	2.88
	Designer 6	14	3.50	2.75
Total		152		

The more heuristics designers used the more creative and practical their designs were rated. This suggests that industrial designers utilized heuristics to identify different solutions. This result also suggests that the industrial designers were not blocked by their lack of technical knowledge in generating creative and practical design concepts. Instead, they may have used design heuristics to compensate for this lack of knowledge.

In both of the design tasks, averaged creativity scores were higher in concepts using higher number of diverse design heuristics. Even though this indicates coherence between the number of heuristics used and the creativity of the design solutions, the heuristics used for each task differed other than *Attaching independent functional components with the product* which was also the most-commonly used heuristic out of 38. For example, concept seen in **FIGURE 4.9A** used a combination of ten heuristics, with *Controlling/changing in function through movement*, and *Adding features from nature to the product* being specific to only this concept. On the other hand, concept seen in **FIGURE 4.9B** which was also scored as highly creative, used another distinct heuristic: *Compartmentalizing functions into distinct* parts as one of six heuristics applied. This heuristic was also specific to this concept. Thus, the high creativity score of the design solution may be due to these three heuristics applied by the designers or it may be related to the number of heuristics used. Since this result relies on case studies, it’s difficult to make an assumption at this point.

FIGURE 4.9A. Example using *Control / Change in function through movement*, and *Add features from nature to the product* for a creative solution

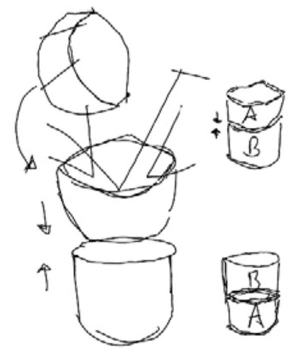


FIGURE 4.9B. Example using *Compartmentalize functions into distinct parts* for a creative solution

Diversity in the solution space of designers working on the Redesign Task was limited, constrained by the initially given form and the already existing item known by designers. It is observed that the designers worked on the Redesign Task used their declarative knowledge as the main supply for solving problems, while designers worked on the Novel Design Task relied on procedural knowledge where they utilized tactics as part of the idea generation process.

The diversity of concepts did not rely on specific heuristics, but relied on the diversity of heuristics applied. Another interesting finding is that heuristics used in Redesign Tasks are more focused, specific, and applied. In contrast, heuristic use in Novel Design Task shows a different characteristic. It appeared that the designers tackling the Novel Design Task used more diverse heuristics, suggesting that they were exploring different parts of the design space, and used a variety of heuristics to do so.

FIGURE 4.10A shows that the designer produced a concept that requires both hands to function; bottom part is for holding, the middle part is for the juice and the top part is for squeezing. Once the designer had decomposed his design concepts into a particular set of elements, different heuristics were applied; such as, *Change where or how product will be used*, and *Add portability*. In the Novel Design Task, designers used more diverse heuristics resulting in more diverse concepts. For example, as shown in **FIGURE 4.10B**, the designer used *Replace solid material with flexible material*, and *Roll product around* *a pivot point* to generate an easy to carry and efficient surface that would both capture the light, convert it into thermal energy, and also be used as a cooking surface.

Similar conclusions could be drawn from the concept sketches produced by other participants. In most cases, changes in design solutions occurred after applying an uncommon heuristic; as in the examples given below: a lemon squeezer without a base to sit on a table, or a solar-powered cooker made out of flexible pad that rolls around itself when it's carried.

FIGURE 4.10A. Example using *Change where or how product will be used*, and *Add portability* for a diverse solution

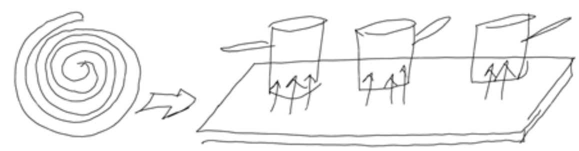


FIGURE 4.10B. Example using *Replace solid material with flexible material*, and *Roll product around a pivot point* for a diverse solution

Concepts generated for the Novel Design Task were judged more creative and diverse compared to the solutions proposed in the Redesign Task. The Novel Design Task required more detail and concern about technicality due to the specifics given in the problem statement. Designers working on the Redesign Task appeared to experience "fixation" more commonly than in the Novel Design Task. Jansson and Smith (1991) were the first to document fixation in an engineering design task. They hypothesized that design fixation might be caused by the examples that sometimes accompany problems given to designers. Although intended to suggest other possible solutions, those examples might, instead, have an inhibiting effect, restricting the problem solver to the components in the example designs. They found that designers are sometimes trapped by the characteristics of a possible solution that has been developed as an example, and by existing precedents for the design.

Purcell and Gero (1996) extended Jansson and Smith's findings by examining the possible occurrence of fixation across different design disciplines and levels of experience. They found that there was a clear fixation effect observed for two groups of mechanical engineering students. In contrast, the fixation effects for the students in industrial and interior design were only marginally significant. They suggested that the complex pictorial example provided to the designers might have affected them in using their own cognitive resources, so that they relied more on the provided examples in order to create a design solution.

The type of the design problem did seem to affect generation, as designers appeared to use their previous knowledge of the existing products used for the same function, and built their concepts accordingly, for the Redesign Task. However, designers in the Novel Design Task were forced to explore new areas of the design space since there were few existing products for comparison; so, the heuristics that they used varied greatly.

4.4. DISCUSSION

The present study examined six professional industrial designers working on short tasks of two types: one a routine, redesign of an existing product, and one a creative design of a novel product. The results showed significant evidence of heuristic use, and a great deal of overlap with the set of heuristics developed through the product analysis in Chapter 2, and the in-depth analysis of a single designer on an extensive design task in Chapter 3. The results also showed the effectiveness of heuristics in generating diverse concepts, suggesting they may, at times, be sufficient to stimulate divergent concepts. Furthermore, the study revealed some differences between designers' behavior in the two types of design problems; specifically, designers working on the Novel Design Task produced a more diverse set of concepts using a more diverse set of heuristics.

Industrial designers in the Novel Design Task structured the context and approached the problem from the user perspective, considering the product's use by families versus individual hikers, the product's use in kitchens versus backyards, and the product as a single entity versus attached to existing products such as a grill or stove. Designers in the Redesign Task did not appear to consider different contexts; however, they also identified differences in the interaction with the user, such as, holding the product with one hand

and squeezing the lemon with the other hand, versus placing the lemon squeezer on the table to achieve the function. Despite the observed differences in heuristic use observed, the major, striking finding is the pervasive presence of heuristics in these differing tasks.

The success of this heuristic analysis method in characterizing differences among candidate designs may suggest ways to assist designers in adding to their concept sets. Further, the validation of the set of heuristics may suggest methods for the development of computational tools to assist in design. For example, the frequency of the heuristics applied could be analyzed in order to understand which of the heuristics are most commonly used, what kind of design problems they were applied to, what kind of new problem spaces they generated, and which heuristics may be relevant given the observed patterns. In particular, this approach may hold promise in instruction for novices as they build their experience with heuristic use and design in general.

CHAPTER 5

VALIDATION OF DESIGN HEURISTICS

"YOU SEE THINGS, AND YOU SAY: 'WHY?' BUT I DREAM THINGS THAT NEVER WERE, AND I SAY 'WHY NOT?"

GEORGE BERNARD SHAW

OVERVIEW

This section presents an empirical study of cognitive processes in design. The goal is to examine utility of explicit instruction on strategy use in design. It begins with research questions and experimental approach, leading to an empirical study is presented examining the use of heuristics in conceptual design.

5.1. INTRODUCTION

The core hypothesis of this section is that design heuristics offer a means of generating possible designs by guiding designers to consider specific types of variations on concepts. At the outset, the question posed was, "What is the role of heuristics in design problem solving?” To further explore the effects of design heuristics, a study was conducted that manipulated how participants learned about a series of heuristics, and measured how they used those heuristics when generating a series of product concepts. In this context of novice designers, I seek to answer the following research questions:

1. Does the use of heuristics in general lead to more creative designs?
2. Which design heuristics are most effective in creating novel designs?
3. Does the effectiveness of heuristics use differ when applied to Redesign problems vs. Novel Design problems?

These questions were addressed in a large-scale study that manipulated training about heuristics, along with their order of presentation and the design problem. This study focuses on the impact of instruction about design heuristics on the creativity and practicality of the resulting design concepts. In addition, the experiment allows examining the effects of each heuristic in the ideation process.

In the present empirical study, two sets of six instructional heuristics were tested for their effectiveness in generating product concepts by novice designers. These heuristics were culled from the ones found in the study described in Chapter 3. By examining the expert’s progression of designs over time, two sets of candidate design heuristics were identified: (1) *Merge*, *Change the configuration*, *Substitute*, *Rescale*, *Repeat*, and *Nest*; (2) *Merge, Press*, *Hollow*, *Bend*, *Reverse*, and *Twist*. The first goal was to examine the effectiveness of two sets of heuristics in helping to develop new concepts. The second goal in this study was to examine how the heuristic approach might differ in Redesign Tasks vs. Novel Design Tasks. "Redesign" here refers to revising an existing design; for example, the “new” Volkswagen Beetle is a complete re-design of a version from the 1960s. The novel design task, on the other hand, describes a product or service that does not yet exist, requiring substantially novel features or functions; for example, the Segway Personal Transporter combines existing technologies with new ones to create a new product. The underlying question of interest here is whether design pedagogy can teach novice designers to use these same design heuristics, and whether doing so results in designs that are considered more creative.

5.2 METHOD

The experiment included two different design tasks: (1) redesigning a familiar object: a pair of salt and pepper shakers, and (2) designing a novel product: a set of drink containers for two novel ingredients, representing male and female genders. The objects in the redesign task are very familiar in Western culture, with many prototypical designs available as commercial products and frequent exposure as everyday objects. The decision to use a redesign task assures adequate domain knowledge by the participants, and avoids the difficulty with vagueness sometimes seen in novel design problems. On the other hand, the second design task was chosen to be a less defined task where the participants were asked to be more imaginative. It differed from the first task in that participants could not draw on prior knowledge of such a container, since the task was novel in focusing on different drink containers for men and women. This task required a set of paired, complimentary objects just like the salt and pepper shaker task; however, the container products were not pre-defined by existing products.

The data collected included 1926 drawings created by 357 first-year college students under twelve instructional conditions. Drawings were coded according to their content, use of heuristics, creativity and practicality. Throughout the experiment, participants used the modality of sketching their designs, along with writing text descriptions to both develop and document their ideas during the design task.

5.2.1. PARTICIPANTS

Three hundred and ninety first-year students were drawn from the Introductory Psychology Subject Pool at a mid-western university, and they earned course credit by their participation. Of the 390 participants, only 357 were included in the analysis, as the other 33 failed to follow the guidelines provided. The subjects ranged in age from 18 to 22; 206 (58%) of them were females, and they were all assigned at random to one of the twelve instructional conditions.

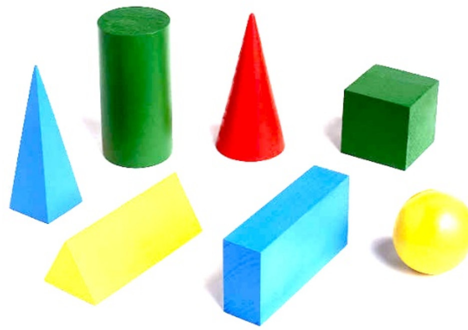
The choice of participants for the study is appropriate for a number of reasons. First, the hypothesis is that expert designers acquire these design heuristics over their lengthy education and experience as designers. As an initial test of whether these heuristics play a role in design success, we need a comparison where subjects have no knowledge of the heuristics prior to the instruction we provide. By choosing subjects with no training in design or engineering, the question of the heterogeneity of pedagogies individuals may have been exposed to in the past is avoided, as well as the potential prior knowledge of design heuristics. In addition, because participants had no formal technical training in sketching or drafting, their skills in sketching are similar. and independent of the influence of the conceptual improvement in design from any heuristic use. Also, the first-year university participants allowed gathering a sample of novice designers with a wide range of demographic and educational backgrounds and interests, potentially supporting the effectiveness of the proposed pedagogical approach in a broader variety of educational programs.

5.2.2. MATERIALS

For the redesign task, participants were asked to draw salt and pepper shakers, while in the novel design task, they were asked to design drink containers for two ingredients representing males and females. For both tasks, participants were directed to show their creativity in their designs.

THE DESIGN TASKS

As part of this study, two design tasks were used for the experimental conditions: a re-design task and a novel design task. In all groups, a short written description of the design task was provided, along with a picture of simple geometric shapes to use in the generation of design concepts. Simple block shapes were included to encourage thinking in three dimensions, but also helped to constrain designs to a manageable set of possible forms. The geometrical shapes and the redesign task are displayed in **FIGURE 5.1**.



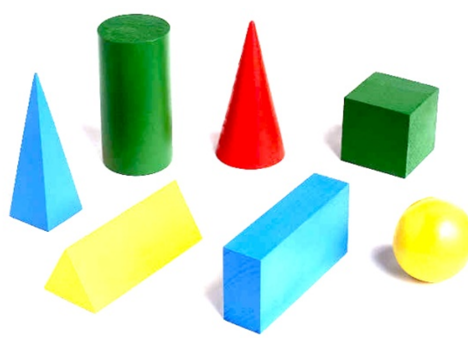
Problem Statement: Imagine that you are working as a product designer in a design consulting firm, and that you are given a rather fun assignment just for today: design salt and pepper shaker sets by utilizing simple geometrical forms and adding as much detail as needed.

"The shakers should not repeat the same form, although they should complement each other. Think about the functionality of the product, where they will be used, how they will used, how they will be cleaned, how to fill them up, etc."

You can tell us details about the materials, colors, and dimensions if you'd like, and they will be evaluated as additional information.

FIGURE 5.1. Problem statement for the Redesign problem used in the empirical study. The blocks are presented in different colors in the study

The novel design task had the same structure in terms of using the geometrical forms to initiate the concepts. In this task, the problem was kept vague intentionally, as the goal was to discover how heuristics are applied in different design tasks. **FIGURE 5.2** shows the description provided to participants.



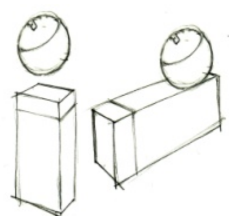
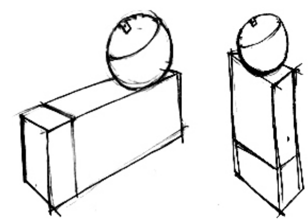
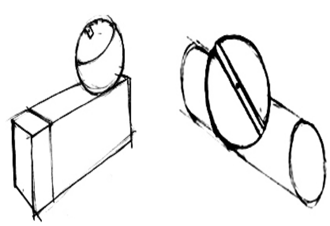
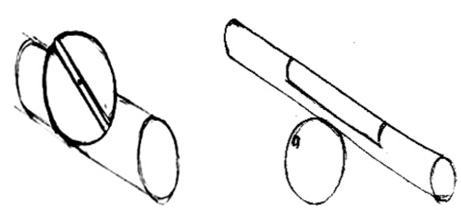
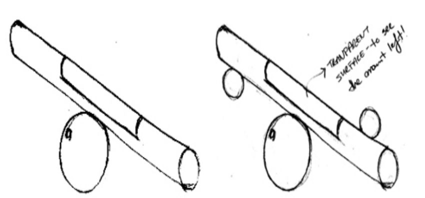
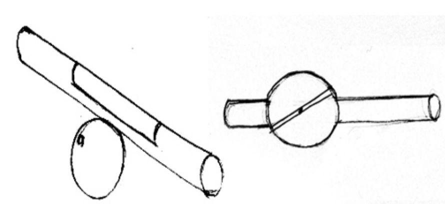
Problem Statement: Imagine that you are working as a product designer in a design consulting firm and that you are given a rather fun assignment just for today:

"Two ingredients for food or drink have been discovered in an uninhabited area of the earth. When the two ingredients are combined, it's said that these ingredients bring together that which represents man and that which represents woman. The two ingredients can only come in contact at the time of use. The company that wishes to bring this to market wants to sell a package with two items, one for the ingredient representing man and another for the ingredient that represents woman. When together, they mean something more than when they are separated (in physical form, not in emotional form). Design the two items utilizing simple geometrical forms and adding as much detail as needed. The two products should not repeat the same form; however, they should complement to each other."

Think about the functionality of the product, where they will be used, how they will used, how they will be cleaned, how to fill them up with ingredients, etc. You can tell us details about the materials, colors and dimensions if you'd like and they will be evaluated as additional information.

FIGURE 5.2. Problem statement for the Novel Design problem used in the empirical study. The blocks are presented in different colors in the study

DESIGN HEURISTICS TRAINING MATERIALS

(1) MERGE: Merge the two selected forms to design a set of the containers as given in the design problem. 	**(2)** CONFIGURE: Change the configuration of the forms in your previous design and design a complementary second product. 
(3) SUBSTITUTE: Substitute one of the forms in your previous design with another geometrical form you select from the ones on the top and design a complementary second product. 	**(4)** RESCALE: Exaggerate the dimensions of the forms in your previous design and design a complementary second product. 
(5) REPEAT: Repeat one of the forms in your previous design 2-3 times and design a complementary second product. 	**(6)** NEST: Nest one of the geometrical forms you used in your previous design inside the other one and design a complementary second product. 

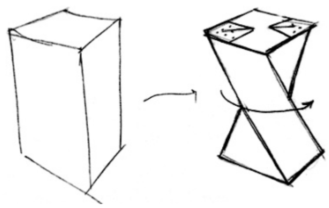
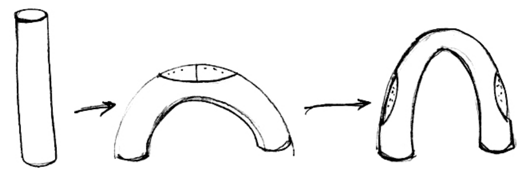
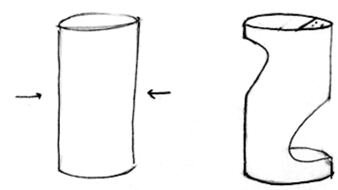
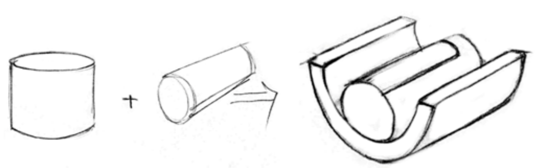
(7) TWIST: Twist one or both of the forms in your previous design and design a complimentary second product. 	**(8)** BEND: Bend one or both of the forms in your previous design and design a complimentary second product. 
(9) REVERSE: Reverse one or both of the forms in your previous design and design a complimentary second product. 	**(10)** PRESS: Press one or both of the forms in your previous design 2-3 times and design a complimentary second product. 
(11) HOLLOW: Hollow out one of the forms in your previous design and design a complimentary second product. 	

FIGURE 5.3. The eleven heuristics selected for the study, each proposing a way to change a form to increase the novelty and variety in the design

Eleven heuristics were included in the experiment in two separate sets: Heuristic Set 1: *Merge*, *Change the configuration*, *Substitute*, *Rescale*, *Repeat*, *Nest*, and Heuristic Set 2: *Merge*, *Press*, *Hollow*, *Bend*, *Reverse*, and *Twist*. These heuristics, presented in **FIGURE 5.3**, were selected as simple, independent changes in design (see Chapter 3). These heuristics are also easy to apply, and can be used to generate alternative forms quickly. These tasks, heuristics and overall instructions were selected to be easy to understand within the short experimental session.

The training materials provided for each heuristic consisted of a brief written explanation of the heuristic and a visual example of how it can be applied to simple forms, as shown in Figure 5.3. The example sketches included an initial concept and the result after the application of the given heuristic. Participants were told that these examples could be used to understand how the heuristic works, but they should not be repeated in their own designs. The instructional materials included both the short written representations of the heuristics and the visual information to clarify how the heuristics could be used.

Concept design pages were provided with the label "Concept" at the top, a large rectangular outline for the sketch, and a bottom space labeled "Explanation:" for nay comments by the participants about their design. There was also a box labeled "Start" and "Finish," where participants wrote in the time they began and ended work on each design. The bulk of the page was blank, providing room for the participants to sketch their concepts and to write comments and label parts of their designs. Eight pages were included in each booklet, for a maximum number of eight designs created by each individual participant in their test booklet.

5.2.3. EXPERIMENTAL DESIGN

The effects of the heuristics on the creativity and practicality of the observed designs were evaluated through twelve instructional conditions. Across all conditions where heuristics were used, the first heuristic presented was the *Merge* heuristic. So, the ten conditions with heuristic instruction -- the eight *Serial Orders* and the two *Heuristic Choice* conditions -- all began with *Merge* as the first heuristic presented. The rationale was that at least two shapes would be present in the first candidate design, making the application of the other heuristics more feasible. The experimental design and the distribution of participants to the twelve different experimental groups are shown in **TABLE 5.1**.

TABLE 5.1. Number of participants per condition

	Redesign Task				Novel Design Task			
	Serial Order 1	Serial Order 2	Heuristic Choice	Control	Serial Order 1	Serial Order 2	Heuristic Choice	Control
Heuristic Set 1	30	30	30	29	32	30	27	30
Heuristic Set 2	27		32		31		29	

There were six experimental conditions that varied the training provided for the subjects. In the *Control* condition, no information about heuristics was presented, and subjects completed a set of concept designs. In the *Serial Order 1* and *2* conditions, the set of six heuristics were presented one at a time, each followed by a concept design page. In the *Heuristic Choice* condition, all six heuristics in the set were presented at the beginning of the session, and the subject was able to choose which heuristics to apply on each subsequent concept design page.

For both tasks, *Serial Order 2* was not included as a condition for Heuristic Set 2 because an initial analysis showed no order effects in the *Serial Order 1* and *Serial Order* 2 for Heuristic Set 1. **FIGURE 5.4** shows the six experimental conditions for each of the two tasks, resulting in twelve separate groups of participants in a between-subjects design.

Heuristic Set 1, Serial Order 1: The six design heuristics were presented one at a time in a single standard order determined at random, with *Merge* as the first heuristic, followed by *Change the configuration*, *Substitute*, *Rescale*, *Repeat*, and *Nest*.
Heuristic Set 1, Serial Order 2: The six heuristics were presented one at a time in a different standard order determined at random, with *Merge* as the first heuristic, followed by *Repeat*, *Changing the configuration*, *Substitute*, *Nest*, and *Rescale*.
Heuristic Set 1, Heuristic Choice: All six design heuristics were presented together in a list, with *Merge* as the first heuristic. Subjects were free to choose which heuristic to attempt next. The order of presentation (of the heuristics) was randomized for each subject.
Heuristic Set 2, Serial Order: The six design heuristics were presented one at a time in a single standard order determined at random, with *Merge* as the first heuristic, followed by *Press*, *Hollow*, *Bend*, *Reverse*, and *Twist*.

Heuristic Set 2, Heuristic Choice: All six design heuristics were presented together in a list, with *Merge* as the first heuristic. Subjects were free to choose which heuristic to attempt next. The order of presentation (of the heuristics) was randomized for each subject.
Control Group: No instructions about design heuristics were provided.

FIGURE 5.4. Overview of the experimental design

Participants were assigned to experimental conditions at random, with the range of 27-32 participants per group. The sessions were conducted in a classroom in small groups of two to fourteen participants. All participants within a testing session were in the same experimental condition.

5.2.4. PROCEDURE

Participants in all twelve conditions were given an introduction page summarizing the design task and presenting the task guidelines (see **FIGURE 5.1** and **5.2**). Because prior research (Harrington, 1975) has shown that creativity test scores are influenced by explicit instructions to "be creative," participants were told, "This task involves drawing creatively. We want you to create concepts that are highly creative, imaginative. That is, please create concepts that are both original (novel, uncommon) and also appropriate (artistically effective)." Participants were given 8.5" by 11" response papers to depict their designs, and were also asked to write labels and notes to clarify their designs. Then, they were told to turn the page and begin, creating a new design concept following the same task instructions. Eight task sheets were provided so that participants could continue to create new designs, turning the page after each one, up to a total of eight different designs. Subjects were given forty minutes to complete the task, and twenty minutes to complete the questionnaires.

Participants were told to develop as many different concepts as possible on the eight concept pages provided, and that each separate concept should be drawn on a new page. They were asked to write in the time they began working on each concept page, and the time they completed it. In the *Control* condition, no training materials were presented, and the eight concept pages followed. Participants paced themselves in their work, and had 40 minutes in total to complete up to eight separate concept pages. For the two *Heuristic Choice* condition, subjects received instructional sheets describing each of the six heuristics (*Merge* being the first heuristic in both tasks) included in the study all at once, at the beginning of the session. They were asked to choose the heuristics they wished to use to help them generate designs. They then proceeded to complete up to eight concept papers in the forty minutes allotted. In the six *Serial Order* conditions, the experimenter directed subjects' progress through the booklet. Within each group, the heuristics instruction sheets were presented one at a time, in a standard order determined at random (see **FIGURE 5.6**). Following each heuristic instructional sheet, a concept design sheet was provided. Subjects were given six minutes to create a design using that particular heuristic, and then the experimenter asked them to turn the page to the next heuristic, and so on until all six heuristics had been presented. In the remaining time, they could proceed to create up to two additional concept pages.

At the end of the design task, all participants were asked two questions to evaluate their response to the task. The two questions, using seven-point Likert scales, were, "How did you find the task?" with "1 = easy" and "7 = difficult," and "Please self-evaluate your success in the task," with "1 = I did great" and "7 = I did not do too well.

5.3. RESULTS

In total, 1926 separate designs were generated by the 357 participants, averaging more than five designs per subject. The majority of the participants (98%) in the ten *Heuristics* conditions generated five or more concepts, with an average of 5.6 (SD = 1.7), and range from 3 to 9. Only nine of these 291 participants generated more than 6 concepts (3%); however, seventeen of the fifty nine participants (29%) in the *Control* condition generated more than 6 concepts. This difference may have arisen because subjects in *Control* condition saw no heuristic instructional materials, and so had more time during the session for generating designs.

Subjects in the six *Serial Order* conditions produced significantly more designs than those in the two *Control* or four *Heuristic Choice* conditions. The effect is stronger in the Novel Design Task. This pattern may result from the experimenter-directed procedures in the six *Serial Order* conditions, where subjects were instructed when to read about each heuristic, and given six minutes to complete a design using that heuristic. By contrast, subjects in the *Control* and *Heuristics Choice* conditions were given initial instructions, but then left to work their way through the multiple design tasks on their own for the forty minute period. As a result, the *Serial Order* participants may have been kept on task and attending well to the instructions. For example, those in the *Serial Order* conditions may have generated more designs because the procedure required them to use a different heuristic in each design.

5.3.1. RATING PROCEDURE

AVERAGE CREATIVITY RATINGS OF DESIGNS

Each concept was separated from the participant's packet and placed in random order in a pile with all other concepts from that condition. This allowed every concept to be rated individually, with no bias from previous drawings within the participant's packet. Each pile was then evaluated independently by two upper level undergraduate students with no formal design training. These judges were selected for convenience, and because previous research (Amabile, 1982; Sternberg & Lubart, 1995) has shown that peers provide reliable and valid judgments of creativity. The two judges were blind to condition and to the experimental hypothesis. For the creativity rating, judges were instructed to use their subjective definition of creativity when evaluating each concept. Prior to beginning, the judges were instructed to quickly look through the concepts to get an idea of the range and quality concepts. Also, both before and after rating a pile, the judges were asked to shuffle the concepts so as to avoid any order effects.

The "sorting" procedure allowed the judges to compare drawings within their categories, and shortened the time required to complete the ratings of 1926 concepts to five sessions of 2 hours each. The reliability of the judges' scores for creativity (computed using Cronbach's Alpha) are listed in **TABLE 5.2,** along with average creativity scores and the standard deviations. The results for all conditions overall provides a high level of agreement.

TABLE 5.2. Interrater reliability statistics (Cronbach's alphas) and average creativity ratings for designs per condition

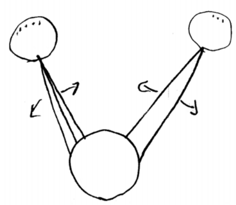
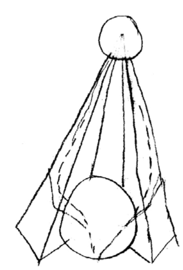
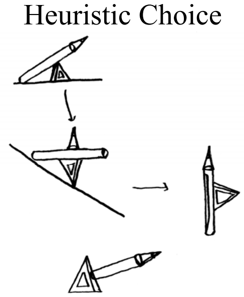
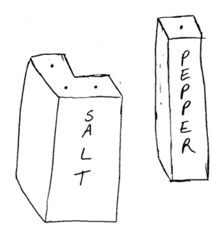
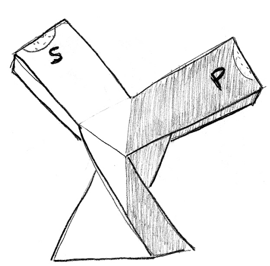
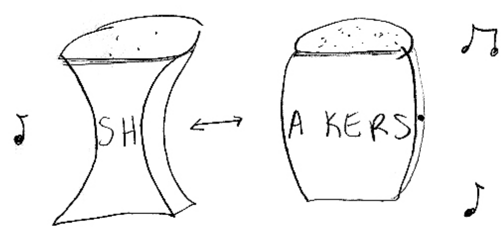
Experimental Condition	**Cronbach's Alphas**	**Creativity Means**	**Standard Deviations**
Redesign Task, Heuristic Set 1, Serial Order 1	.849	3.14	1.612
Redesign Task, Heuristic Set 1, Serial Order 2	.808	2.87	1.511
Redesign Task, Heuristic Set 1, Heuristic Choice	.742	3.10	1.440
Redesign Task, Heuristic Set 2, Serial Order 1	.768	3.84	1.582
Redesign Task, Heuristic Set 2, Heuristic Choice	.779	3.66	1.409
Redesign Task, Control	.822	2.34	1.551
Novel Task, Heuristic Set 1, Serial Order 1	.885	3.30	1.800
Novel Task, Heuristic Set 1, Serial Order 2	.820	3.43	1.845
Novel Task, Heuristic Set 1, Heuristic Choice	.851	2.83	1.766
Novel Task, , Heuristic Set 2, Serial Order 1	.718	2.96	1.441
Novel Task, Heuristic Set 2, Heuristic Choice	.844	3.03	1.616
Novel Task, Control	.810	2.31	1.491

A One-Way ANOVA using a random effects model with designs nested within subjects was conducted to compare the creativity scores across the twelve conditions. The average creativity ratings over the two judges show differences for the twelve instructional conditions. The two *Control* conditions show the lowest creativity scores (2.34 in the Redesign Task and 2.31 in the Novel Design Task). These two conditions do not differ from each other, but are significantly different from all of the heuristic conditions based Bonferroni post hoc comparisons (p's $< .05$).

For the Redesign Task using Heuristic Set 1, the *Heuristic Choice* condition was rated higher in creativity (3.10), and did not statistically differ from the ratings for *Serial Orders 1* (3.14) and *2* (2.87*)*. However, the second set of heuristics in the Redesign task resulted in even higher ratings for both groups in the Redesign Task, with 3.66 in the *Heuristics Choice* condition and 3.84 in the *Serial Order* condition. These groups using

Heuristic Set 2 on the Redesign Task did not differ from each other, but both were rated as significantly more creative than the other groups in the redesign task.

For the Novel Design Task with Heuristic Set 1, the *Serial Order 1* (3.30) and *Serial Order 2* (3.43) conditions were rated significantly higher than the *Heuristics Choice* condition (2.83), according to Bonferroni post hoc comparisons (p's < .05). For Heuristic Set 2, the average ratings on *Heuristic Choice* (3.03) and *Serial Order 1* (2.96) did not differ from the *Heuristic Choice* on Set 1. Heuristic Set 1's *Serial Order* conditions were rated higher than Heuristic Set 2 for this Novel Design Task. The higher creativity ratings observed for the *Heuristics* conditions in both tasks suggest that these instructions resulted in more successful designs compared to the *Control* condition. A sample of highly rated concepts for each condition can be seen in **FIGURE 5.5.**

Redesign Task, Heuristic Set 1, Serial Order 1 	Redesign Task, Heuristic Set 1, Serial Order 2 
Redesign Task, Heuristic Set 1, Heuristic Choice 	Redesign Task, Control 
Redesign Task, Heuristic Set 2, Serial Order 	Redesign Task, Heuristic Set 2, Heuristic Choice 

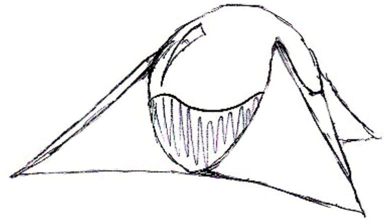
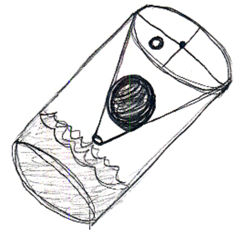
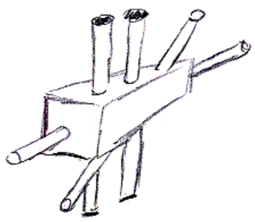
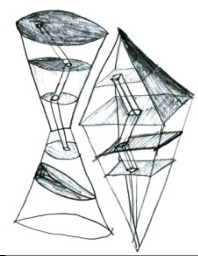
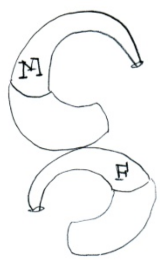
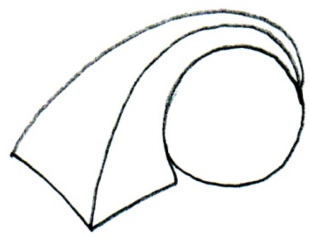
Novel Design Task, Heuristic Set 1, Serial Order 1 	Novel Design Task, Heuristic Set 1, Serial Order 2 
Novel Design Task, Heuristic Set 1, Heuristic Choice 	Novel Design Task, Control 
Novel Design Task, Heuristic Set 2, Serial Order 	Novel Design Task, Heuristic Set 2, Heuristic Choice 

FIGURE 5.5. A design drawing from each condition receiving the highest creativity rating of "7”or “6.5”

When compared with the *Control* group, the highly creative concepts in the *Heuristics* conditions are visually more detailed, have indications (directional arrows) of how they will be used and how contents will come out of the container, have variations in the arrangement of the design elements, and are rarely labeled. These differences suggest the heuristics allowed the participants consider the design differently, resulting in greater novelty in the resulting design forms.

In the Redesign Task, the designs from the heuristics instructions do not appear to resemble any existing shakers or alternative product containers (e.g., soda bottles), as seen in the *Control* condition example. In the Novel Design Task, the pattern was similar. In the *Heuristic* conditions, concepts show a commonality in the combination of both substances into one container with or without detachable parts. Another strong difference is visible in how the products are designed for use. Some of the concepts in the *Heuristic* conditions suggest different ways of dispensing the product or mixing them before using them; for example, in one of the concepts, a sphere holding the substance is placed inside a cylinder. When the cylinder is shaken, the ball drops to the bottom, and the pressure of the contact will force the substance out of the ball and through holes in the bottom of the cylinder. On the other hand, the two containers used in the *Control* group were often designed as separate entities from each other. Heuristics appear to noticeably change participants' designs, resulting in more visual forms. This type of concept generation behavior has been observed in expert designers (Cross, 2004).

When judges were asked to verbalize the underlying factors of their creativity scores, they spoke about the relationships of the design elements to each other, the different ways the products would be used, and about techniques of styling and elaboration of the design. According to them, the highly creative ones had unique, interesting and innovative styles not found in most of the containers sold in stores. Some additional trends were also observed in the highly creative designs, such as, the container was divided into two parts without detachments, or two complimentary containers would fit together when they are not used in certain ways.

For example, in the Redesign Task, in **FIGURE 5.6A**, the participant explained the sketch as:

> ".. I repeated the forms in the previous concept but altered it slightly by reorganizing it and cutting certain shapes in half. The pepper shaker can be placed on top of the salt shaker for convenience."

In **FIGURE 5.6A**, the geometrical forms given to the participant were arranged with opposite angles using the repetition of the same form. The component used for shaking was triangle with again opposite direction from the one provided in the task. The most interesting part is the way they are aligned on top of each other; the participant used the upper surface of the larger shaker as the space for the smaller shaker.

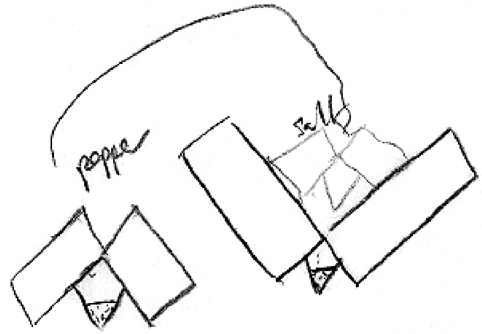


FIGURE 5.6A. Example using *Repeat*, *Configure*, and *Rescale* for a creative solution

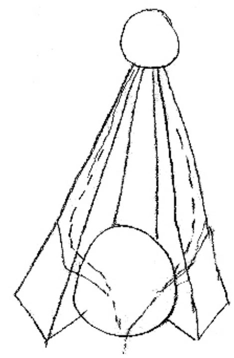
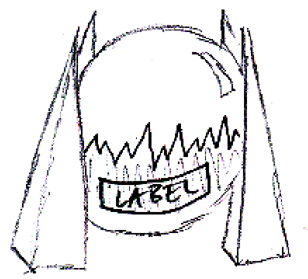


FIGURE 5.6B. Example using *Repeat*, *Configure*, and *Rescale* for a creative solution

In **FIGURE 5.6B**, another participant repeated the elements and created a process where the salt and the pepper particles are mixed in the central ball before they are served and this is achieved through pressing the spherical form on the top. The two containers are merged into one as part of a system.

In the Novel Design Task, since the two genders were asked to be represented in the drink containers, most concepts utilized this as a way to generate distinction. "Male" containers were designed to represent the ideal male shape: wide shoulders, narrow waist. "Female" containers were just the opposite. The most creative ones; however, were the ones using gender roles rather than their physical representations as part of the visual cues. Male containers were the "protectors" and "rigid", while the female was "soft" and "vulnerable." Where the containers complemented each other, the female usually depended on the male, for either physical (literally) or emotional support. Design concepts also took into account whether the user would get enjoyment out of using the containers. Some designs were made to be a game (i.e. Tetris or blocks) or have some kind of interaction with the user apart from just a salt and pepper container sitting on a table.



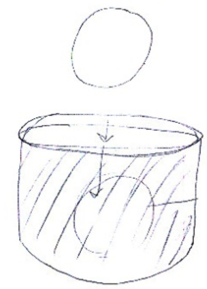


FIGURE 5.7A. Example using *Repeat*, *Configure*, and *Rescale* for a creative solution

FIGURE 5.7B. Example using *Nest* for a creative solution

In **FIGURE 5.7A**, male container is divided among 4 triangular prisms, which are arranged in a square supporting the spherical female container. Analogy used was "lifting the weight of the world with ease" and supporting a "time vessel." The design has a unique appearance due to the alignment of individual parts around a larger, central component, and the way it reflects the meaning to each of the containers.

The concept in **FIGURE 5.7B**, even though very simple, was also rated highly creative. The reason for this decision was probably the distinct way of the components' interaction. The spherical container representing woman fits inside the cylindrical one representing male and floats inside.

AVERAGE PRACTICALITY RATINGS OF DESIGNS

Each of the designs was again coded by the same two judges following the sorting procedure described above, this time rating the practicality of the concepts (using their own understanding of this term) on a seven-point scale, with "1" meaning "Not at all practical," and "7" indicating "Extremely practical." The designs were again rated in isolation from the subjects' booklets, in a different random order for each judge, and required another five sessions, lasting two hours each. **TABLE 5.3** shows a high level of agreement between the two judges in their perception of the practicality of designs.

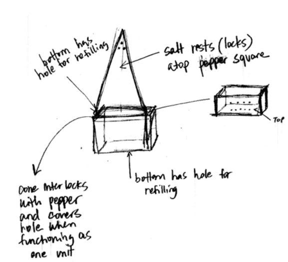
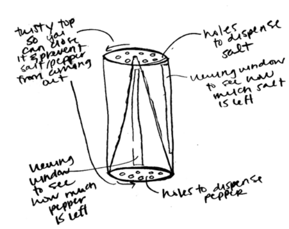
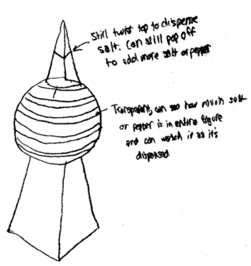
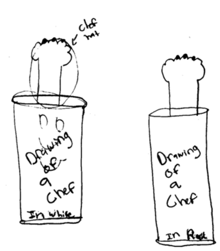
TABLE 5.3. Interrater reliability statistics (Cronbach's alphas) and average practicality ratings for designs per condition

Experimental Condition	Cronbach's Alphas	Practicality Means	Standard Deviations
Redesign Task, Heuristic Set 1, Serial Order 1	.753	4.04	1.766
Redesign Task, Heuristic Set 1, Serial Order 2	.660	4.67	1.706
Redesign Task, Heuristic Set 1, Heuristic Choice	.712	4.56	1.824
Redesign Task, Heuristic Set 2, Serial Order 1	.690	4.94	1.648
Redesign Task, Heuristic Set 2, Heuristic Choice	.650	4.85	1.613
Redesign Task, Control	.603	5.97	1.254
Novel Task, Heuristic Set 1, Serial Order 1	.742	4.72	1.668
Novel Task, Heuristic Set 1, Serial Order 2	.796	4.89	1.623
Novel Task, Heuristic Set 1, Heuristic Choice	.774	4.84	1.585
Novel Task, Heuristic Set 2, Serial Order 1	.703	4.41	1.445
Novel Task, Heuristic Set 2, Heuristic Choice	.791	3.83	1.671
Novel Task, Control	.750	5.15	1.464

TABLE 5.3 also shows the means and standard deviations of the practicality ratings. A One-Way ANOVA using a random effects model with designs nested within subjects was conducted to compare the practicality scores across the twelve conditions. There were noticeable differences in the mean scores of the twelve instructional conditions. For the Redesign Task, the *Control* condition resulted in the highest practicality scores (5.97), significantly higher than any other group in the study. The practicality ratings for Heuristic Set 1 on the Redesign Task resulted in *Serial Order 1* (4.04) receiving significantly lower ratings than the *Heuristic Choice* (4.56) and *Serial Order 2* (4.67) conditions as determined by Bonferroni correction comparisons (p's < .05). These last two groups did not differ from the *Heuristics Set 2* conditions on the Redesign Task, 4.94 for the *Serial Order* and 4.85 for *Heuristics Choice*. In the Novel Design Task, the *Heuristic Set 1* conditions did not differ from each other, with the *Heuristic Choice* (4.84), *Serial Order 1* (4.72) and *Serial Order 2* (4.89) showing no significant

differences, while all three of these groups differed from the scores for Heuristics Set 2 on this Novel Design Task. The *Serial Order* condition (4.41) and the *Heuristic Choice* (3.83) were scored significantly lower on practicality as determined by Bonferroni correction comparisons (p's < .05). This analysis suggests choosing heuristics led to less practical solutions in the Novel Design Task, and in the Redesign Task, the *Control* condition produced the highest practicality ratings in the study.

FIGURE 5.8 shows a sample of designs rated as "highly practical" in each of the twelve conditions. The drawings considered more practical than others in all conditions demonstrated higher clarity of how parts come together, and had more written details about the materials, surface patterns, and mechanisms. They were commonly concepts proposing a relationship between the two complimentary containers, in both tasks. The product designs in the *Control* condition in the Redesign tended to depict functionality, such as explaining how the salt and pepper containers will be filled, cleaned, and stored. This result implies that design heuristics may lead to more abstract or varied form considerations, and therefore more creative solutions; however, this may occur at the expense of practical concern with function, as evidenced in the Redesign *Control* conditions' higher practicality scores.

Redesign Task, Heuristic Set 1, Serial Order 1	Redesign Task, Heuristic Set 1, Serial Order 2
	
Redesign Task, Heuristic Set 1, Heuristic Choice	Redesign Task, Control
	

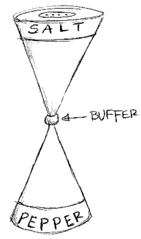
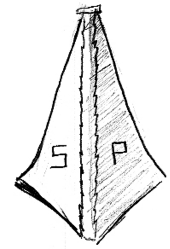
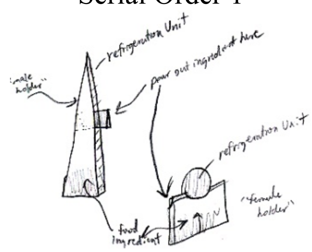
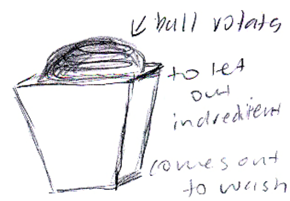
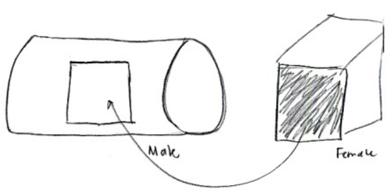
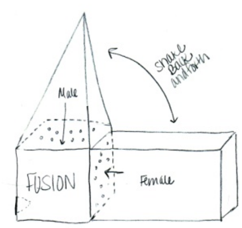
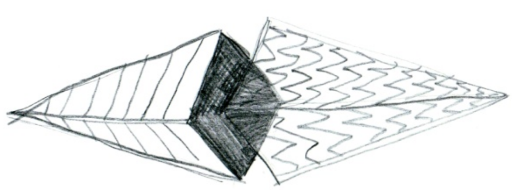
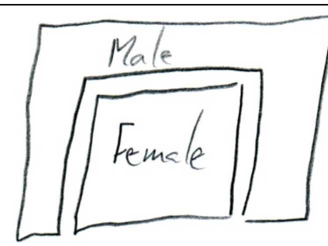
Redesign Task, Heuristic Set 2, Serial Order	Redesign Task, Heuristic Set 2, Heuristic Choice
	
Novel Design Task, Heuristic Set 1, Serial Order 1	Novel Design Task, Heuristic Set 1, Serial Order 2
	
Novel Design Task, Heuristic Set 1, Heuristic Choice	Novel Design Task, Control
	
Novel Design Task, Heuristic Set 2, Serial Order	Novel Design Task, Heuristic Set 2, Heuristic Choice
	

FIGURE 5.8. A design drawing from each condition receiving the highest practicality rating of "7" or “6.5”

5.3.2. HEURISTIC USE

All of the design concepts created were also coded for the presence of one or more of two heuristics in the study (*Merge*, *Change the configuration*, *Substitute*, *Rescale*, *Repeat*, *Nest, Press*, *Hollow*, *Bend*, *Reverse*, and *Twist*). Coding instructions were provided to the two independent judges scoring for the presence of specific design heuristics in the concepts. For each heuristic, the judges were shown the instructional text and an example form that were provided to subjects for each coding (see **FIGURE 5.3**). **FIGURE 5.9** shows an example of the use of heuristics in one participant's concepts in the Redesign task.

Further illustration is provided to show that participants used the heuristics in a variety of ways within their designs (see **FIGURES 5.10 AND 5.11**). These example designs illustrate differences from the simple examples provided in the task instructions, and in the instructions for each heuristic. These designs, in contrast to the *Control* conditions, show intentional variation of the form using the heuristics. Heuristic use led to more complex and detailed visual forms depicted in the subjects' designs. In the *Control* conditions, many of the designs maintained the same form, but introduced a function, descriptive detail, or thematic element.

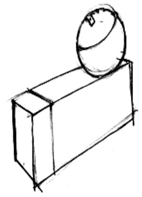
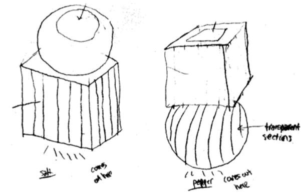
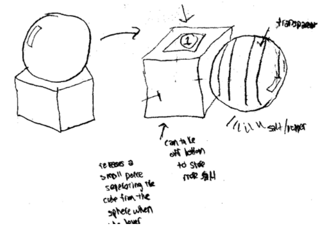
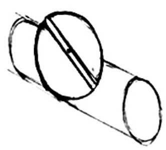
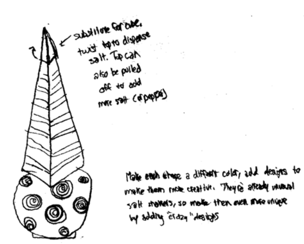
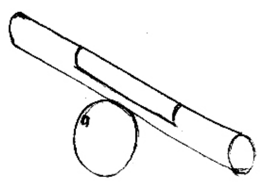
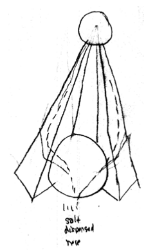
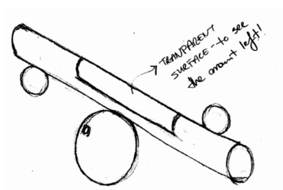
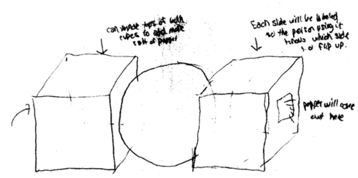
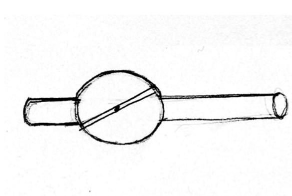
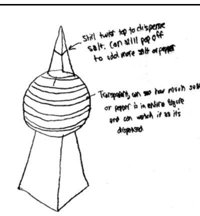
Text Instructions	**Visual Form Example**	**Participant's Concept in Redesign Task**
MERGE Merge the two selected forms to design a salt shaker and design a complementary pepper shaker.		
CHANGE THE CONFIGURATION Change the configuration of the geometrical forms in your previous design.		
SUBSTITUTE Substitute one of the forms in your previous design with another geometrical form.		
RESCALE Change the scale of the geometrical forms in your previous design.		
REPEAT Repeat one of the geometrical forms in your previous design 2-3 times.		
NEST Nest one of the geometrical forms you used in your previous design inside another.		

FIGURE 5.9. Example of concepts generated in a session by one participant in the Heuristic Set 1, *Serial Order 1* condition

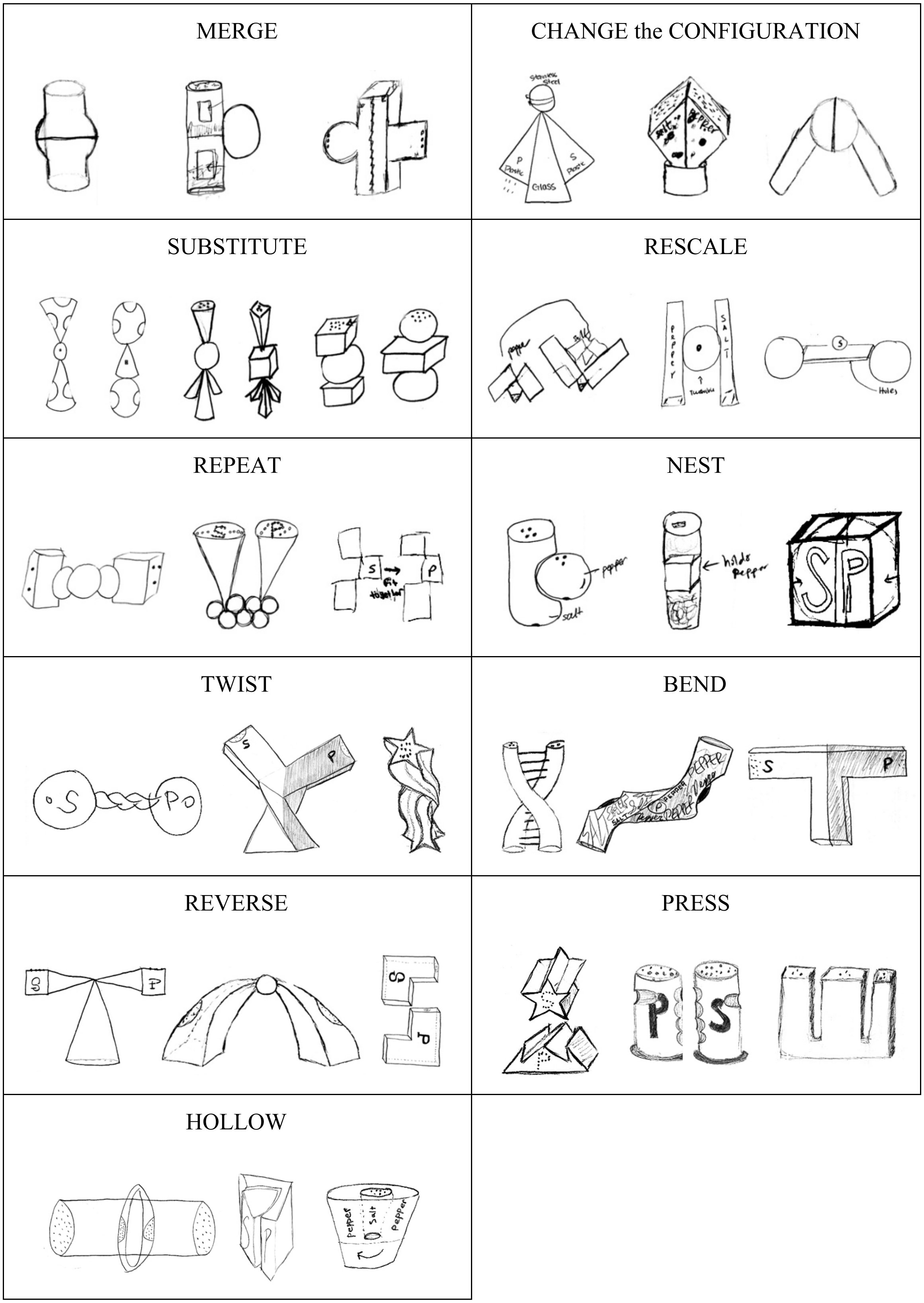


FIGURE 5.10. Three separate final designs generated by different subjects in the Redesign Task in the Heuristics conditions

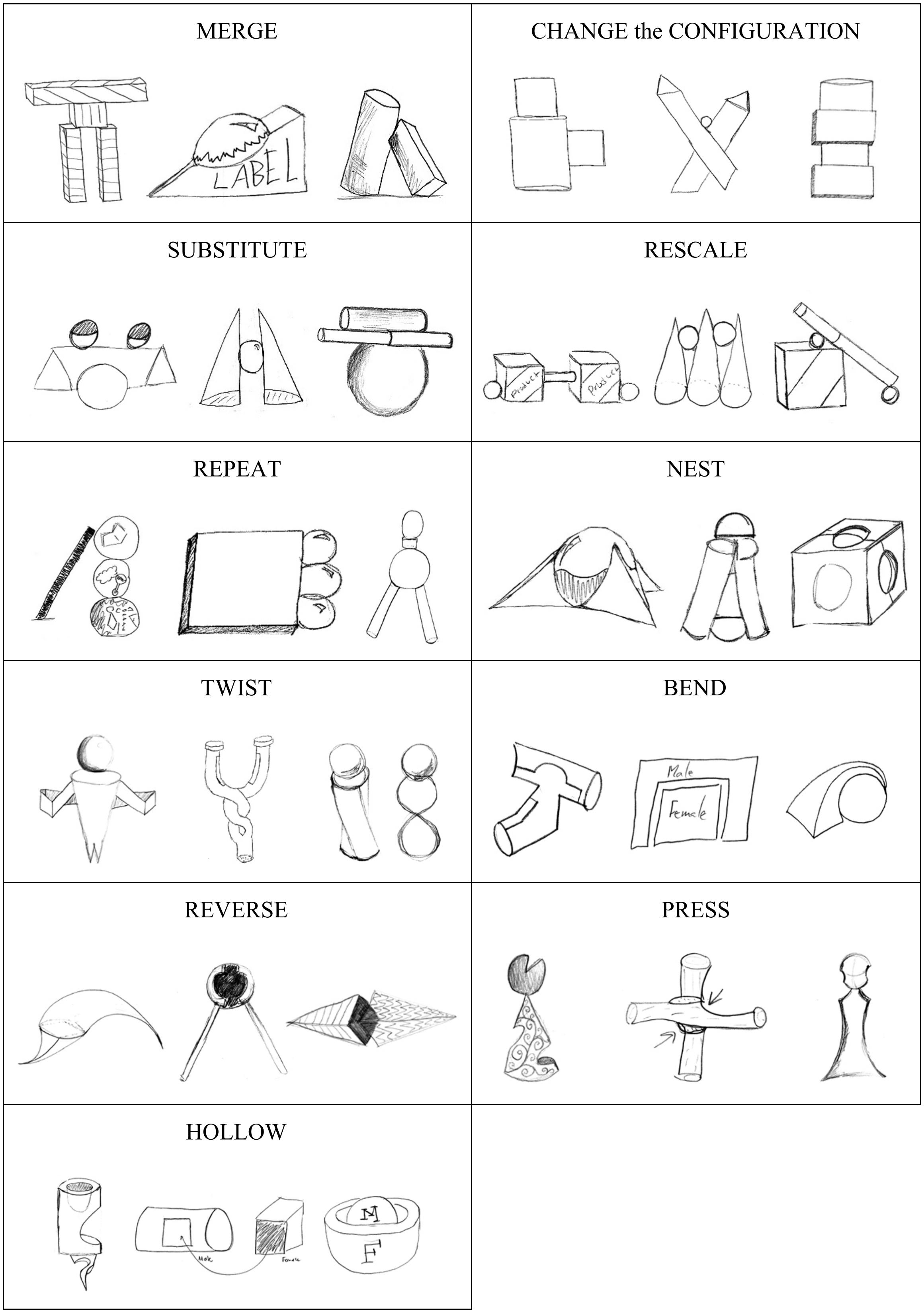


FIGURE 5.11. Three separate final designs generated by different subjects in the Novel Design Task in the Heuristics conditions

TABLE 5.4 shows the number of times each heuristic in Heuristic Set 1 (*Merge, Change the configuration, Substitute, Rescale, Repeat, and Nest*) was observed (by the two judges) by instructional conditions, as well as the two *Control* conditions, for the two tasks. In terms of the number of heuristics observed, heuristics used in both tasks show similar patterns: the four *Serial Order* conditions were coded as showing many more uses of heuristics than the two *Heuristic Choice* or the *Control* conditions, perhaps not surprising given the experimenter-driven task procedure discussed above, where each heuristic was presented serially with time provided to use it. In the *Heuristic Choice* condition, subjects were able to choose whether and which heuristics to use, and as in the four *Serial Order* conditions, the designs incorporated *Merge* and *Change the configuration* much more often than the others. All three *Heuristics* conditions show the greatest use of *Merge*, which was the first heuristic introduced in all of these booklets. However, they also show many uses of *Change the configuration*. Since these conditions also had higher average creativity scores, it appears their advantage may be carried by the use of this heuristic more than any other. Substituting one form with another and nesting one form inside another were used least often in the *Heuristics* conditions.

TABLE 5.4. Observed frequency of six heuristics observed in designs using Heuristic Set 1 and the *Control* groups, including scores from the raters for eight conditions

Experimental Condition	Merge	Change the Configuration	Substitute	Rescale	Repeat	Nest	**Total Number of Concepts**
Redesign Task, Serial Order 1	147	94	34	54	40	31	152
Redesign Task, Serial Order 2	174	76	29	26	47	39	180
Redesign Task, Heuristic Choice	149	74	41	36	44	43	171
Redesign Task, Control	78	28	23	12	22	9	157
Novel Task, Serial Order 1	187	86	31	54	51	42	194
Novel Task,	155	86	42	56	51	46	161

Serial Order 2							
Novel Task, Heuristic Choice	122	77	50	45	45	28	142
Novel Task, Control	80	36	10	18	31	31	142
Total Number of Heuristics Observed	1092	557	260	301	331	269	1299

Surprisingly, in the *Control* groups (where there was no instruction on heuristics), heuristic use averaged one for each design for the Redesign Task, and one for each design in the Novel Design Task, with *Merge* and *Change the configuration* used most often. Other frequently used heuristics in the Novel Task were *Repeat* and *Nest;* on the other hand, *Substitute* was used more often in the Redesign Task within the *Control* condition. This difference may be caused by the symbolic representation of the two genders utilized in the concepts as an analogy in the Novel Task. Commonly, anatomical references, or the suggestions of stereotypes and roles were observed where *Nest* and *Repeat* were applied. In general, the evidence of heuristic use in the *Control* conditions suggests that the heuristics were already known or easy to apply during the design tasks, even for these novice designers. Most prominently, substituting one shape for another appears to play a role in the designs created in the *Control* conditions independent of the context provided in the design problem.

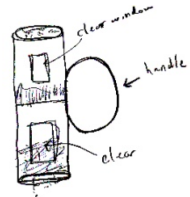
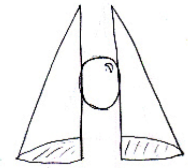
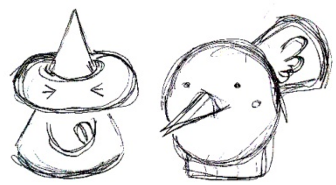
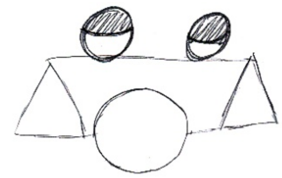
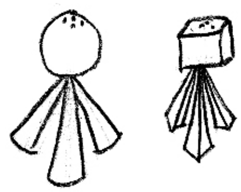
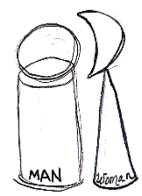
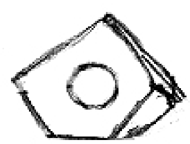
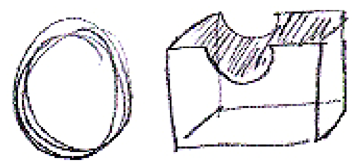
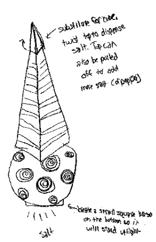
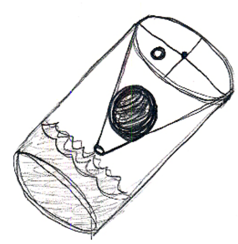
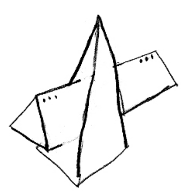
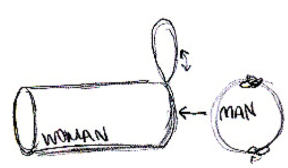
TABLE 5.5 shows the number of times each heuristic in Heuristic Set 2 (*Merge, Press, Hollow, Bend, Reverse, and Twist*) was observed (by the two judges) for the four conditions where their instruction was provided.

TABLE 5.5. Observed frequency of heuristic use in the designs using Heuristic Set 2 including scores from the raters for all four conditions where instruction was provided

Experimental Condition	Merge	Press	Hollow	Bend	Reverse	Twist	**Total Number of Designs**
Redesign Task, Serial Order	14	36	37	44	42	23	145
Redesign Task, Heuristic Choice	50	50	39	44	24	27	167
Novel Task, Serial Order	123	32	48	33	50	32	168
Novel Task, Heuristic Choice	60	42	43	44	26	35	147
Total Number of Heuristics	247	160	167	165	142	117	627

Introduction of the heuristics in this second set was effective, with more uses observed in the *Serial Order* condition in the Novel Task (318 heuristics used in total), whereas participants in the *Heuristic Choice* condition used more heuristics in the Redesign Task (234). The difference seems to result from applying *Merge* as a major heuristic for three fourths of the concepts in the *Serial Order* condition in the Novel Task (123), but not applying it as instructed in the *Serial Order* condition in the Redesign Task (14). In both *Heuristic Choice* conditions, *Press* is used more often than the *Serial Order* conditions in contrast to *Reverse,* which is more evident in *Serial Order* conditions.

Commonalities among designs were also evident in the presence of additional components (handles, stands, etc.), use of analogy (real-world, non-imaginative designs), complementary forms (paired forms), context, cuts (missing parts not represented anywhere else), details (providing additional details), interactions (multiple forms interacting), movements (the expression of motion), splits (cutting the form, and then representing it somewhere else), and support by using forms leaning towards each other (examples shown in **FIGURE 5.12**).

<table>
<tr><th></th><th>Redesign Task</th><th>Novel Design Task</th></tr>
<tr><td><u>Addition:</u> using an additional components</td><td>
</td><td></td></tr>
<tr><td><u>Analogy</u>: using analogy</td><td></td><td></td></tr>
<tr><td><u>Complementary</u>: paired forms</td><td></td><td>
</td></tr>
<tr><td><u>Context</u>: concrete context</td><td>
</td><td></td></tr>
<tr><td><u>Cut</u>: cutting forms</td><td></td><td></td></tr>
<tr><td><u>Detailed</u>: detailed information</td><td></td><td></td></tr>
<tr><td><u>Interaction</u>: Interacting forms</td><td></td><td>
</td></tr>
</table>

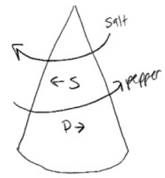
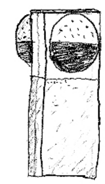
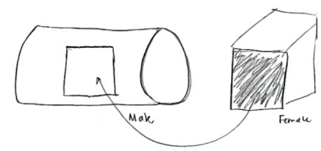
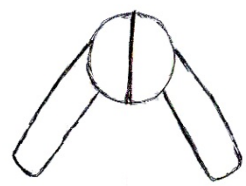
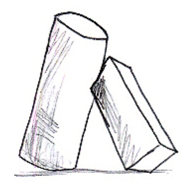
<u>Movement</u>: expressing motion		
<u>Split</u>: splitting forms		
<u>Support</u>: forms leaning towards each other		

FIGURE 5.12. Other categories commonly observed for all design concepts

Two categories that most distinguish the *Control* conditions from the ten *Heuristic* conditions are the use of context and analogy. For example, one control drawing labeled the form with a university logo to make it distinctive based on content rather than form, and this was a frequent strategy in the *Control* group. Similarly, most concepts in the *Control* condition used analogy to other known objects, such as animals, gender roles, and anatomical features to bring distinct ideas in without creating distinctions in form. Previous studies have provided evidence for the role of analogy as an important cognitive process during design (Benami & Jin, 2002). For our novice participants, left without heuristic instruction in the *Control* condition, analogy helped them to make use of knowledge and memory for existing product sources.

In sum, the designs in the two *Control* conditions include many with simple forms, and variation was introduced by adding a new function, detail, or theme. In the ten *Heuristic* conditions, the designs show more intentional variation and greater complexity of form, presumably assisted by using the design heuristics available from the instruction. This analysis of design content supports the conclusion that heuristics instruction can assist even novice designers in creating more varied visual forms, leading to designs rated as more successful and creative.

5.3.3. TASK PERCEPTIONS

Two final questions asked participants about their perceptions of the task. When asked, "How did you find this task?" (with "7" meaning "difficult"), most indicated they found it challenging, with an average rating of 4.8 across conditions. There were no differences by experimental condition for these ratings, $F(11, 348) = .688$, $p > .05$. The mean ratings in the *Serial Order* conditions for Redesign Task using Heuristic Set 1 (*Serial Order 1*: $M = 4.7$, *Serial Order 2*: $M = 4.8$) were somewhat lower than the *Heuristic Choice* ($M = 4.9$) and the *Control* ($M = 5.1$). The mean ratings of the responses per condition are seen in **TABLE 5.6**.

TABLE 5.6. Mean ratings for the question "How did you find the task?" per condition

	Redesign Task				Novel Design Task			
	Serial Order 1	Serial Order 2	Heuristic Choice	Control	Serial Order 1	Serial Order 2	Heuristic Choice	Control
Heuristic Set 1	4.7	4.8	4.9	5.1	4.7	5.1	5.0	4.6
Heuristic Set 2	4.9		4.7		4.7		4.6	

When asked to self-evaluate their success in the task (with "7" indicating, "I did not do too well"), the average ratings were again similar across conditions, $F(11, 348) = 1.101$, $p > .05$. For the novice participants, the design tasks were challenging, and resulted in low expectations of success across conditions. The mean ratings of the responses per condition are seen in **TABLE 5.7**.

TABLE 5.7. Mean ratings for the question "Please self-evaluate your success in the task" per condition

	Redesign Task				Novel Design Task			
	Serial Order 1	Serial Order 2	Heuristic Choice	Control	Serial Order 1	Serial Order 2	Heuristic Choice	Control
Heuristic	4.9	4.7	5.0	4.9	4.8	5.0	5.0	4.8

Set 1								
Heuristic Set 2	4.7		4.5		4.5		4.7	

These ratings results suggest that the participants found the tasks challenging, and they did not feel entirely successful in their performance however, their perceptions did not differ based on experimental condition.

5.4. DISCUSSION

This empirical study suggests the potential effectiveness of instruction on design heuristics. Even for novice designers, a few minutes of text and illustration on specific heuristics led to designs reliably judged as more creative, in both the Redesign and the Novel Design Tasks. Through use of heuristics, the designs appeared more engaged with visual form, more varied, and more successful than those in the *Control* conditions. The results suggest that the ideation phase of design can be assisted by explicit instruction on design heuristics.

The most creative concepts emerged from the experimental conditions where heuristics were introduced. Heuristics appeared to help the participants "jump" to a new problem space, resulting in more varied designs, and a greater frequency of designs judged as more creative. The findings suggest that simple demonstration of design heuristics may, at times, be sufficient to stimulate divergent thinking, perhaps because these heuristics are readily grasped and contextual application is not required. Based on these findings, a conceptual model for design education emphasizing the importance of using a variety of heuristics is proposed in Chapter 8. These results suggest that learning can be enhanced through exposure to a variety of design heuristics, and can supplement formal education and foster personal development in design learning.

5.4.1. Evaluation of Findings

In the context of this empirical study of design creation with novice designers, I sought to answer the following research questions:

Question 1: Does the use of heuristics in general lead to more creative designs?

Design heuristics, when applied to the design problem in the study, increased the creative success of designs. The concepts generated by participants through the use of heuristics appeared more diverse and unusual, concentrated more on visual form, and were judged as more creative. Variation was also introduced by subjects in the *Control* condition, primarily through reference to themes and labels, analogy to other objects, and functional qualities. However, these diverse designs were not judged to be as creative as those produced through the heuristic instruction conditions. Heuristic use led novice designers to consider candidate designs outside of ones they could generate alone, leading them to more diverse and creative ideas. This result has important implications for the way we should teach designers how to think about design creation, and for the kinds of cognitive strategies they may learn through instruction in design.

Question 2: Which design heuristics are most effective in creating novel designs?

Eleven candidate design heuristics were compared in the process of generating creative designs. Two of these heuristics, provided in the Heuristic Set 1 conditions for both design tasks, *Merge* (93%) and *Change the Configuration* (49%) were used the most in designs created by the six heuristics instruction groups. The use of these two heuristics alone appears to have been a major factor in the success of these designs. Both heuristics focus attention on the individual forms and their composition. This may encourage the consideration of alternative combined forms that are more complex, and therefore more distinctive. In the *Heuristic Choice* conditions alone, where people were free to select any heuristic, *Merge* appeared in over 85% of the designs, and *Change the configuration* is seen in 48% of the designs. By their ubiquity, they appear to play an important role in the success of the heuristic-based designs. The other four heuristics in Heuristics Set 1 (*Substitute*, *Scale*, *Repeat*, and *Nest*) were observed in 20-28% of the designs. These heuristics may be more appropriate in only some candidate designs; even so, each appears in more designs than expected.

In the conditions using Heuristic Set 2 (*Merge*, *Press*, *Hollow*, *Bend*, *Reverse*, and *Twist*), *Merge* was used the most (40%). This percentage appeared to be considerably higher in the *Serial Order* condition working on the Novel Design Task where 73% of the designs created used *Merge* as a heuristic in alternative solutions. On the other hand, in the Redesign Task, *Merge* was utilized only in 10% of the designs. This difference suggests that participants working on the Novel Design Task may have needed more design elements to create concepts than the participants in the Redesign Task.

QUESTION 3: DOES THE EFFECTIVENESS OF HEURISTIC USE DIFFER WHEN APPLIED TO REDESIGN PROBLEMS VS. NOVEL DESIGN PROBLEMS?

The differences in creativity outcomes based on Heuristic Set (1 vs. 2), and on *Serial* vs. *Choice* orderings, point to possible differences in the usefulness of a given heuristic depending on the design task and context. Further studies are needed to investigate the effects of the ordering and combination of heuristics across sessions, as observed in the naturalistic studies of designers in Chapters 3 and 4. In the following chapter, heuristics are further discussed, and a system designed to facilitate their selection for use in specific design settings is proposed in Chapter 7.

One implication of this research is that heuristic use can be supported with simple written instructions along with visual examples. Another implication is that heuristics are applied frequently once they are learned even when not under instructions to do so; for example, the ten instructional groups on average used more than two heuristics within *each* design. The results also indicate that more than eighty percent of the participants in the *Control* condition used one or more heuristics without any instruction. This implies that generating concepts using heuristics may be a natural approach to design, and that providing specific instructions on design heuristics will take further advantage of their utility.

This study also suggests that creativity can increase through heuristic instruction even in novice designers. The student sample used in this study provides a test bed for examining the effects of heuristics on novices, a population that may exhibit more malleability in training compared to seasoned experts. Further, the design task involved no technical or background knowledge and this may be helpful in learning to generalize the use of the heuristics appropriately. These factors will be important to consider when extending the design pedagogy for heuristics to design settings.

CHAPTER 6

DESIGNING WITH DESIGN HEURISTICS

"THE WAY IS LONG IF ONE FOLLOWS PRECEPTS, BUT SHORT... IF ONE FOLLOWS PATTERNS."
LUCIUS ANNAEUS SENECA

OVERVIEW

This chapter presents each design heuristic explored in previous chapters. Each page includes one design heuristic, the primary and secondary purposes for each heuristic's application; i.e. interest, user, whether it is a specific (S) or a general (G) use heuristic, two examples selected from the analysis done in Chapter 2 and their descriptions explaining how the heuristic is used in the product, and where in the thesis they are observed. This section investigates design heuristics further with example products and detailed descriptions of how these heuristics can be used in idea generation. Process heuristics follow; however, since they represent the process rather than an outcome, examples are selected from Chapter 3, Chapter 4, and Chapter 5.

6.1. THE RELATIONSHIP OF DESIGN HEURISTICS TO PURPOSE

The purpose of using each heuristic is split into Primary and Secondary Purposes. These purposes can be defined in the design task, and/or decided by the designer or the design team. The purposes are used in investigating the reasons for professional designers to

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6.1. THE RELATIONSHIP OF DESIGN HEURISTICS TO PURPOSE

The purpose of using each heuristic is split into Primary and Secondary Purposes. These purposes can be defined in the design task, and/or decided by the designer or the design team. The purposes are used in investigating the reasons for professional designers to utilize some heuristics but not others. **FIGURE 6.1** shows the definitions of each purpose used in the heuristics categorization.

Heuristic combinations have been identified repeatedly in prior chapters; however, for the clarity of heuristic presentations, they are not mentioned in this guide to heuristics. Example products are also presented for each heuristic.

Purpose	**Description**	**N**	**%**
Cost	Reducing cost for manufacturing.	21	14%
Diversity	Creating diversity by outlining conditions for change.	7	4%
Efficiency	Creating efficiency in use or manufacturing without wasting time or energy.	13	8%
Engineering	Solving the technical problems in an analytical way.	17	11%
Interest	Engaging interest or excitement in using.	21	14%
Multifunctionality	Featuring more than one function.	23	15%
Sustainability	Meeting the needs of the present without harming the environment.	9	6%
Usability	Creating functional relationships between people and the products and the systems.	32	21%
User	Focusing on the user.	11	7%

FIGURE 6.1 Definitions of each purpose used in the categorization of heuristics and their frequency in the heuristic presentation

6.2. DESIGN HEURISTICS

The design heuristics identified in each chapter are listed below. Each heuristic is explained and examples showing how they are applied to products are provided.

1

ADD FEATURES FROM NATURE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Explore commonalities in the product and the potential examples in nature, and implement the dominant characteristics from nature within the product.

S

The task light uses "the great heron" as the inspiration, and displays similar versatility in the neck flexibility.

The bright, unbreakable lines of suction cupped accessories are attached to the walls and allow users create flower gardens with them in their bathrooms.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

2

ADD GRADATIONS OR TRANSITIONS TO USE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Use a series of gradual/transitional changes in the use of design elements. Identify different ways or sizes the product can be used by keeping the function stable and facilitate gradual transitions between those different uses.

S

The product is designed as a drying rack with gradations for different dishes.

The dish rack can be custom tailored to the individual needs of each person by replacing the individual components that create the entire product.

3

Add Motion to the Product as a Playful Attribute

Apply motion as part of the product's function to create an emotional attachment with the user, and to decrease the need for user activity.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The vacuuming is done by a robotic floorvac which cleans the place by itself throughout the day.

The alarm clock is designed to jump off the table and move using the two wheels on the sides while emitting loud sirens.

4

ADD PORTABILITY

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Portability can be provided within a design through many channels: by replacing material with a lighter-weight one, using wheels and handles as part of the design, folding the components to reduce the size, or stacking components.

S

Porcelain is used for convenience in carrying the product. Attaching a handle also makes it easy to carry.

The lantern's energy source is converted into a portable one by making it rechargeable. This way, it can be used as a table lamp, but also carried to different locations.

Adjust Functions to Needs of Differing Demographics

5

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Formulate the functions specific to different characteristics of a population, such as age, gender, education, occupancy, and diverse abilities.

S

The cardio fitness product adapts and instantly customizes to fit to each individual user's body size through a variety of connected parts and adjustable components.

The laptop is specifically designed for kids living in developing countries. The size, colors, and interface all contribute to the playfulness of the product.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

Align Components around a Central Main Function

6

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Orderly arrange components around a circular or cylindrical design element using the central piece for the main function. A reconfigurable device consisting of a core central structure may allow for aligning or positioning different peripheral parts.

G

The device allows for six audio devices to be shared with one another. All the components are collected in the center, and the six input jacks are placed around it.

By combining the central mechanism with a self-pull corkscrew, the product removes the cork from the bottle easier and faster.

7

Animate Look by Adding Human Features

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Replicate human features in an abstract way in order to improve the usability, likability, or functionality of the product. Different emotions or behaviors people experience can also be part of the abstraction.

S

	
The dish soap dispenser is designed to mimic a human body with a head, neck, and main body.	The set of salt and pepper shakers hug each other, abstracting human figures. The black and white colors also suggest balance and harmony.

8

APPLY A MECHANISM IN A NEW WAY

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

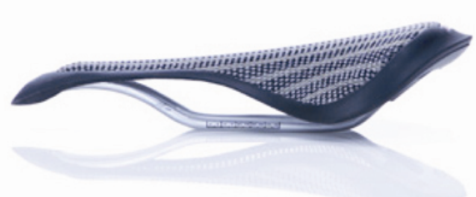
USABILITY

USER

Identify basics of mechanisms for similar functions in different contexts, and determine how they can be applied in new settings. Consider the transfer and scaling effects that may undermine the success of the mechanism and adapt them accordingly.

S

The device allows for the tape measure used as a digital tape measure with an LCD display.



The bicycle seat design is inspired by office seat technology and applies a similar elastomeric mesh surface to the bikes.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

9 ATTACH INDEPENDENT FUNCTIONAL COMPONENTS

Several different parts or systems with distinct functions can combine to create a single device. Define each function independently, assign form to each, and add a connection between parts.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The product combines a paint roller with onboard paint storage. This way, two products working independently are attached to work together and increase efficiency.

The protective inner shell and the outer cover are combined for the helmet. Each owner can also customize the outer cover while separating it for cleaning.

10 ATTACH THE PRODUCT TO THE USER

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Design the product around user so that the user becomes part of the function. Attach the product to different body parts, such as user's head, finger, or feet, and redefine how the product will be used by that part.

S

The product functions as a wellness tracker in the form of a wireless device, and is clipped to clothing during exercise.

The vegetable peeler functions as an extension of the hand. It is slipped onto the finger like a ring.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

11

BEND INTO ANGULAR OR ROUNDED CURVES

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Form an angular or rounded curve by bending a continuous material in order to assign different functions on the bent surfaces. The up and down indents can also be used as part of an elevation or a stand.

G

The molded tray uses the same material to serve a variety functions by bending from multiple corners. Bending also assists in creating cavities with differing angles.

The bent product is used to help those with limited hand mobility to control objects.

12

CHANGE THE CONFIGURATION OF THE ELEMENTS

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

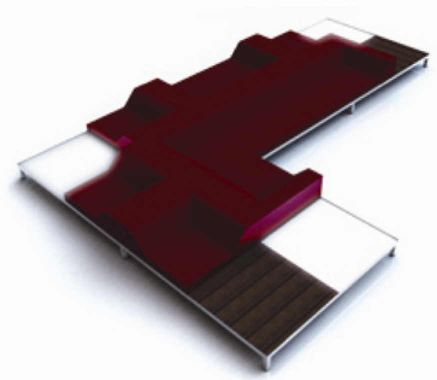
USABILITY

USER

Identify similar functional clusters in the product, and define their relationships with other elements. Provide flexibility in use through elements that can be reconfigured according to user needs and desires. The optional changes can be achieved by simple attachments or alignments of components.

G

The modular power strip enables users to add or subtract sockets as needed. The modules can also be rotated 180 degrees for easy access.



The seating unit is composed of a continuous flow of foam cushions with broad arms. It is based around two cushions that can be oriented in numerous configurations.

13

CHANGE THE DIRECTION OF ORIENTATION

Perform different functions based on the orientation or angle of the design elements in a product, such as flipping a product from vertical to horizontal direction.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The wheels are shifted inwards to provide more balance to the bicycle at lower speeds and support stability.

The activity gym converts to a toddler keyboard by flipping 90 degrees for use through 24 months.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

14 CHANGE THE GEOMETRICAL FORM

Use simpler geometrical forms to achieve the same function, and explore the capabilities of the new form. Changing the form from the familiar ones also redefines the interaction of the product with the user.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The circular microwave uses a base and a lid, allowing access from all angles, making it easier to pick up the food.

The grater bucket turns the traditional hand-held grater upside down by changing the form to a cylindrical one.

15 Change the Surface Material at Points of Human Contact

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Use a different material on the product where the user will touch the product for safety or comfort purposes. Apply a different color or pattern to communicate where to hold or touch the product.

G

The handle used in the tea pot has a distinct look and color provided by the selected material, showing the user where to grab or hold.

The material used on the hammer is changed on the handle to have better shock-absorbance and to provide more comfort to the hand.

16

CHANGE WHERE OR HOW THE PRODUCT WILL BE USED

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Determine alternative ways of using existing products according to the needs of users and differing circumstances. This can create a new spectrum of products.

S

The hands-free braking and turning system allows athletes to maintain control without using their hands. This is achieved through body motion controls, such as leaning.

The tracking ball feature in the computer mouse is taken from the bottom of the product and placed it on the top, and the control is given to the thumb.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

17

Compartmentalize Functions into Distinct Parts

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Define distinct compartments within the product that are used for complimentary functions. This can be achieved either with flexible or rigid materials, and improves user interface with the product as well as multi-functionality.

G

The neoprene bag is split into two compartments for drink and food. Since this separation is done within the same product, they function together.

The car cleaning tools are carried within the same basket where the water is held by splitting the product into two compartments.

18

COMPRESS PRODUCT SURFACE TO CREATE CONTROLLER

Apply pressure to a part of the product for adjusting or controlling the function. Then, position controls and information on the compressed parts by separating them from the main body and changing their levels.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The music player's controlling buttons are designed to be part of the product.

The light is controlled by the inner glass and the pressed sections on it.

19 CONTROL OR CHANGE FUNCTION THROUGH MOVEMENT

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Control the degree of function by moving the product's parts, or the entire product. Create structures that would produce different types of motions, such as rotating or sliding motions, and use them while transferring one function to another as a control mechanism.

S

The light's glow is altered by pushing and pulling the external shade up and down, instead of using a traditional switch.

This round device includes an easy-to-hold-and-use interface that allows personalization in the alarm sound by rolling over the clock around its center.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

20

CONVERT PACKAGING TO ANOTHER USE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Convert packaging into something else (such as a game) after the product is removed. This allows reuse of packaging to achieve another function.

S

The Y-shaped bottles turn into a game after their use. They can be attached to each other in various configurations to make interesting sculptural forms.

Discarded plastic bottles are used to collect rainwater and convert it into drinking water through an attached component that cleans the water.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

21 Convert Two-Dimensional Materials into Three-Dimensional

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Create an object by manipulating two-dimensional geometrical surfaces around an axis, or twisting them in various directions in order to generate a three-dimensional product; change or create a curvature or an inner surface by using sheet materials to produce different functional outcomes.

S

A trash can is made out of recycled sheet plastic rolled around its center. Since it can be entirely flat, it also enhances the efficiency of transportation and storage.

A light made out of sheet metal is twisted around to give directional options for controlling light intensity.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

22 COVER / FORM SHELL / WRAP SURFACE FOR OTHER USE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Overspread the surface of the product with another component to utilize the inner surface. Through the additional material, products can be customized, inner components can be protected, and safety can be increased.

G

The fabric cover keeps the tea hot and accentuates the sleek lines of the glass jar, as well as protecting the user's hands.

The product features a desktop that can be personalized with nine interchangeable color casings covering the inner component, and oriented vertically or horizontally.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

23 COVER OR REMOVE JOINTS FOR SAFETY AND VISUAL CONSISTENCY

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Remove joints in the design, cover them with other materials, or change their orientation. Eliminating joints reduces the number of parts, which reduces the risk of fracture.

S

These glasses do not use any screws, coil springs, or welds. All the design elements are clipped to each other, and can be customized by users individually.

The lid of the trash can is connected to the edge without any fasteners.

24

CREATE A HIERARCHY OF FEATURES TO MINIMIZE STEPS

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Present the user with functions in a set order to assist them while using the product. Make the steps for reaching each function clear, for example, by not allowing the user to access the second function without going through the first.

S

The interactive water bottle determines the amount of water passing through an impeller assembly, monitors real-time fluid consumption, and paces fluid intake.

The outer surface of the pill bottle is used for the prescription information, and the inside is used for holding the pills. Colored bands allow personalization.

25 CREATE A SYSTEM USING A PROCESS

Connect parts with different functions to develop a multi-stage system to achieve an overall goal.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

A pump attached to the pedal crank draws water from a large tank, through a filter and into a smaller, clean tank, creating a filtering system using the bike.

The product works with one-touch dispensing of the cleaning solution, which is connected to the disposable cloth, allowing the floors to then be mopped with this combination.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

CREATE MODULAR UNITS BY REPEATING, SUBSTITUTING, OR SPLITTING COMPONENTS

26

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Repeat the same design element multiple times in order to generate modular units. Product modules are distinct building blocks that combine to form machines, assemblies, or components that accomplish an overall function.

S

These modules allow several combinations (shelf, table, or closet), offering flexibility and rapid adaptation to varying user needs.

The user configures the gaming tower. Splitting the functions into independent modules also allows for an open structure where they are visible and air flow is improved.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

27 CREATE RECYCLE RETURN TO MANUFACTURER

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Compose mechanisms with a service approach where the products are part of a manufacturer system, and are returned after their shelf lives. The service approach requires products to be easy to disassemble, durable and reliable.

S

The phone is leased to the user as a service and is returned to the manufacturer after a year. Some of the parts are replaced for reuse as a next generation of the product.

The product is used as a public collection bin for batteries, using leftover power to light the attached LED street lamps. The batteries are then sent to the manufacturer for discarding.

DESIGN USER ACTIVITIES TO UNITE A COMMUNITY

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

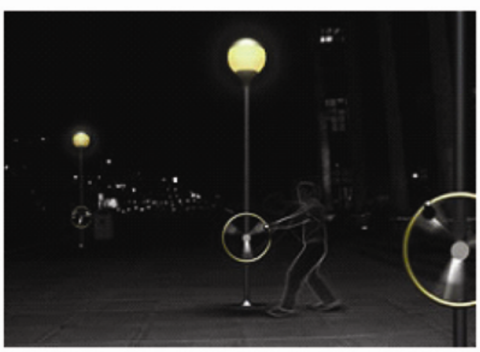
SUSTAINABILITY

USABILITY

USER

Connect communities through products and activities required for products' functions.

S



The sustainable street lighting system is composed of a network of street lamps collecting energy from pedestrians who take a turn at the crank-wheel to generate light.

The business cards express the company's identity, and are manufactured with used packages collected by the company's staff.

29

Elevate or Lower Product Base

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Raise up or lower either the entire product or its parts. Elevating can provide adjustability in use by allowing ergonomic solutions, and can suggest additional functions.

G

Ergonomics are improved by a single action that lifts the display and keyboard at the same time.

The folding rubber feet provide the option of an attractive vertical position for the modular networking device while hiding screw holes.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

30 EXPOSE / UNCOVER INTERNAL COMPONENTS

Show the inner components of the product by removing the outer surface or making it transparent. This enhances reliability and makes the product appear more user friendly.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The watch doesn't only show the inner mechanism through the transparent surface, but it also uses different hand colors.

The soap dispenser designed for public bathrooms uses a translucent plastic enclosure, allowing cleaning staff see how much soap is left at a glance.

Express User Values in the Product

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Observe users' behaviors; for example, how they approach similar products, how they bring cultural cues to the product's use, and how they share these products with others. Carry these observations to the product by changing the approach, material, etc.

S

With this stroller, parents are able to safely interact face-to-face with their children because babies are facing their parents rather than the opposite way.

The baton is designed for runners. As the runners meet at each handoff point, they fill each cup with water for a toast: a fitting ritual that embodies the cause.

32 EXTEND SURFACE AREA FOR MORE FUNCTIONS

Widen the surface of the product to allow for additional functions or adjustments in functions.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

Due to its asymmetric design, the storm umbrella makes it comfortable and easy to use in windy weathers.

The material is extended to serve a secondary function using the same material: a handle for the ruler.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

33 FLATTEN PRODUCT SURFACE

Compress the product until it becomes a flat surface. Flattening the product can provide combinations of different mechanisms by using flexible or elastic materials.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The lighting unit collapses (when not in use) on the cavity that is defined by the bottom support of the product.

The container has several layers that are nested inside each other for storage when the product is not in use.

34 FOLD PRODUCT PARTS WITH HINGES, BENDS, OR CREASES TO CONDENSE SIZE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Create relative motion between parts or surfaces by hinging, bending, or creasing to condense the size. Foldable structures are capable of automatically varying their shape from a compact, packaged configuration to an expanded form.

G

The faucet can be extended entirely or compactly folded from three joints, giving flexibility to the user.

The task lamp puts the light where it's needed due to the adjustability created by multiple joints, including the one on the head of the lamp.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

35 HOLLOW OUT INNER SPACE FOR ADDED COMPONENT PLACEMENT

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Remove the inner part of the product to allow for the placement of another component.

G

The inner part of the product is hollowed out to place the garlic, and the attached metal paddle is used for crushing multiple cloves.

The individual tools are kept inside the gap in the main body.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

Include Users in Customizing or Assembling the Product

36

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Make the user part of the process by giving them options in customizing their products, or giving them individual parts for assembly. People feel ownership when they are involved in the decision process, which allows them to be more aware of the products and their use.

S

The line of do-it-yourself paper cars with a high-gloss realistic finish gives children a sense of ownership and achievement, and teach them how to reuse paper.

The plastic slippers have holes designed for air flow, but also used for attaching small buttons reflecting the user's preference and personality.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

37 INTEGRATE OR ATTACH THE PRODUCT TO AN EXISTING ITEM

Utilize an existing product as part of the function of the new product.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The hanger prevents laundered clothes from sliding down the clothes line through an additional component attached to the hanger with a spring.

The two-piece customizable buttons cover existing buttons by snapping on, accommodating restyling.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

38 Make Components Attachable and Detachable

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Make individual parts attachable or detachable for additional flexibility. Detached design elements make the product easy to clean, easy to carry, and easy to fix.

G

The grill is equipped with a detachable storage compartment for user convenience. This allows for easy cleaning and serving by using the detached component as a tray.

The tweeter and two bass speakers are assembled in a cylindrical construction to protect the speakers while in transit.

39

MAKE THE PRODUCT EXPANDABLE TO FIT VARIOUS SIZES

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

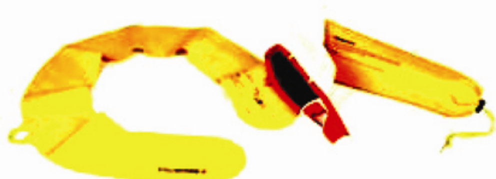
SUSTAINABILITY

USABILITY

USER

Fill an enclosed space constructed of flexible material with air or fluid to create changes in form and adjust function. Or, use flexible structures to provide expansion in the product by leaving gaps in the connecting parts within the product.

S



The rescue stick inflates when it touches the water. This way, it can be used by anyone regardless of their size.

The lightweight polymer provides flexibility and expansion by using the same material throughout, and removing the aligning component in the watch.

40 MERGE FUNCTIONS THAT CAN USE THE SAME ENERGY SOURCE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Combine products that work separately but use the same energy source, and align them around the source or stack them on top of each other to create a single functional device.

S

The washing machine combines drum dryer, hand-washing sink, and water heater within the same unit.

The product is a combination of a faucet and filter, allowing the same water source to be used for two distinct purposes.

41

MERGE SURFACES

Bring together functions complimenting each other or suggesting a common use, and merge the surfaces of the functions to create a product.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The product combines four tools into one solid tool. Both the top and the bottom of the handle are used for different functions.

By removing middle section, the double pin design holds cords and wires with more stability.

42

Mirror Shapes for Symmetry

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Mirror an equivalent element around a central axis or line to create symmety between elements. Symmetry in forms may result in equally shared force for different functions, reduce the manufacturing cost, receive more attention, and are better recalled after being seen.

G

The framing hammer has a modular head design, allowing customization with different combinations of head types.

The magnets aligned on each side are used as a paper clip by snapping them towards each other. The units also suggest a toy by attaching the magnets to each other.

43 NEST (HIDE / COLLAPSE / FLATTEN) ELEMENTS WITHIN EACH OTHER

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Place an object inside another object entirely or partially, wherein the internal form of the containing object is similar to the external form of the contained object: One object is placed inside the other or one object passes through a cavity or interfaces with a cavity in another object.

G

The portable computer has a hidden keyboard nested inside the main body, and can be taken out when in use.

The cable management accessory attached to the armband manages headphone cable length, and keeps the unused section inside.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

44 OFFER OPTIONAL COMPONENTS AND ADJUSTABLE FEATURES

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Provide additional components that can change function or add adjustability. These components can be attached to the main body, carried in a separate case, or can be stored at another place and used when needed.

S

The cleaning tool combines 3 functions in a single tool by using both sides of the brush, and attaching different heads with varying surfaces and materials for different functions.

The storage system consists of 20 parts, and can be combined to make more than 80 products creating a variety of configurations.

Redesign Components to Add on, Fold in, or Take out

45

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Separate the parts with distinct functions within the product, determine the ones that can be attached, folded in, and taken out to provide alternatives to the user. Interchangeable and folded in components reveal new surfaces to alter functionality.

S

The all-in-one composition converts the product into 3 different products according to the needs of child's first three years.

Reconfigurable training tables are used alone or grouped to transform any workplace into any communication configuration, while folding flat when it is stored.

Reduce the Amount of Material Needed for the Function

46

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Simplify the design by removing unnecessary parts and flattening the functioning components.

S

The folding plug transforms the bulky three-pin plug into a portable one for people on the go. Folding the product enhances compactness as well.

The fitness device is designed as part of a room, giving accessibility to users ready in seconds for an impromptu workout.

47

Refocus on the Core Function of the Product

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Remove unnecessary complexity, select clear and consistent forms for the core function, and present only relevant visual information in the product. Evaluate elements within the design and reduce as many as possible without compromising function.

S

The pointed end of the chopping board ensures that the user aims straight into the bowl when tipping ingredients. The raised edges are used to keep the food inside.

The lightweight, aluminum bowl is designed by stamping the sheet material to its physical limits.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

48 REMOVE PRODUCT PARTS TO INCREASE FIT DURING USE

Remove parts from the product for better fit to other products, or to the user's body.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The flashlight is designed for people who run or hike at night. The contoured handle allows users to hold the flashlight in a natural, comfortable position.

By removing middle section, the double pin design holds cords and wires with more stability.

CHAPTER 2 | **CHAPTER 3** | CHAPTER 4 | **CHAPTER 5**

49 REPLACE LIMITED-USE PARTS WITH MULTIPLE USE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

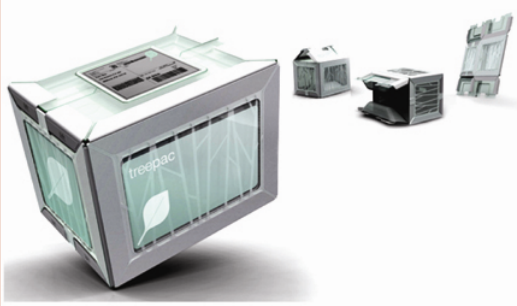
SUSTAINABILITY

USABILITY

USER

Identify materials that can replace the disposable or limited-use parts in products, and replace them with more permanent ones. Modify the design according to the capabilities of the new material.

S



The reusable shipping container is designed to replace cardboard boxes, suggesting a lower environmental impact while maintaining the collapsibility feature of cardboard.

The shopping bags are designed as an alternative to the paper and plastic shopping bags. The bags are returned to public compost bins, initiating community based efforts.

50

Replace Materials with Recycled and / or Recyclable Ones

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Keep the function stable while exploring the use of recycled or recyclable materials within the product. The structure of the product and the context of how it will be used will be redefined accordingly.

S

The disposable footwear is made from recycled newsprint and is completely biodegradable, which allows the product to be used in hospitals and salons.

The paper water bottle made from renewable food-safe resources attempts to replace plastic bottles thrown away daily.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

51 Replace Solid Material with Flexible Material

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Change a product's material into a flexible one to create different structural and surface characteristics. Replacing the solid material with a flexible one gives potential for it to stretch in length or area, facilitates or enhances new functions, and aids in adjustability of the form.

S

The material of the colander is replaced with silicon in order to add collapsibility and allow for multiple functions with the same tool.

The squishable, leak-proof, easy to fill travel bottles allow users carry the liquids comfortably.

52 Return Sensory Feedback to the User

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Return some of the output of a system (tactile, audio, visual) as input to aid control of the use process. In order to prevent or reduce errors, use confirmations and warnings, provide additional information in different forms, and include reversible actions.

S

The thermometer provides parents with a noninvasive way to take their child's temperature, and displays color-coded results.

With its integrated timer and counterweight infuser, the teapot removes the loose leaves from the water when they are perfectly steeped.

53

REVERSE DIRECTION OR ANGLE OF COMPONENT FOR EACH FUNCTION

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Turn a part of the product upside down for an additional feature, or exchange internal components with external ones.

G

The product combines regular seating and dining seating for children in the same solution. The function changes when the seat is reversed.

The tray is used as a seating surface when its cover is reversed giving multifunctionality to the product.

54 Roll Product Around a Pivot Point

Revolve a part or the entire product over on a center point or a supporting surface. Rolling can embody combinations of both flexible and rigid materials within the same product, and enhance collapsibility and spheriodality.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The portable net makes it possible to play table tennis in indoors and outdoors. The truncated, conical form at the edges allows it to fasten and fit a variety of tables.

The battery has an elastic thin-film solar cell built into its metal cover. By setting it under the sun, the battery gathers light source to recharge without a separate charger.

CHAPTER 2 | **CHAPTER 3** | **CHAPTER 4** | CHAPTER 5

55 ROTATE ON A PIVOT AXIS

Change a product's function by manipulating its geometrical surfaces around an axis. Rotating may expose new surfaces for different functions, and opens and closes the interior space of the products.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

Besides opening the can, the product protects the unconsumed content of the drink. It works both ways: to open and close the can while staying on the container.

The top of the phone rotates 360 degrees around the round display to open and close the phone.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

56

SCALE SIZE UP OR DOWN

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Change physical dimensions of the product or its parts up or down in order to save storage space by nesting or stacking them, to provide options to the user by suggesting alternative sizes, or to meet different specifications required by the functions.

G

The square and rectangular shapes available in different sizes allow the containers to be stackable in various ways. This also provides space-efficiency when they are stored.

The multifunctional dish system offers a range of sizes that can be used in different combinations for almost any purpose.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

57 Slide Components Across Product's Surface

Move one component smoothly along a surface or another component while remaining in contact with it in order to open and close surfaces, rearrange components or adjust the height of the product.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The cover (used to protect the lens of the camera when it's not in use) slides to left when the function is needed.

The lighting unit is designed as a street light with different arm styles and fixtures. The height of the light is adjusted through sliding and affixing it on the vertical component.

58

Split or Divide Surfaces into Components

Divide single, continuous parts or surfaces into two or more elements or functions. The separation of continuous components creates independent parts that can then be reconfigured, and the repetition of a component can also assist in generating reconfigurations.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The water bottle is designed as a continuous surface with a lid cut from that. It also offers one-handed operation.

The snap-assembly is used to bring any color combinations together for various configurations.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

59

STACK COMPONENTS

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Rest a product on another in a vertical direction or inside each other in order to save space, protect the inner component, or create visual effects by placing them in different configurations.

G

The floor lamp comprises individual cylinders of colored glass, and gives the flexibility of different combinations by stacking them.

Stacking wine glasses on top of each other adds another function: covering the carafe when not in use.

60 SUBSTITUTE / SWAP AN OLD COMPONENT WITH A NEW DESIGN

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Replace the form, or a design component, with another to achieve the same function. Identify other materials that can be used to achieve the same function and replace the existing one with it.

G

The trapezoid shaped stick replaces the traditional rectangular stir stick. Larger, curved handle allows for better leverage and comfort.

In the basting brush, the metal springs are used instead of the brushes to absorb the oil.

61 SYNTHESIZE

Combine two or more functions to produce a new, more complex product by joining them to form a new device.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

G

The existing backpack is reinforced with an exterior frame to take the load off the shoulders while allowing the bag to stand upright, and protecting the inner components.

The laptop is combined with pen and notebook on the same surface, and the entire system is stored as a binder when not in use.

62 TELESCOPE LONG COMPONENTS TO REDUCE SIZE WHEN NOT IN USE

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Move one part of the product sliding out from another along an axis, lengthening or shortening the object. By moving the components of the product along one particular direction, the created stretch or enclosed volume may change the product's functionality in addition to providing adjustability and collapsibility.

G

The telescobing, dual-rod system functions as both a shower curtain rod and a towel bar.

The height of the bike is adjusted through the telescopic tubing. By removing the handle bars, the bike better suits the needs of its users.

63 TRANSFER OR CONVERT TO ANOTHER FUNCTION

Design the product with multiple stable stages, and define transitions between these stages by changing the relationships of the design elements to each other.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The laptop is transformed into a flat screen home entertainment center by a sliding hinge attached to the back of the screen.

The design features a folding top that flips up or down, allowing tables to be used as room dividers.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

64

Twist Geometric Forms to Add Variation

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Turn simple geometrical forms in the opposite direction, single or multiple times, to create a playful, iconic product. Twisting may also enhance function by providing a larger surface space for different functions, and increasing stability.

G

The twisted forms are used both as a stool and a side table, with an inner light functioning as a floor lamp for children's rooms.

By twisting the form, the head and the handle of the tool become perpendicular to each other, and provide maximum grip area when applying force.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

UNIFY DESIGN ELEMENTS FOR LOWER COST AND VISUAL CONSISTENCY

65

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Cluster design elements according to intuitive relationships such as similarity, dependence, proximity, etc. to unify them for visual consistency. This method can also be used in designing product families, or sets of products complimenting each other.

S

The product combines a spill-proof cup and a snack holder, and creates a visual consistency between the components, structuring a continuous look using color and curvature.

Using the same geometrical form in various sizes for different functions within the same product creates visual consistency.

66 Use a Common Base or Railing System to Hold Multiple Components

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Facilitate use of multiple modules together through aligning them on the same base or railing system. This may reduce the number of parts needed, allow users to rearrange the location of components, and make products more compact.

S

The adjustable shower caddy organizes bathroom products by aligning two shelving units on the same base, and flipping them vertically when needed.

The movable base serves multiple functions by attaching different parts on the top and positioning them in a way so that seated and standing users can access them.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

67

USE A COMMON COMPONENT FOR MULTIPLE FUNCTIONS

Perform two or more discrete functions using a single part. The part achieves different functions required by the different configurations of the device.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

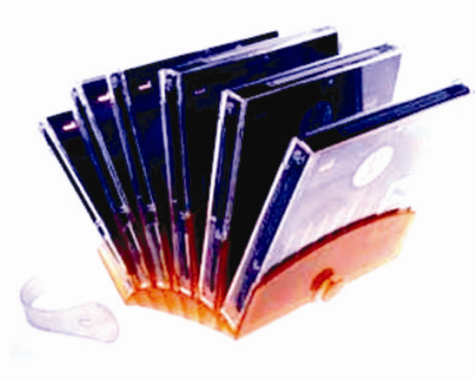
MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S



Using an elastomeric band, the unit can bundle CDs for transport or storage, then release them in a splayed array that maximizes viewing and access.

The sandals' straps are used for keeping them on the feet, and attach them to each other so there is less chance of losing one.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

68 Use an Environmental Feature as Part of the Product

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

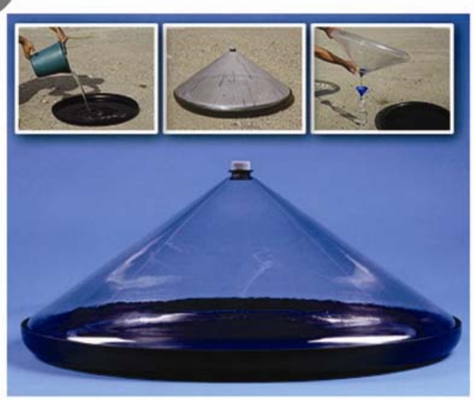
SUSTAINABILITY

USABILITY

USER

Use the environment as part of the product by designing around it rather than distinguishing the product from its environment.

S



The conic design is a simple device that uses a combination of solar energy and condensation to produce drinking water, especially helpful for developing countries.

The music pergola provides people a place to listen to music. People can select music that harmonizes with the time of the day, the weather, or the seasons.

69

USE HUMAN-GENERATED POWER AS ENERGY

Human kinetic energy, using natural body movement, can be transferred to the power source of products in a number of ways, such as pedaling, pulling, pushing, and running.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The playful monster lamp operates by pulling the attached cord repeatedly. Since human actions are needed for the function, it also enhances the awareness of energy resources.

The portable laundry-machine is hand-powered and intended for delicates and hand-washables.

70 USE MULTIPLE COMPONENTS TO ACHIEVE ONE FUNCTION

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Different parts of the product can contribute to the same function. These components can be identical to each other with minor changes (size, color) to facilitate adjustability in use, or they can be different but serve similar functions.

G

The mp3 player can be controlled either by the main component, or the smaller sub-component which can be attached to clothes while exercising.

The product accommodates two ovens in the space of a single one, enabling customers to simultaneously cook two or more dishes at two different temperatures.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

USE PACKAGING AS A FUNCTIONAL COMPONENT WITHIN THE PRODUCT

71

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Embed the packaging within the product, where the packaging performs a different function: Create a shell or cover for a component or the entire product using the package, and uncover it when it's used.

S

A set of colored pencils is located inside a package that also serves as a stand during use.

When the packed components are opened, the package supports the structure, and functions as a necessary shade component rather than as a separate, unused feature.

72 Use Outer or Inner Surface Area for Different Functions

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Design the product as a shell; having a distinct exterior and an interior space with different functions, or create an inner gap and assign a second function to that gap by reconfiguring the product.

S

The inner part of the bottle stopper is used as a bottle opener, and it is reinforced by another material inside.

The outer surface of the product is used as a child's seat, whereas the inner compartment provides storage.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

73

Use the Same Material Throughout the Product

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Define the different functions the product will facilitate, find alternative ways to create connections between the parts, and apply one continuous material to the attached parts. Using the same material reduces the number of parts and joints, as well as reducing complexity of the product.

S

The trash can has handles built in, and is shaped so that the trash goes in and out easily.

The clip hanger uses a single material (PET- the most recycled plastic) instead of using 5 different materials as in existing solutions.

74 USE THE SAME SURFACE AREA FOR MULTIPLE FUNCTIONS

Use one continuous surface made out of one material for a variety of functions complimenting each other. Bend the continuous material in order to assign the functions, or create indents by applying pressure to certain locations.

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

S

The dining chair contains hidden storage spaces and pockets by using a continuous fabric as part of the seat.

The plate's wide outer rim is generously sized and slopes inward toward the center dipping dimple. The same surface is used for two functions by having different indents.

75

VARY PHYSICAL DIRECTION FOR PRODUCT APPROACH

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Use different ways of approaching the product (such as from the side instead of front). The pre-assigned directions in the existing products that define how they will be used may be revisited, and those directions may be removed to create more flexible solutions.

S

The sofa does not dictate any the direction as experienced in existing ones; instead, it is used as a corner piece, and provides a larger surface space for comfort.

The retractable front wheel and frame make the stroller suitable for use on difficult terrain, such as walking on the beach or climbing up stairs.

76 VISUALLY SEPARATE PRIMARY AND SECONDARY FUNCTIONS

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Create visual, hierarchical relationships among the functions within the product by changing the individual design elements' dimensions, locations, colors, and materials: Visually emphasize which functions are the most important to facilitate the ease of use by improving the interface.

S

Even though the two attached forms look alike, the size differs to communicate the two different functions: medicine and drink container.

The form and color suggest two similar functions; however, the size difference in the forms emphasizes the different functions used in water flushing.

CHAPTER 2 | CHAPTER 3 | CHAPTER 4 | CHAPTER 5

77

VISUALLY SEPARATE SIMILAR FUNCTIONS

COST

DIVERSITY

EFFICIENCY

ENGINEERING

INTEREST

MULTIFUNCTIONALITY

SUSTAINABILITY

USABILITY

USER

Use color and size distinctions to attract attentions to certain parts or functions, to group elements that are dependent to each other, and to enhance aesthetics. Using appropriate color combinations and size groups can also create emotional connection with the users.

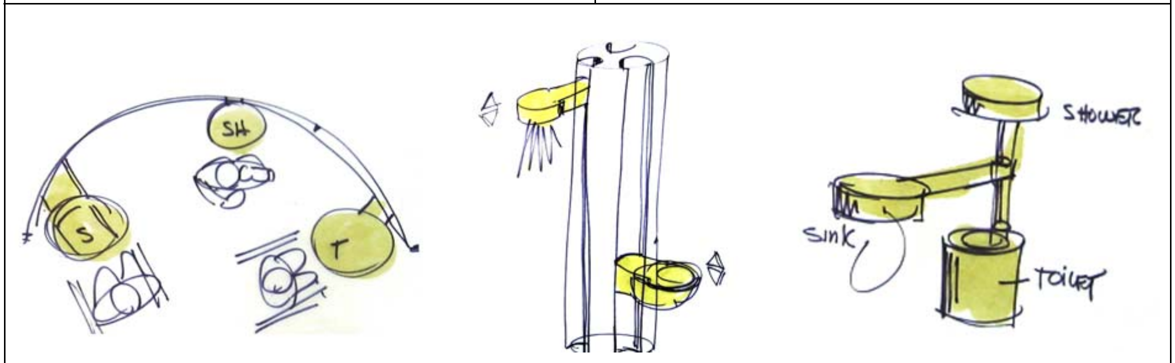
S

The plate and the spoon combination are designed specifically for kids, and the colors for the surfaces are changed according to the parts that interact with hand and food.

The cover of the digital camera uses the same outline of the main body, but due to color, it can easily be distinguished from the main component.

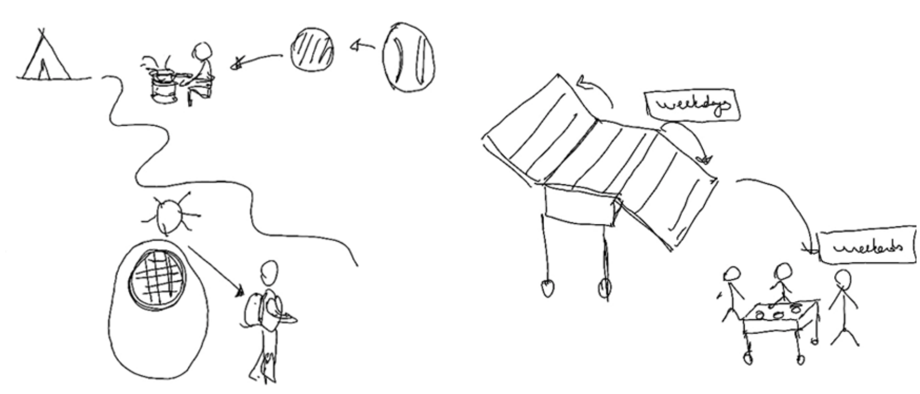
6.2.1. Process Heuristics

Process Heuristics	Descriptions
1. Assign form to each function	Giving form to each function separately, and creating a relationship between this forms (separate, attached or merged pieces)

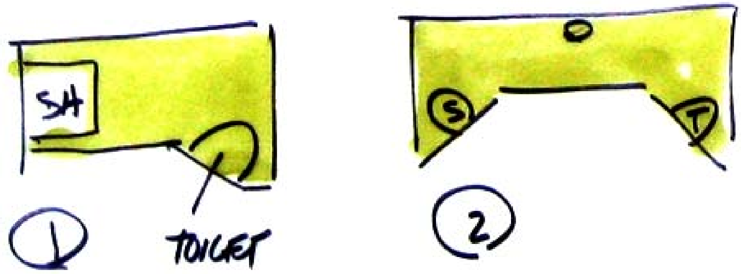


2. Brain-write	Using brainstorming sessions and generating words describing the constraints and variables to suggest new concepts

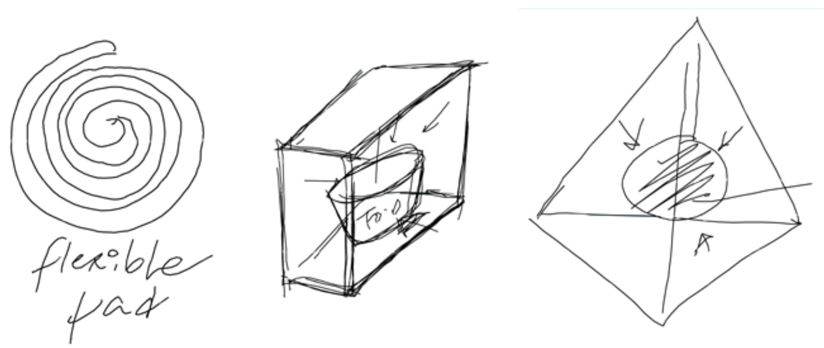
3. Contextualize	Assigning a context or changing it if it exists



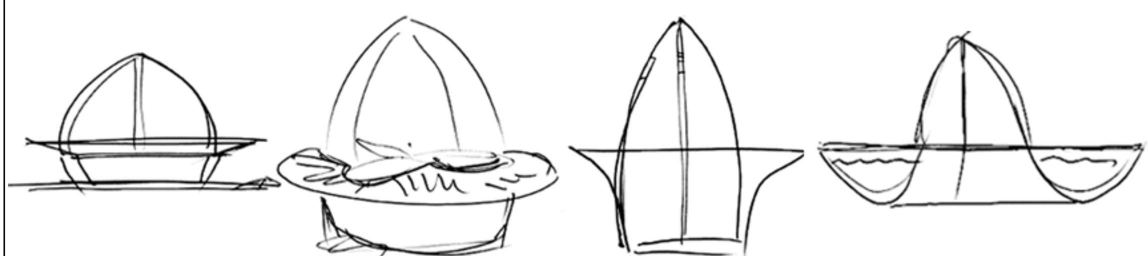
4. Evaluate	Placing value to the idea and then staying with or leaving it



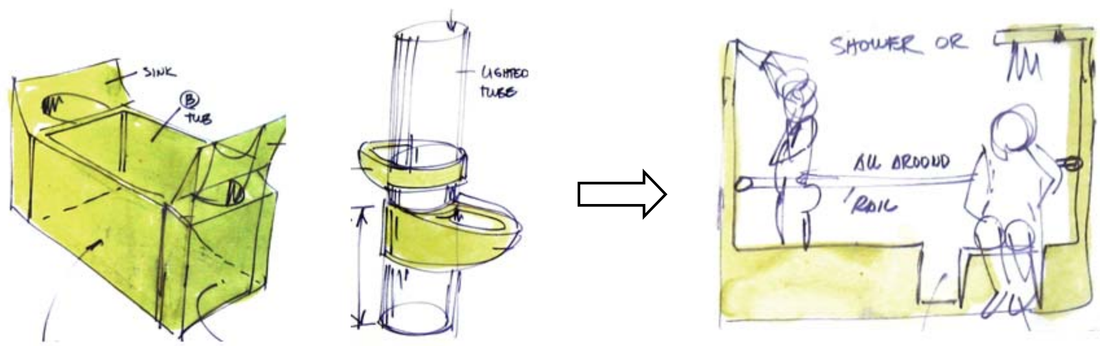
5. Prioritize certain constraints	Selecting and prioritizing certain constraints and developing concepts satisfying those

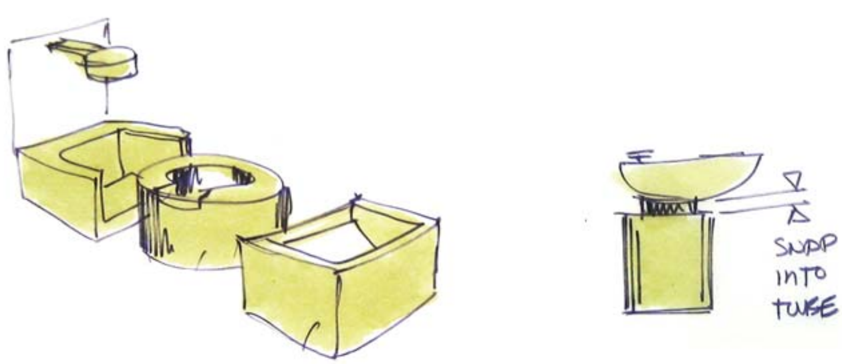


6. Redraw earlier concepts	Redrawing the previously proposed concepts

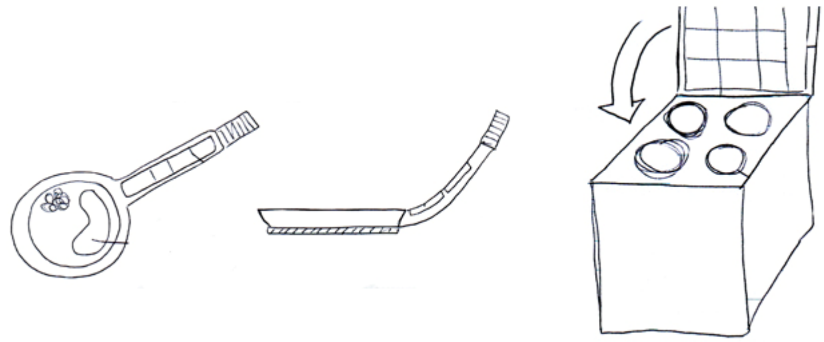


7. Synthesize	Merging different concepts into one
	

8. Analyze morphology	Identifying different ways of achieving the same function and combining and substituting each way to generate a new concept
	

9. Switch level of focus	Change from a general system-level design focus to one on a specific concept element, and back
	

10. Propagate	Once a new concept element is identified, try to apply it to other existing concepts.



CHAPTER 7

CONCLUSIONS

"KNOWING IS NOT ENOUGH; WE MUST APPLY. WILLING IS NOT ENOUGH; WE MUST DO."

JOHANN WOLFGANG VON GOETHE

7.1. CONCLUSIONS

The central objective of this thesis has been to show that heuristic rules acting through human cognition provide a feasible and valuable way to generate and explore product design solutions. This thesis has been presented in three connected parts. Part One examined the role of heuristics in design and presented a series of studies and analysis, each extracting design heuristics from different sources and perspectives. Both existing products and sequences of exploratory sketches reveal the use of design heuristics. Part Two presented an empirical study focusing on the validation of heuristics use by novices, and suggested pedagogical instructions for heuristic applications. This study tested the effects of heuristics on creativity, diversity and practicality of design concepts. Part Three includes two sections describing implications of design heuristic use in design pedagogy and practice, and proposing a matrix demonstrating which heuristics are most suited to design criteria as defined in the problem.

The results of the empirical studies and the content analysis included in this thesis must be considered in context. Ultimately, the research agenda is to create a set of design heuristics and instructional materials that will serve as a viable pedagogy for passing on the strategies used by professional designers. Part of this agenda included identifying successful design heuristics within the actual production of expert designs.

Chapter 2 presented analyses of award-winning designs across a wide variety of product types; however, the available data included no information about the design process leading to the final outcome. The analysis of an expert designer’s sketching process (Chapter 3), presents a single case study, with conclusions based on an individual. By working with the designer's project scroll as data, the design process itself, and its duration, could not be observed. The designer may have done other sketches on other media, or built mock-up prototypes; certainly, thought processes took place that were not captured in the scroll. Using a scroll as media to keep track of ideas is not currently common in designers’ working traditions, so finding similar data archives to explore heuristic use is challenging. This research would be greatly improved by the ability to compare sketches and collect process data across other expert designers.

Chapter 4 included cases studies of more individual industrial designers; however, the number of participants was still small, so comparisons across the two groups are likely to be limited in generalizability. Second, these studies involved very short, one-time design tasks, a paradigm unlike typical work environments in design. The controlled tasks allowed comparison of individuals on the same design problem, but as isolated, one-time, limited-time sessions, not capturing a typical work setting for many designers.

However, the heuristic analysis method was successful in characterizing differences among designers, and suggested ways to assist designers in adding to their ideation skills. In particular, this approach may hold promise in instruction for novices as they build their experience with heuristic use and design in general. Chapter 5's study of novices provided evidence that design heuristics can be taught, and that they do lead to more creativity in the end designs. However, this convenience sample of novices was selected without regard to potential design ability, interest, or motivation. Certainly, these participants were less technically sophisticated than industrial design or engineering design students, and presumably had little exposure to this type of design task. As non-designers, these individuals vary in their ability and comfort with sketching, and as a result may have a more difficult time expressing their creative ideas visually. But because the participants were assigned to experimental condition at random, individual differences would occur in all of the conditions, and not bias the results towards more creativity in any particular one.

In addition, the novice study took place as a one-time lesson within one hour's time, limiting any conclusions about the usefulness of the instruction on future design creation. These conditions allowed for a successful experiment demonstrating the power of heuristic instruction, but limit the generalizability of its conclusions. It is posssible that other design problem characterizations, designer profiles, session variables, and outcome measures could potentially be important to the success of heuristic instruction. These conditions are not similar to those in product design tasks within design schools, and will likely either over- or underestimate any effects of design heuristic instruction. Laboratory studies can be helpful in testing specific hypotheses, leaving questions of potential robustness to later studies. While these results demonstrate that design heuristics are easy to grasp and use, and that their use leads to more creative design, further evidence of their viability in design practice and design pedagogy will require further research.

The broader impact of this research is the improvement in the novelty, quality, and the variety of design solutions following the use of design heuristics. By identifying heuristics from designers of industrial products, and teaching them to novice designers, this research demonstrated that design heuristics enhance creativity. This finding will provide ways to improve instructional methods in industrial design, and in design engineering.

7.2. USING DESIGN HEURISTICS

When designing products, especially those to be launched in competitive markets, the three levels of consumer needs – functionality, usability, and pleasure (Jordan, 2000) – must be satisfied. Certainly, an attractive product is unlikely to be successful if it is not functional, but a functional and usable product may also fail if its emotional values are incompatible with consumer values. How do designers apply these intangible characteristics to their products? Are there certain design heuristics that may assist them in the exploration of the design space?

To answer these questions, a set of desired properties, or design *criteria*, was identified from descriptions of the award-winning products and concepts analyzed in Chapters 2, 3, and 4. Along with the designs, the descriptions provided with products were collected and analyzed. A set of 21 specific criteria was identified. The list of criteria shown in this section is sufficient to account for the products and concepts analyzed in the prior chapters, but it can of course be further extended. The criteria are not context-dependent; that is, they are not specific to a single specific design problem, but are applicable in multiple designs. This set of 21 criteria for product designs is provided in **TABLE 7.1.**

TABLE 7.1. Design criteria commonly used in products and their descriptions

	Criterion	**Description in Product Design domain**
1	Adjustable / Adaptable / Flexible	Capable of change
2	Affordable	With a price lower than the market
3	Biodegradable	Using materials capable of decomposing naturally within a relatively short time period
4	Cohesive / Consistent	Well-integrated, consistent-looking as a whole
5	Collapsible	Can be reduced in size to save storage space or change function, such as stacked or folded
6	Compact / Portable	Light and small enough to be carried
7	Customizable / Personalized	Can accommodate differences between individuals
8	Durable / Reliable / Robust	Able to withstand stresses, pressures, or changes in the

		use or circumstances
9	Dynamic	Allow interaction, or change in action
10	Emotional	Elicit emotional responses
11	Intuitive	Easy user understanding and operation
12	Light-weight	Lighter weight for carrying or less production expense
13	Modular	Composed of modules that create systems through simple attachment
14	Multi-functional / Versatile	Functions included from separate products
15	Playful	Increase enjoyment by look or use
16	Practical	Feasible and function well
17	Recyclable	Can be reused (after reprocessing)
18	Safe	Free from danger or harm in use, or in environmental impact
19	Simple	Minimal or few parts for ease in use and interaction
20	Sustainable	Long-lasting, with minimal environmental impact
21	Universal / Accessible	Effective for diverse users

Next, the criteria were tied to the heuristics that are most likely to address them. A matrix (see **FIGURE 7.1**) presents these design criteria in the row. For each criterion, heuristics are listed that are likely to be effective in generating solutions. The larger circles indicate a strong likelihood for that specific heuristic to function well for the corresponding criteria. The smaller circles represent a possibility that the heuristic will assist in accomplishing the criteria. And the absence of a circle indicates that heuristic is less likely to be helpful given the design criteria.

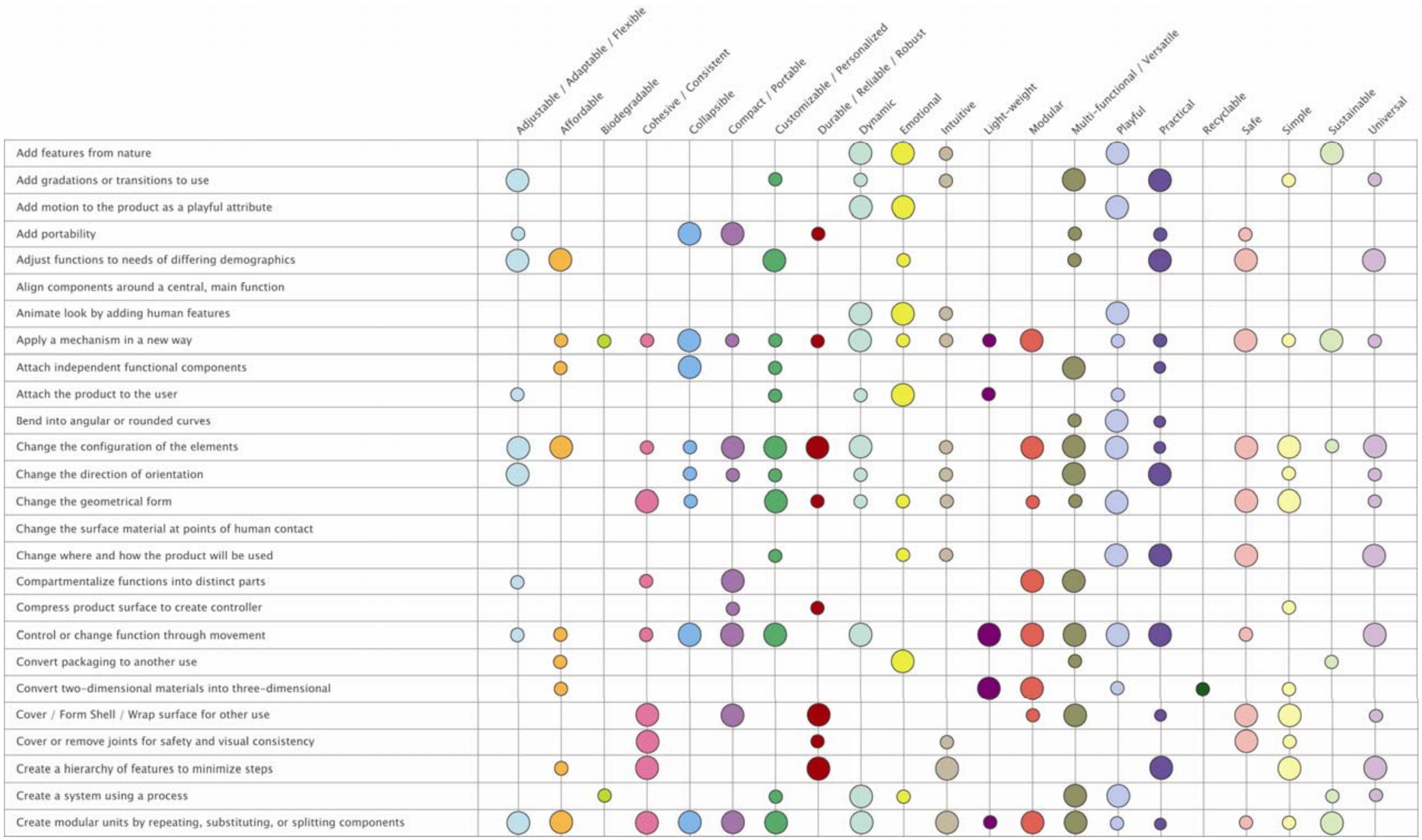


FIGURE 7.1. Matrix showing how each heuristic corresponds to each criterion defined in the design problem

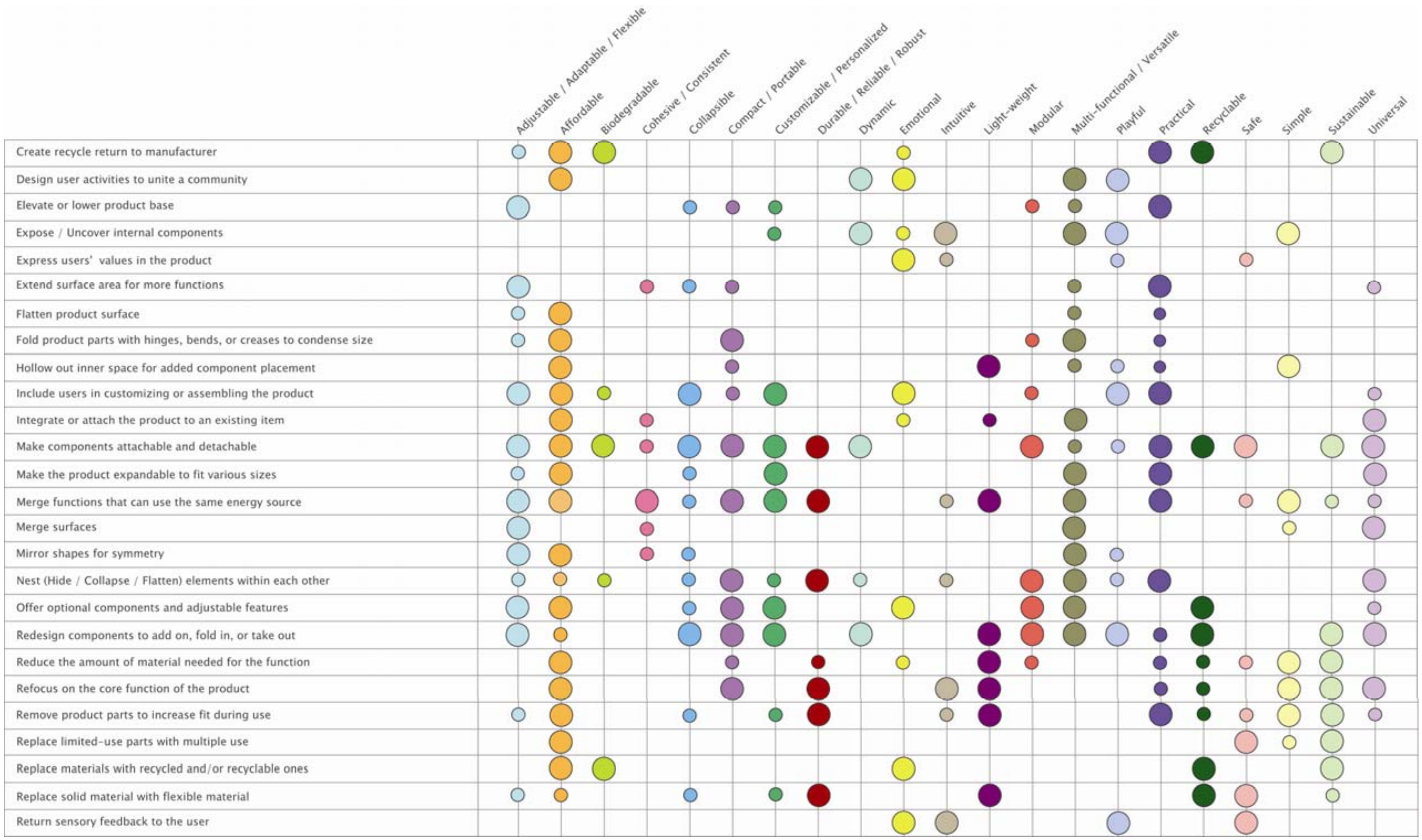


FIGURE 7.1. Matrix showing how each heuristic corresponds to each criterion defined in the design problem

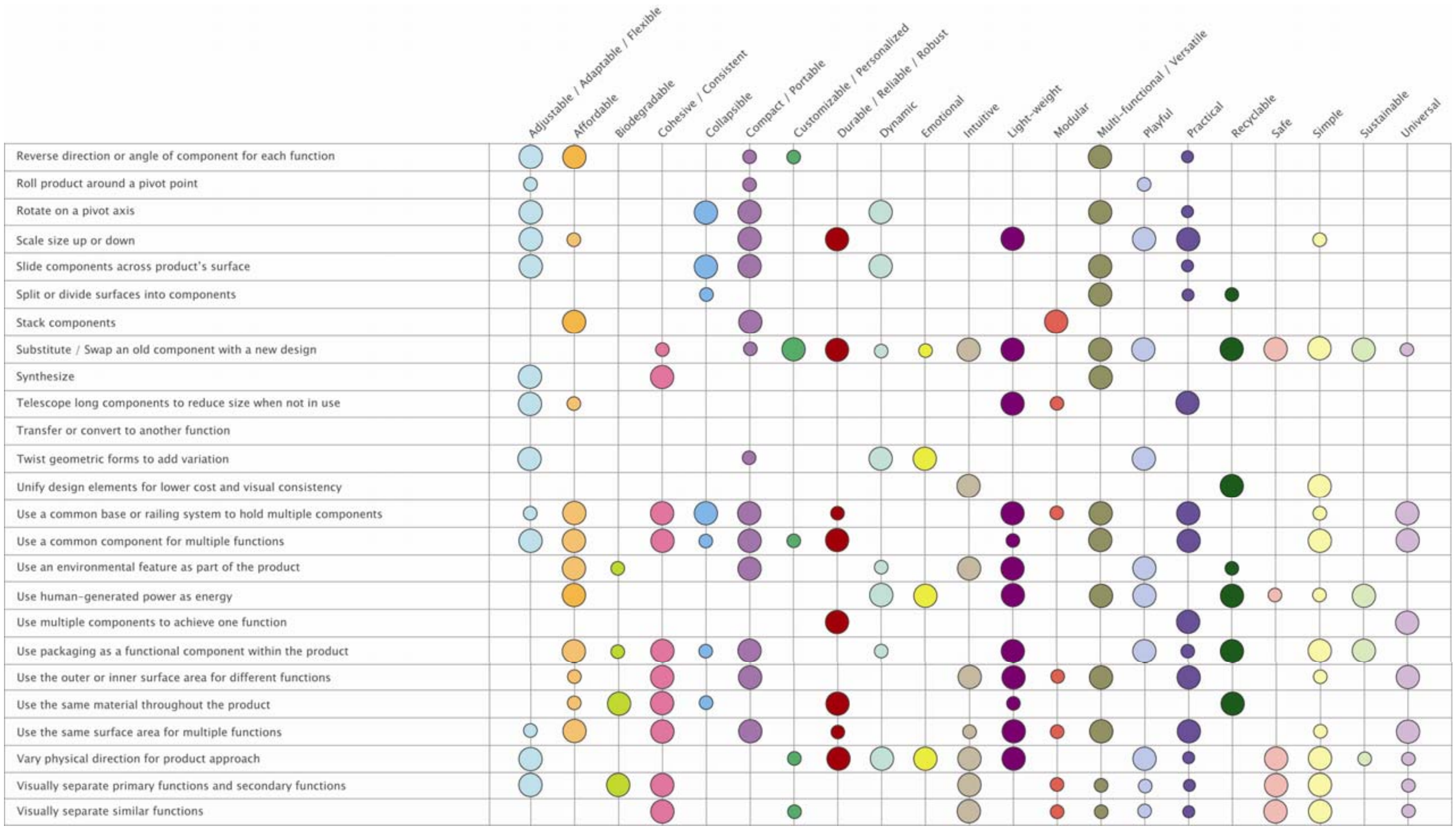


FIGURE 7.1. Matrix showing how each heuristic corresponds to each criterion defined in the design problem

Some of the criteria in the list change meaning depending on the context defined in the problem. For example, products that need to be “safe for children”, “safe for the environment”, or “safe to use” change the relevance of different heuristics. For present purposes, these differences in contexts are not defined, and only more generalized descriptions (like "safety") are considered. For many other, more general criteria, such as, “Attractive”, “Comfortable”, and “Educational,” many heuristics may be equally relevant, and so no specific heuristics are given priority.

To use this matrix in the design process, the designer poses questions; for example, a designer might ask, "Which heuristics should I apply to create a novel concept that will satisfy this given criteria? What secondary heuristics that would open new solution spaces?” For example, the product seen in **FIGURE 7.2A** shows the inside of the product (the mechanism) and is a good example of how the *Expose / uncover internal components* heuristic can create a “Dynamic” product compared to others. Another example is using *Add features from nature to the product*, or *Animate look by using human features* heuristics, which may generate solutions that feel “Intuitive” to use and create “Emotional” bonds with the user (**FIGURE 7.2B**).

FIGURE 7.2A. Maurice Lacroix watch showing the mechanism

FIGURE 7.2B. ‘Hug’ salt and pepper shakers carrying human features

Such products use human or natural features as analogies to suggest these designs behave in a similar manner. In **FIGURE 7.2B**, the salt and pepper shakers hug each other using arms to hold them together, while the colors represent the differences, along with the harmony and balance between the two items. So, the application of the design heuristic creates in the user an understanding of how the product functions. Intuitiveness and revealing emotions bring simplified and familiar solutions into the designers' and users' minds.

The mapping from design criteria to design heuristics suggests a natural correspondence between ways of altering designs and the goals of the design process. While any heuristic may be helpful in a given design process, there may be connections between problems and heuristics that come up frequently across experiences with design. It is possible that part of expertise in design is knowledge of these correspondences, and when specific directions in design ideation may prove fruitful. By examining how experts use design heuristics across varied design tasks, an understanding of the utility of specific design heuristics can be developed.

7.3. Educational Implications

A major implication of this research is its ability to inform pedagogy within design curricula in schools of art and design and in colleges of engineering. Design education tends towards a pragmatic view regarding the definition of creativity. Ideally, the outcome of design education is that students produce original work that is original, and adds value to the existing domain. Previous studies suggest techniques that require self-reflection can be successful in engineering education (Adams, Turns, & Atman, 2003). A meta-analytic review of the effectiveness of creativity training (Scott, Leritz, & Mumford, 2004) found that more successful programs were likely to focus on the "development of cognitive skills and the heuristics involved in skill application," along with the use of realistic exercises appropriate to the domain at hand. These training programs produced gains in performance that generalized across criteria, settings, and target populations.

7.3.1. Heuristics in Design Education

Using heuristics in product design adds to one's ability to generate multiple creative ideas, and also motivates the students by demonstrating multiple ways to move into new areas to consider as solutions. Rather than getting stuck in one idea, the design student can choose a heuristic, apply it to the current problem, and see where the resulting transformation leads. This approach may prove superior to brainstorming because it provides a cognitive process: to take a starting point, and vary it in systematic ways validated by other designers as productive paths. This process of considering many alternatives before "jumping in" to a solution strategy has been identified as key in human problem solving (Wertheimer, 1959); however, supporting new designers who need to generate alternatives has been challenging. This thesis proposes specific design strategies that can lead students to *diverse* and *creative* solutions.

The findings of this research suggest that simple demonstration of design heuristics may, at times, be sufficient to stimulate divergent thinking, perhaps because these heuristics are readily grasped. Indeed, simple exposure to relevant heuristics, or strategies, for divergent thinking has proven effective in other studies e.g. (Clapham, 1997; Warren & Davis, 1969). The success of the *Serial Order* conditions (Chapter 5), where the students were told which heuristic to apply, and the *Heuristic Choice* conditions, where students had to decide for themselves, suggests that there may be a scaffolding process. During design training, exposure to a variety of heuristics, and experience in applying them on many different problems, may lead to learning which design heuristic to apply in optimal circumstances. For many design students, simply having an arsenal of design heuristics to try might lead to more success in moving within in the design space. In fact, one variable in the study may be a motivational factor: It is possible that demonstrating the effectiveness of heuristics for creative tasks may, through feelings of efficacy, motivate creative efforts, just as the outcomes of creative efforts lead to an appreciation of creative work (Basadur, Graen, & Wakabayashi, 1992; Davis & Scott, 1971).

How can design heuristics be taught? Within an educational environment, it is often difficult to develop an awareness of design thinking through conventional classroom activity. As the instructions are not systematized, students may have difficulty in formulating conceptual structures and strategies, and reapplying them to the new design problems. Normally, when faced with a design problem, an appropriate heuristic is not obvious; rather, one is applied only if it can be accessed from memory or instruction. This research shows it is possible to demonstrate design heuristics through engaging in constructive processes, providing a medium for learning when and how to apply designs. Improvement in the use of heuristics might be indicated by a growing level of complexity in the external representations of the concepts proposed, indicating an understanding of the design heuristics and their application as idea-triggering strategies. Increasing sophistication of integrating and implementing these heuristics in design creation may demonstrate the gradual acquisition of knowledge about the interaction of design strategies and design knowledge.

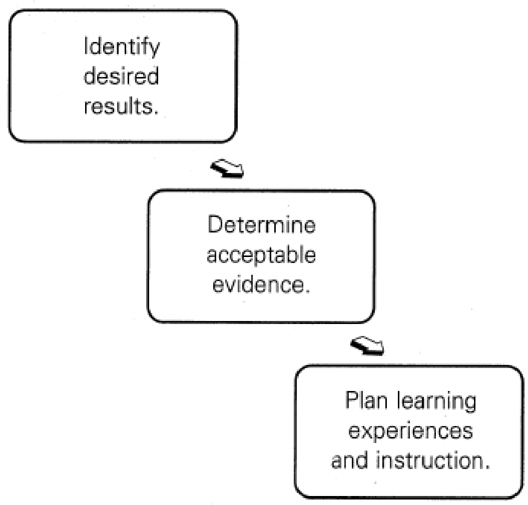


FIGURE 7.3. Stages in the backward design process (Wiggins & McTighe, 2000)

Wiggins and McTighe (2000) propose a backward design method for curricular design. One starts with the endpoint – the desired results (goals or standards) – and then derives the curriculum from the evidence of learning or performances called for by need to equip students to perform. The assessment tasks are designed prior to the learning experiences. As seen in **FIGURE 7.3**, the sequence of curriculum has three stages: Stage 1 focuses on the goals and the established content standards, which require reviewing curriculum expectations. Stage 2 is designed to encourage teachers to first think like an assessor before designing specific lessons, and thus to consider up front how they will determine whether students have attained the desired understanding. Stage 3 is used for instructional activities with leading questions; for example, what enabling knowledge (facts, principles) and skills (procedures) will students need to perform effectively and achieve the desired results?

Some other models suggest the statement, “to teach is to engage students in learning” (Christensen, Garvin, & Sweet, 1991). In other words, the real challenge in education is not covering the material for the students; it’s uncovering the material *with* the students (Smith, Sheppard, Johnson, & Johnson, 2005). Among many other models, studio-based design education is based on a problem-based learning process (Barrows, 1996). The model features six core features:

1. Learning is student-centered
2. Learning occurs in small student groups
3. Teachers are facilitators or guides
4. Problems are the organizing focus and stimulus for learning
5. Problems are the vehicles for the development of clinical problem-solving skills
6. New information is acquired through self-directed learning

This model is mainly used for helping students to develop skills and confidence for formulating problems they have never seen before – which is the same procedure promulgated in design education.

Based on these findings, an approach to a pedagogy for design heuristic instruction can be envisioned. For heuristic use in the design process, two pedagogies are proposed: one relying on the findings coming from the validation study (Chapter 5), and a second one that is broader, more detailed, and uses a combination of these models for design pedagogy.

7.3.2. An Instructional Lesson Using Design Heuristics

The pedagogy proposed here involves a conceptual model for design education emphasizing the importance of using a variety of design heuristics when approaching a new problem. As an example, the following instructional assignment can be completed within a one-hour session to provide experience with design heuristics.

Design problem: Current outlets are difficult for elderly people and people who have back problems to bend over to plug in their electrical devices, and the cords are disorganized and look cluttered. Design a device that will solve the problems defined.

1. Ask the students to write down one or two key features of the product with simple words rather than long sentences, and ask them to keep those in mind at all times during the design session. Start with providing randomly selected, simple, three-dimensional forms that would allow students to step back from the existing visual form of a current electric outlet.
2. Ask the students to create a new design each time they are given a heuristic, turning a page to allow a clean surface to begin. Previous concepts can be carried over, but the new space for design may help to start fresh with each heuristic. Ask them not to replicate the existing, familiar products. Remind them that the goal of the exercise is to be as creative as possible. They should sketch each design idea, and provide written labels and explanations to clarify.
3. Introduce *Merge* as a heuristic by showing the examples of merged concepts that do not carry visual cues of the problem given. For example, show one or two example products that have merged design elements, or use the instruction examples from the study. Ask the students to select two forms from the set provided, and merge them to generate a device that would function as an outlet. Give only five minutes for applying this heuristic.
4. Next, ask the students to turn the page and give them the next heuristic to use to create a new design. Choose the order of the heuristics at random, as the study showed that the order doesn't alter the results. Give the students 5 minutes to complete each design. Repeat this process, continuing through all six heuristics, providing five minutes to consider and apply each heuristic separately.
5. Finally, ask the students to self-reflect on the concepts they generated using the heuristics. Ask them to describe the most varied forms, and the features they found most innovative. Allow ten minutes for this reflection.

FIGURE 7.4 and **7.5** show an example of this exercise (steps 1 through 5) completed by a design student:

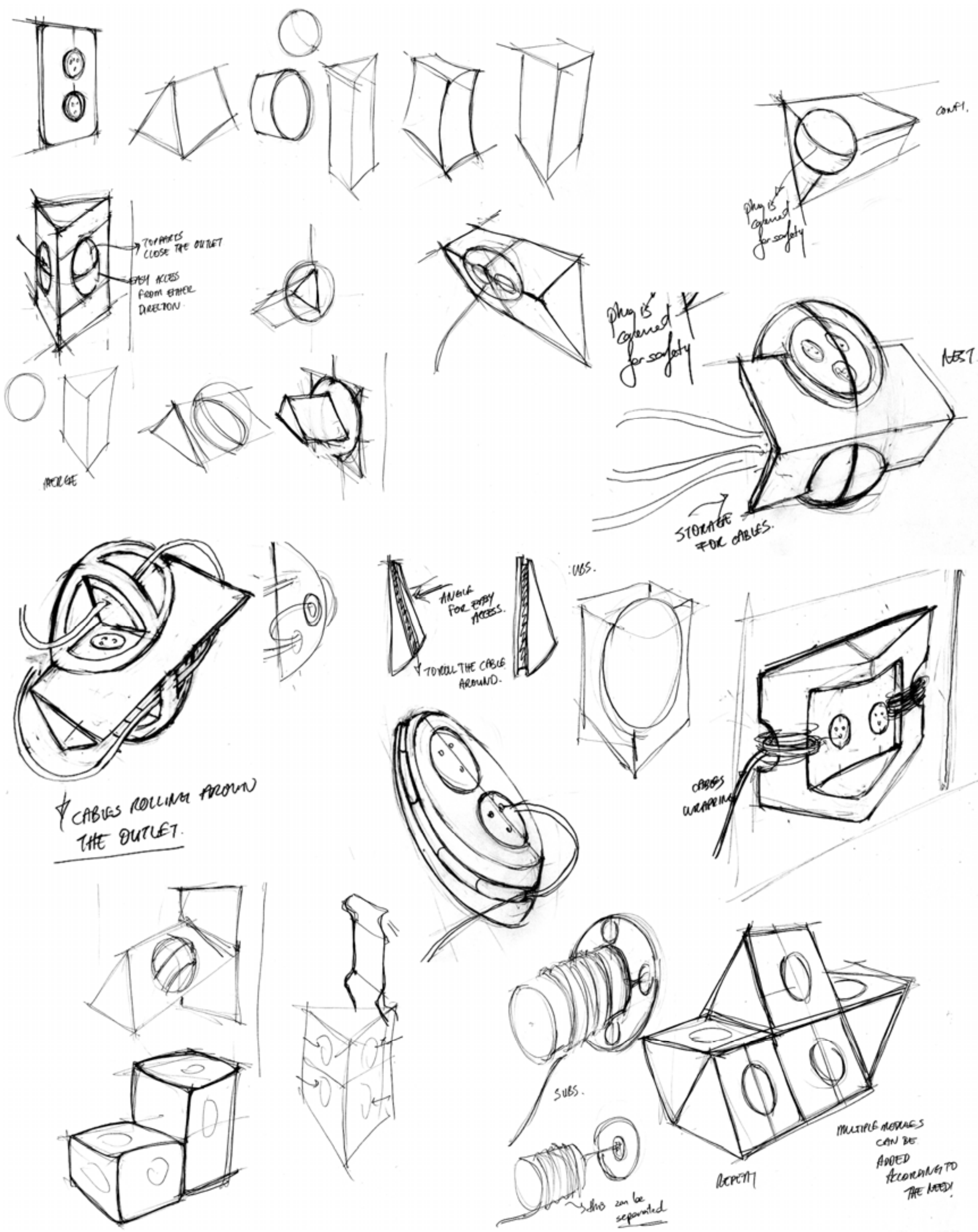


FIGURE 7.4. Example set of drawings showing the application of design heuristics by a design student

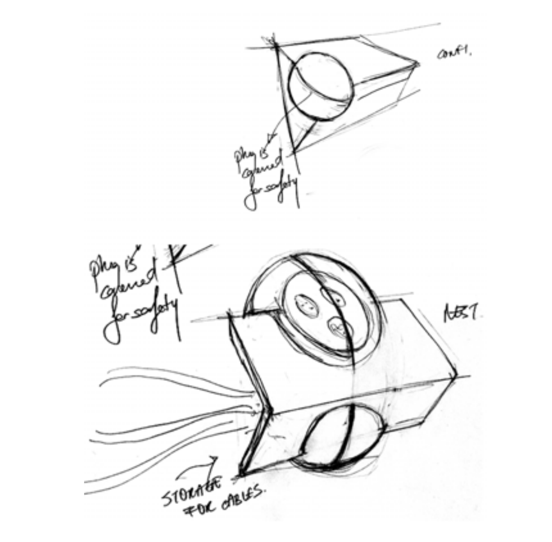


FIGURE 7.5A. Example sketch using *Nest* as a heuristic

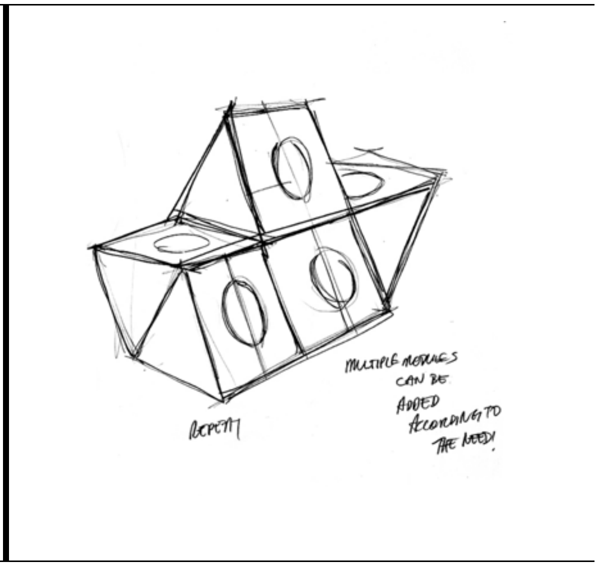


FIGURE 7.5B. Example sketch using *Repeat* and *Change the configuration* as heuristics

FIGURE 7.5A shows the transformation of the previous form into a new concept by the application of the *Nest* heuristic. So, the triangular form is covered inside the spherical form. **FIGURE 7.5B** shows the application of the *Repeat* and *Changing the Configuration* heuristics. Triangular modules are repeated multiple times, and the way they are arranged is varied.

From this student's exercise, several goals for the pedagogy can be readily observed. First, a large number of designs were created in a single one-hour session, providing experience with the flow of design ideas. Second, the variety of designs created shows the success of applying heuristics. Beginning with simple forms and existing models, the designs created move to forms with rounded versus flat panel shapes, consideration of multiple solutions for allowing the point of insertion to project outward into space (aiding accessibility), and single versus multiple plug solutions. When initially considering the design space for outlets, many of these designs may not have been apparent to the student. However, after applying the heuristics in succession, the student was able to examine alternative solution types, exploring areas of possible designs made evident by the intentional variation provided by design heuristic use. The result of this short exercise is an expanded perspective on the possible design space for this simple problem. Repeated exercises with other problems would allow practice with the design heuristics and a growing sense of which heuristics are helpful in particular types of design problems.

As an alternative to providing the heuristics one at a time, the same exercise can be conducted by providing all six heuristics at once, and by asking the students to decide on the order of use. The study found the designs judged most creative resulted from examples where students chose which heuristic to apply. However, the serial order presentation of heuristics produced a greater number of creative designs by walking the students through the process of taking a heuristic, applying it to a design, and then beginning again with a new heuristic. Structuring the lesson by keeping the students on track with the repeated attempts to apply heuristics for a short time period (five minutes) and then moving on to try another may be very helpful with novice designers. Both the self-selection of heuristics and the instructor-presented order of heuristics should be successful using this timed task procedure.

7.3.3. An Instructional Course Using Design Heuristics

This course is designed as a three week, six session unit focusing on learning about design heuristics. It is composed of 3 stages, as advocated in backward design process (Wiggins & McTighe, 2000).

1. Identify desired results

- Students will understand how to apply design heuristics to advance their concepts.
- Students will learn to be comfortable in selecting heuristics from a given heuristic set.
- Students will learn how to apply heuristic combinations.
- Students will understand the differences between process, local, and transitional heuristics, and when to use each while generating concepts.
- Students will engage in learning about design heuristics while going through this process.

2. Determine acceptable evidence

- Assess the creativity scores of final concept sketches using the consensual assessment technique (Amabile, 1982). Count the number of diverse concepts after each session, as well as the number of *Local* and *Transitional* heuristics used for each concept.
- Assess the overall concept generation process at the end of the third week in order to identify *Process* heuristics.
- Assess whether students are gradually increasing their use of heuristics by applying the previously learned ones in a combination with new heuristics.
- Assess whether students are applying a given heuristic accurately to understand whether they capture the essence of each heuristic at the end of each session.
- Assess how the design problem is understood, and redefined, by the student after each heuristic as part of assessing students' level of engagement.
- Assess the learner reports that will prompt self-reflection collected at the end of the third week. These reports may have questions such as: "Which heuristic assisted you the most?", or "What kind of a change did you experience in your thinking process after the design heuristics instruction?"
- Assess students' knowledge of heuristic application by asking them to present their sketches and the overall process at the end of the third week in front of the class, describe which heuristics helped in generating each concept and how, and how they assisted in the exploration of new design spaces.

3. Plan learning experiences and instruction

A. Introduction to design heuristics

1. For the **1st session**, select two or three criteria from the criteria-to-heuristic matrix.
2. Define an open-ended problem; such as, "design a sustainable product for cleaning which is also collapsible when not in use". This product can be used for cleaning the house, the car, or dishes making the definition broad so that the students will start observing many ways of cleaning.

3. Ask students to bring three already existing cleaning products (used for different cleaning purposes) that they think can be improved further, to the classroom.
4. In the **2nd session**, bring images of fifteen to twenty products from the heuristic database that demonstrates one of the two criteria to the classroom. First, ask the students to describe the potential strategies evident in them, and then explain the *local* heuristics used in each by creating connections with the selected criteria. Explain at least ten heuristics by this method. The related heuristics can be selected from the same criteria-heuristics matrix.
5. Give the list of heuristics to the students with the product examples. Give them ten minutes for analyzing the product examples in terms of the heuristics provided, and ask them to present one of those products with the potential heuristics, and its relationship to the criteria, in front of the class. This method will help them to learn the new information through self-directed learning, as suggested in the problem-based learning process.
6. Ask students to generate five "different" concepts for the next session.

B. Applying design heuristics

1. In the **3rd session**, demonstrate how each heuristic can be used to organize the design process by using sketches in the database. This will help students understand that design heuristics are not only observed in final products, but also in preliminary sketches created in the early stages of the ideation process.
2. Ask students to select three heuristics out of ten introduced in the class, and apply them individually to each concept that they brought to the classroom. Explain this application of *transitional* heuristics, since they apply the heuristics to previously drawn concepts to develop them further. Give them 5-10 minutes for each heuristic, and ask them to select another three for the next half hour.
3. Ask students to label each concept with the heuristics used in them, and suggest they try to use multiple heuristics at the same time.
4. In the **4th session**, introduce *process* heuristics with examples selected from the database. Assign different process heuristics to students and ask them to

apply it to their ideation processes to generate alternative solution concepts as in the previous session.

5. In the **5th session**, select another ten heuristics; but this time, select ones that are identified as less relevant to the given criteria.
6. Repeat the steps in the 3rd and the 4th sessions once again with the new set of heuristics.

C. Assessing the heuristic process

1. In the **6th session**, ask students to present their heuristic design process to the class, and ask them to explain which heuristics helped them the most, and how.
2. Return learner reports to the students with questions written prior to the session. Ask students to analyze how many times they redefined the problem, and which heuristics they used in this restructuring. You can ask specific questions about process, local, and transitional heuristics as well.
3. Ask students to place their sketches on tables or on the walls so everyone can see them. Give students post-its labeled 1 to 7, in equal numbers (five 1s, five 2s, etc.). Ask them to stick those post-its to each other's concept sketches according to their creativity (7 being the "most creative"), and emphasize that these numbers will not affect grades (as grades will be given according to student's commitment to the learning process).
4. Collect sketches, creativity ratings, and learner reports for further analysis of heuristic use.

This approach transcends the educational logic of conventional design education in classrooms and studios. It suggests that design learning can be enhanced through visual and verbal instruction about a variety of heuristics, and can supplement formal education and foster personal development in design learning. It can motivate students by assisting them in jumping from one solution space to another while reducing fixation. As for the potential of future applications of this methodology, I believe that the resulting relationships between cognitive models of design, design domain knowledge, and the incorporation of computational technology has theoretical and practical implications for design education in the broad spectrum of design domains. Students learn to generalize and abstract rules from their practice of design as they develop an understanding of why their cognitive processes result in more or less successful paths to design. My approach, demonstrated in the empirical studies presented here, is to make explicit the types of design heuristics used by expert designers in ideation; then, to prepare a design pedagogy that presents these heuristics to students as part of their own idea generation practice. Over time, these design heuristics may become internalized and applicable in design problems where the need to be creative is a driving concern.

7.4. Design Practice

The process of generating creative ideas is enhanced by providing creative individuals with three main elements: nurture, freedom (Mauzy & Harriman, 2003) and time (Sternberg & Lubart, 1993). However, in this competitive environment, time is the one thing that is a luxury even for creative work. The need for high quality ideas often conflicts with the time provided. Thus, tools to assist designers in generating creative solutions in this fast-paced atmosphere are required. Within industry, creativity is not necessarily equal to success; however if its importance is ignored, long-term failure is inevitable (Cox, 2005). In order to produce the creative ideas required for innovation, the preferred technique within industry is still the traditional brainstorming (Osborn, 1957) despite the growing body of research identifying its limitations (Isaksen & Gaulin, 2005).

In this research, design heuristics are shown to lead designers and design students to creative solution concepts. The same approach can also be implemented in design practice. Design heuristics specific to an industry or product type can be identified, and added to the list already generated. Through instructional sessions with individual designers and design teams, heuristics can be introduced, and their impact on design solutions can be analyzed. Designers' sessions can be recorded, and how designers' discussions or thinking processes are altered by heuristic application can be specified, forming a basis for additional instructional sessions. The results can be reported back to the company for their advancement of creative problem solving.

Besides company-specific instructional sessions, 2-3 day workshops can be arranged for introducing design heuristics, describing examples and applications, asking designers to apply them to their current concepts, reflecting on how heuristics change idea generation processes. A similar step-by-step approach (explained in Section 7.3.3) can be applied in this compact workshop setting with the participation of design professionals including engineers, industrial designers, architects, and others. The crucial aspect for learning within a team is the creation of shared understanding, so workshop sessions will be more beneficial to the participants when design teams are gathered together. Different *process*, *local*, and *transitional* heuristics can be provided to each design team while keeping the design task the same to see how each heuristic set affects solution quality and creativity. At the end of each day, the teams can be asked to give short presentations to the rest of the group about their concept ideas, which heuristics were more applicable to their solutions, and how heuristic use, in general, changed their perspective in design thinking and applying strategies. These steps can be repeated in the following days by changing the design teams, design task, criteria, and the set of heuristics introduced. Instead of assigning detailed, day-long problems to teams, different problems can be considered within each 90-minute session so that the participants have a broader understanding of how heuristics can be applied to various design problems.

The identification of heuristics suggests ways for computational tools to assist in the design process. For example, the frequency of heuristics applied could be analyzed to understand which of the heuristics are most commonly used, what kind of design problems they were frequently applied to, what kind of new concepts they generated, and which heuristics may be relevant given the observable patterns. The results can then be incorporated into a computerize tool that can take simple information about the design problem as input, and propose heuristics to apply, assisting the designer as they move through a work session. This tool would help the designer to organize the session's process, making use of heuristics found to be relevant in related problems. This would add an external motivation and support for moving through a large set of heuristics, supporting the generation of a larger body of diverse concepts. The availability of such a tool would help to improve design practice based on evidence of the success of design heuristics.

7.5. Future Research

Several areas of further work are suggested by the research reported in this thesis. First, more empirical studies with expert designers are needed to confirm details of how heuristics change design concepts, and to generalize the findings. The empirical investigations reported here are suggestive rather than conclusive as to what happens to concepts when design heuristics are applied in the idea generation process. A more direct way to test the theory that heuristic use increases with expertise is to conduct longitudinal studies following designers through their educational and practice experiences.

Second, the use of content analysis, protocol studies, case studies, and observations provided a rich set of information about design heuristics in individual cases. Further empirical studies are needed to carry the heuristic use analysis from individual designers to design teams. How do design teams solve problems at various stages of the project, how do they utilize heuristics, and how does design heuristic use differ with teams? These questions could be explored through protocol studies with design teams.

Third, this thesis presented a validation study of heuristics as instructional materials, and demonstrated their impact on concept creativity. Further study of design heuristics at design firms would provide evidence of the impact of instruction at more sophisticated levels of design. Beginning with practicing designers, multiple design sessions supported by instruction could be recorded, and the resulting design outcomes analyzed. This data would support heuristics instruction in a more naturalistic setting where the dynamics of the design process are evident among designers in the workplace.

A final direction for future work is an exploration of teaching design heuristics as part of design pedagogy. Using the educational method proposed in this chapter, an empirical study can be conducted. Students in interdisciplinary design courses could participate in sessions where design heuristics are taught with descriptions, examples, and abstractions, and the sessions can be analyzed. The effectiveness of these sessions could be evaluated by random assignment of heuristics to design teams, as well as using control groups. Support from this type of study could be instrumental in providing evidence of the design heuristics' effectiveness in design education.

PUBLICATIONS

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2010). Design heuristics in ideation across engineering and industrial design domains. *In the Proceedings of the International Conference on Engineering and Product Design Education, Trondheim, Norway. (in review)*

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2010). A comparison of cognitive heuristics use between engineers and industrial designers. *In the Proceedings of the 4th International Conference on Design Computing and Cognition, DCC'10, Stuttgart, Germany*.

Yilmaz, S., Seifert, C. M., Gonzalez, R. (2010). Cognitive heuristics in design. *In the Proceedings of the 4th International Conference on Design Computing and Cognition, DCC'10, Stuttgart, Germany.*

Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2010). Cognitive heuristic use in engineering design ideation. *In the Proceedings of American Society for Engineering Education Annual Conference, ASEE, Louisville, Kentucky.*

Yilmaz, S., & Seifert, C. M. (2010). Cognitive heuristics in design ideation. *In the Proceedings of 11th International Design Conference, DESIGN 2010, Dubrovnik, Croatia.*

Yilmaz, S., & Seifert, C. M. (2009). Cognitive heuristics employed by design experts: A case study. *In the Proceedings of 4th International Conference of International Association of Society of Design Research, IASDR, Seoul, Korea*.

Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2009). Cognitive heuristics in design: Instructional strategies to increase creativity in idea generation. *Journal of Artificial Intelligence in Engineering Design and Manufacturing, AI EDAM, Special Issue: Design Pedagogy*.

Park, J. A., Yilmaz, S., & Kim, Y. S. (2008). Using visual reasoning model in the analysis of sketching process. *In the Workshop Proceedings of 3rd International Conference on Design Computing and Cognition, DCC'08, Atlanta*.

Yilmaz, S., Park, J. A., & Kim, Y. S. (2008). Effects of cognitive activities on designer creativity and performance: A detailed look into the visual reasoning model. *In the Workshop Proceedings of Korea-Japan Design Engineering Workshop, Seoul, Korea.*

BIBLIOGRAPHY

Adams, R. S., & Atman, C. J. (1999). Cognitive processes in iterative design behavior. *In the Proceedings of 29th ASEE/ IEEE Frontiers in Education Conference, San Juan, Puerto Rico*.

Adams, R. S., Turns, J., & Atman, C. J. (2003). Educating effective engineering designers: the role of reflective practice. *Design Studies, 24*(3), 275-294.

Ahmed, S., Wallace, K. M., & Blessing, L. T. M. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design, 14*(1), 1-11.

Akin, O. (2001). Variants in design cognition. In C. M. Eastman & W. M. McCracken (Eds.), *Design knowing and learning: Cognition in design education* (pp. 105-124): Elsevier.

Akin, O., & Akin, C. (1996). Frames of reference in architectural design: analysing the hyperacclamation (Aha-!). *Design Studies, 17*(4), 341-361.

Altshuller, G. (1984). *Creativity as an exact science*. New York, NY: Gordon and Breach.

Amabile, T. (1982). Social psychology of creativity: A consequensual asessment technique. *Journal of Personality and Social Psychology, 43*(5), 997-1013.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89*(4), 369-406.

Anzai, Y., & Simon, H. A. (1979). The theory of learning by doing. *Psychological Review, 86*(2), 124-140.

Atman, C. J., & Bursic, K. M. (1998). Verbal protocol analysis as a method to document engineering student design processes. *Journal of Engineering Education, 87*(2), 121-132.

Atman, C. J., Chimka, J. R., Bursic, K. M., & Nachtman, H. L. (1999). A comparison of freshman and senior engineering design process. *Design Studies, 20*(2), 131-152.

Ball, L. J., Ormerod, T. C., & Morley, N. J. (2004). Spontaneous analogising in engineering design: a comparative analysis of experts and novices. *Design Studies, 25*(5), 495-508.

Barrows, H. S. (1996). Problem-based learning in medicine and beyond: A brief overview. In L. Wilkerson & W. H. Gijselaers, eds. (Eds.), *New directions for teaching and learning* (Vol. 68, pp. 3-11). San Francisco, CA: Jossey-Bass Publishers.

Basadur, M. S., Graen, G. B., & Wakabayashi, M. (1992). Identifying differences in creative problem solving style. In S. J. Parnes (Ed.), *Source book for creative problem-solving*. Buffalo, N.Y.: Creative Education Foundation Press.

Benami, O., & Jin, Y. (2002). Creative stimulation in conceptual design. *In the Proceedings of DETC, Montreal, Canada*.

Bharadwaj, S., & Menon, A. (2000). Making innovation happen in organizations: Individual creativity mechanisms, organizational creativity mechanisms or both? *The Journal of Product Innovation Management, 17*(6), 424-434.

Boden, M. A. (1990). *The creative mind*. UK: Abacus.

Boden, M. A. (1995). Creativity and unpredictability. *Constructions of the Mind: Artificial Intelligence and the Humanities, Stanford Electronic Humanities Review, 4*(2), 123-137.

Candy, L., & Edmonds, E. (1996). Creative design of the Lotus bicycle: implications for knowledge support systems research. *Design Studies, 17*(1), 71-90.

Chan, C. (1990). Cognitive processes in architectural design problem solving. *Design Studies, 11*(2), 60-80.

Christensen, B. T., & Schunn, C. D. (2009). The role and impact of mental simulation in design. *Applied Cognitive Psychology, 23*(3), 327-344.

Christensen, C. R., Garvin, D. A., & Sweet, A. (1991). *Education for judgment: The artistry of discussion leadership*. Cambridge, Mass. : Harvard Business School.

Christiaans, H. H. C. M., & Dorst, K. H. (1992). Cognitive models in industrial design engineering: a protocol study. *In the Proceedings of Fourth International Conference on Design Theory and Methodology, ASME, 42*, 131-140.

Clapham, M. M. (1997). Ideational Skills Training: A Key Element in Creativity Training Programs. *Creativity Research Journal, 10*(1), 33 - 44.

Cox, G. (2005). Cox review of creativity in business: Building on the UK's strengths. *Independent reviews from* *http://www.hmtreasury.gov.uk/independent_reviews/cox_review/coxreview_index.cfm*

Cox, V. (1987). An application of cognitive science to understanding problem solving activity for well structured problems: Cognition, algorithms, metacognition and heuristics. *In the Proceedings of the Frontiers in Education Conference, Session 27B5*, 664-669.

Cross, N. (1990). Design skills: past, present and future.

Cross, N. (1997). Descriptive models of creative design: Application to an example. *Design Studies, 18*(4), 427-455.

Cross, N. (1999). Natural intelligence in design. *Design Studies, 20*(1), 25-39.

Cross, N. (2000). *Engineering design methods: Strategies for product design* (3rd. ed.). Chichester, UK: John Wiley & Sons Ltd. .

Cross, N. (2003). The expertise of exceptional designers. In N. Cross & E. Edmonds (Eds.), *Expertise in Design*. Sydney, Australia: Creativity and Cognition Press.

Cross, N. (2004). Expertise in design: an overview. *Design Studies, 25*(5), 427-441.

Cross, N., & Cross, A. C. (1998). Expertise in engineering design. [10.1007/BF01607156]. *Research in Engineering Design, 10*(3), 141-149.

Dahl, D., & Moreau, P. (2002). The influence and value of analogical thinking during new product ideation. *Journal of Marketing Research, 39*(1), 47-60.

Davis, G. A., & Scott, J. A. (1971). *Training creative thinking*. New York: Holt, Rinehart & Winston.

Dorst, K. H., & Cross, N. (2001). Creativity in the design process: co-evolution of problem-solution. *Design Studies, 22*(5), 425-437.

Duncker, K. (1945). On Problem-Solving. *Psychological Monographs, 58*(5).

Eberle, B. (1995). *Scamper*. Waco, Texas: Prufrock.

Eckert, C. M., Stacey, M. K., & Clarkson, P. J. (2000). Algorithms and inspirations: creative reuse of design experience. *In Greenwich 2000 International Symposiums: Digital Creativity, 13-15 January, 2000, London, UK*.

Ericsson, K. A., Charness, N., Feltovich, P., & Hoffman, R. R. (2006). *Cambridge handbook of expertise and expert performance*. Cambridge: Cambridge University.

Ericsson, K. A., & Simon, H. A. (1993). *Protocol analysis: Verbal reports as data*. Cambridge, MA: The MIT Press.

Eysenck, M. W., & Keane, M. T. (2000). *Cognitive Psychology : A Student's Handbook* (4th ed.). New York, NY: Psychology Press Ltd.

Finke, R. A., Ward, T. B., & Smith, S. M. (1992). *Creative cognition: Theory, research, and applications*. Cambridge, MA: The MIT Press.

French, M. J. (1985). *Conceptual design for engineers*. London, UK: The Design Council/Springer.

Gero, J. S. (1990). Design prototypes: A knowledge representation schema for design. *AI Magazine*, *11*(3), 26-36.

Gero, J. S. (2001). Mass customization of creative designs. *In the proceedings of International conference on Engineering Design, Glasgow*.

Gilovich, T., Griffin, D., & Kahneman, D. (2002). *Heuristics and biases: The psychology of intuitive judgment*. Cambridge, UK: Cambridge University Press.

Goel, V. (1995). *Sketches of thought*. Cambridge, MA: MIT Press.

Goel, V., & Pirolli, P. (1992). The structure of design problem spaces. *Cognitive Science, 16*(3), 395-429.

Goldenberg, J., & Mazursky, D. (2002). *Creativity in product innovation*. Cambridge, UK: Cambridge University Press.

Goldschmidt, G. (1995). Development in architectural designing. In M. B. Franklin & B. Kaplan (Eds.), *Development and the arts* (pp. 79-112). Hillsdale, NJ.

Goldschmidt, G., & Tatsa, D. (2005). How good are good ideas? Correlates of design creativity. *Design Studies*, *26*(6), 593-611.

Gordon, W. J. J. (1961). *Synectics*. New York: Harper & Row.

Gotzsch, J. (1999). Design orientation in new product development. In B. Jerrard & R. e. a. Newport (Eds.), *Managing new product innovation* (pp. 38-60). London, UK: Taylor & Francis.

Harrington, D. M. (1975). Effects of explicit instructions to "be creative" on the psychological meaning of divergent thinking test scores. *Journal of Personality, 43*(3), 434-454.

Howard, T. J., Culley, S. J., & Dekoninck, E. (2008). Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies, 29*(2), 160-180.

Hybs, I., & Gero, J. S. (1992). An evolutionary process model of design. *Design Studies, 13*(3), 273-290.

Isaksen, S. G., & Gaulin, J. P. (2005). A reexamination of brainstorming research: Implications for research and practice. *Gifted Child Quarterly, 49*(4), 315-329.

Jackson, P. W., & Messick, S. (1965). The person, the product, and the response: Conceptual problems in the assessment of creativity. *Journal of Personality, 33*(3), 309-329.

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies, 12*(1), 3-11.

Jin, Y., & Chusilp, P. (2005). Study of mental iteration in different design situations. *Design Studies, 27*(1), 25-55.

Jordan, P. W. (2000). *Designing pleasurable products: An introduction to the new human factors*. London, UK: Taylor & Francis.

Kahneman, D., Slovic, P., & Tversky, A. (1982). *Judgment under uncertainty: Heuristics and biases*. Cambridge, UK: Cambridge University Press.

Kaplan, C. A., & Simon, H. A. (1990). In search of insight. *Cognitive Psychology, 22*(3), 374-419.

Kavakli, M., & Gero, J. S. (2002). The structure of concurrent cognitive actions: a case study on novice and expert designers. *Design Studies, 23*(1), 25-40.

Klein, G. (1998). *Sources of Power: How People Make Decisions*. Cambridge, MA: The MIT Press.

Koen, B. V. (1991). A heuristic look at the differences in engineering design. *International journal of applied Engineering, 7*(6), 489-491.

Kolli, R., & Pasman, G. J. (1993). Some considerations for designing a user environment for creative ideation. *In the Proceedings of Interface '93, Human Factors and Ergonomics Society, Santa Monica, USA*, 72-77.

Kolodner, J. (1993). *Case-based reasoning*. San Francisco, CA: Morgan Kaufmann Publishers Inc.

Kruger, C., & Cross, N. (2001). Modeling cognitive strategies in creative design. . In J. S. Gero & M. L. Maher (Eds.), *Computational and cognitive models of creative design V*: University of Sydney, Australia.

Kruger, C., & Cross, N. (2006). Solution driven versus problem driven design: Strategies and outcomes. *Design Studies, 27*(5), 527-548.

Lawson, B. R. (1994). *Design in mind*. Oxford, UK: Butterworth Architecture.

Lawson, B. (2006). *How designers think*. Oxford, UK: Architectural Press.

Lawson, B., & Dorst, K. H. (2009). *Design expertise*. Burlington, MA, USA: Elsevier Ltd.

Lemaire, P., & Siegler, R. S. (1995). Four aspects of strategic change: Contributions to children;s learning of multiplication. *Journal of Experimental Psychology: General, 174*(1), 83-97.

Linsey, J. S., Laux, J., Clauss, E. F., Wood, K. L., & Markman, A. B. (2007). Effects of analogous product representation on design-by-analogy. *In the Proceedings of International Conference on Engineering Design, ICED, Paris, France*.

Linsey, J. S., Wood, K. L., & Markman, A. B. (2008). Increasing innovation: Presentation and Evaluation of the wordtree design-by-analogy method. *In the Proceedings of ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, DETC2008-49317, New York, USA.*

Lloyd, P., & Scott, P. (1994). Discovering the design problem. *Design Studies, 15*(2), 125-140.

Lloyd, P., Lawson, B., & Scott, P. (1995). Can concurrent verbalization reveal design cognition? *Design Studies, 16*(2), 237-259.

Maher, M. L., & Gomez de Silva Garza, A. (1997). Case-based reasoning in design. *IEEE Expert: Intelligent Systems and Their Applications, 12*(2), 34-41.

Mauzy, J., & Harriman, R. (2003). Three climates of creativity. *Research-Technology Management, 46*(3), 27-30.

Mumford, M. D., & Gustafson, S. B. (1988). Creativity syndrome: Integration, application, and innovation. *Psychological Bulletin, 103*(1), 27-43.

Neiman, B., Do, E.-L., & Gross, M. D. (1999). Sketches and their functions in early design: A retrospective analysis of two houses. *Design Thinking Research Symposium '99*.

Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood, NJ: Prentice-Hall.

Nielsen, J. (1993). *Usability engineering*. San Diego, CA: Academic Press.

Osborn, A. (1957). *Applied imagination: Principles and procedures of creative problem-solving*. NY: Scribner.

Ottosson, S. (2001). Dynamic concept development, a key for future profitable innovations and new product variations. *In the Proceedings of International Conference on Engineering Design, Glasgow*.

Pahl, G., & Beitz, W. (1996). *Engineering design: A systematic approach*. Verlag: Springer.

Park, J. A., Yilmaz, S., & Kim, Y. S. (2008). Using visual reasoning model in the analysis of sketching process. *In the Workshop Proceedings of 3rd International Conference on Design Computing and Cognition (DCC'08)*.

Pasman, G. J. (2003). *Precedents in design. Doctoral Dissertation*: Delft University of Technology, Delft, The Netherlands.

Pietersen, C. (2002). Research as a learning experience: A phenomenological explication. *The Qualitative Report, 7*(2).

Prahalad, C. K., & Ramaswamy, V. (2003). The new frontier of experience innovation. *MIT Sloan Management Review [1532-9194], 44*(4), 12-20.

Prats, M., Lim, S., Jowers, I., Garner, S. W., & Chase, S. (2009). Transforming shape in design: Observations from studies of sketching. *Design Studies, 30*(5), 503-520.

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies, 17*(4), 363-383.

Riel, A. J. (1996). *Object-oriented design heuristics*. Reading, Massachusetts: Addison-Wesley Professional.

Schank, R. C. (1982). *Dynamic Memory: A Theory of Reminding and Learning in Computers and People*. New York: Cambridge University Press.

Schon, D. A., & Wiggins, G. (1992). Kinds of seeing and their functions in designing. *Design Studies*, *13*(20), 135-156.

Schunn, C. D., McGregor, M. U., & Saner, L. D. (2005). Expertise in ill-defined problem-solving domains as effective strategy use. *Memory & Cognition*, *33*(8), 1377-1387.

Scott, G. S., Leritz, L. E., & Mumford, M. D. (2004). The effectiveness of creativity training: A quantitative review. *Creativity Research Journal, 16*(4), 361-388.

Scott, G. M., Lonergan, D. C., & Mumford, M. D. (2005). Conceptual combination: Alternative knowledge structures, alternative heuristics. *Creativity Research Journal, 17*(1), 79-98.

Shah, J., Vargas-Hernandez, N., Summers, J., & Kulkarni, S. (2001). Collaborative Sketching (C-Sketch) - An Idea Generation Technique for Engineering Design. *Journal of Creative Behavior, 35*(3), 168-198.

Smith, K. A., Sheppard, S. D., Johnson, D. W., & Johnson, R. T. (2005). Pedagogies of engagement: Classroom-based practices. *Journal of Engineering Education, 94*(1), 87-101.

Soosay, C. A., & Hyland, P. W. (2004). Driving Innovation in Logistics: Case Studies in Distribution Centres. *Creativity and Innovation Management, 13*(1), 41-51.

Sternberg, R. J., & Lubart, T. I. (1993). Investing in creativity. *Psychological Inquiry, 4*(3), 229-233.

Sternberg, R. J., & Lubart, T. I. (1995). *Defying the Crowd: Cultivating Creativity in a Culture of Conformity*. New York: Free Press.

Suwa, & Tversky, B. (1997). What do architects and students perceive in their design sketches? A protocol analysis. *Design Studies, 18*(4), 385-403.

Taghavi, T., Hghiasi, S., Ranjan, A., Raje, S., & Sarrafzadeh, M. (2004). Innovate or perish: FPGA physical design. *In the Proceedings of the 2004 International Symposium on Physical Design*, 148-155.

Thompson, G., & Lordan, M. (1999). A review of creativity principles applied to engineering design. *Journal of Process Mechanical Engineering, 213*(1), 17-31.

Tovey, M. (1989). Drawing and CAD in industrial design. *Design Studies, 10*(1), 24-39.

Tynjälä, P. (1998). Traditional studying for examination versus constructivist learning tasks: Do learning outcomes differ? *Studies in Higher Education, 23*(2), 173-189.

Ullman, D. (1992). *The mechanical design process*. New York: McGraw-Hill.

Von Oech, R. (2003). *Creative Whack Pack: Sixty Four Strategies to Provoke and Inspire Your Thinking*. Stamford, CT: US Games Systems, Inc.

Ward, T. B., & Finke, R. A. (1995). *Creativity and the mind: Discovering the genius within*. London, UK: Plenum Press.

Warren, T. F., & Davis, G. A. (1969). Techniques for creative thinking: An empirical comparison of three methods. *Psychological Reports, 25*(1), 207-214.

Watson, I., & Marir, F. (1994). Case-based reasoning: A review. *The Knowledge Engineering Review, 9*(4), 327.

Weisberg, R. W. (1988). Problem solving and creativity. The nature of creativity: Contemporary psychological perspectives. In R. J. Steinberg (Ed.), *The nature of creativity: Contemporary psychological perspectives* (pp. 148-176). New York, NY, US: Cambridge University Press.

Wertheimer, M. (1959). *Productive thinking* (enlarged ed.). New York: Harper & Brothers.

Wiggins, G., & McTighe, J. (2000). *Understanding by design*. Upper Saddle River: Prentice Hall.

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2010). A comparison of cognitive heuristics use between engineers and industrial designers. *In the Proceedings of the 4th International Conference on Design Computing and Cognition (DCC'10), Stuttgart, Germany*.

Yilmaz, S., & Seifert, C. M. (2009). Cognitive heuristics employed by design experts: A case study. *In the Proceedings of 4th International Conference of International Association of Society of Design Research, IASDR, Seoul, Korea*.