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Design Heuristics in Innovative Products

Current design theory lacks a systematic method to identify what designers know that helps them to create innovative products. In the early stages of idea generation, designers may find novel ideas come readily to mind, or may become fixated on their own or existing products. This may limit the ability to consider more and more varied candidate concepts that may potentially lead to innovation. To aid in idea generation, we sought to identify "design heuristics," or "rules of thumb," evident in award-winning designs. In this paper, we demonstrate a content analysis method for discovering heuristics in the designs of innovative products. Our method depends on comparison to a baseline of existing products so that the innovative change can be readily identified. Through an analysis of key features and functional elements in the designs of over 400 award-winning products, 40 heuristic principles were extracted. These design heuristics are outlined according to their perceived role in changing an existing product concept into a novel design, and examples of other products using the heuristics are provided. To demonstrate the ease of use of these design heuristics, we examined outcomes from a classroom study and found that concepts created using design heuristics were rated as more creative and varied. The analysis of changes from existing to innovative products can provide evidence of useful heuristic principles to apply in creating new designs. [DOI: 10.1115/1.4032219]

1 Introduction

Exciting product designs depart from what is currently on the market [1]. For this reason, one design strategy is to generate as many creative solutions as possible that fit the problem requirements in the initial concept generation phase [2]. By generating multiple alternative concepts with varied features, the designer can then select the best prospects for further development. One estimate is that only 8% of development costs are incurred during the early design phase; yet, decisions made in this phase determine up to 70% of the total cost over the product's life [3]. Perhaps as a result, researchers have investigated the cognitive processes that occur in the concept generation phase of design creation [4–10]. While a common ideation technique in industry is traditional team brainstorming [11], a growing body of research has identified its limitations [12]. Designers can also become "fixated" [13–16], where their attention is focused on a single past example or on one new idea. How do designers generate more and more varied concepts in order to produce product innovations?

Design expertise is a complex subject to study empirically because the creative process appears unpredictable and opportunistic [17]. But studies of expert designers have uncovered some of the behaviors associated with the generation of designs: An expert designer draws upon precedents [18], is able to restructure a design problem space through transformations [19], makes long interrelated chains of moves (and retrieves larger knowledge chunks from memory) [20], and identifies "clues" to good designs [21]. Experts within a domain learn to incorporate a variety of cognitive changes that improve performance [22,23]; in particular, they learn to use domain-specific, implicit knowledge derived from their experiences [24]. This implicit knowledge in expertise appears to take the form of simple rules of thumb used to generate a judgment or decision [25]. While the term "heuristic" more commonly refers to strategies that use existing information to guide search in problem-solving [26], cognitive heuristics are "best guesses" at potential solutions and are not guaranteed to lead to a determinate solution. Psychological research shows that experts use cognitive heuristics constantly and effectively, and their efficient use of domain-specific heuristics distinguishes them from novices [27]. For example, an expert firefighter arrives at a scene and instantly recognizes what approach to take to the fire based on implicit knowledge built from many experiences with other scenes; then, that knowledge serves as a heuristic to direct action in this novel setting [28]. The cognitive heuristic directs behavior in the new setting, though it is not certain to be successful.

We draw upon this concept of cognitive heuristics to describe an experience-based rule of thumb in memory that can be useful in suggesting new design concepts, called design heuristics [29,30]. In this approach, specific cognitive heuristics are posited as implicit knowledge based on past experiences that help the designer to explore the solution space of potential designs [30,31]. Successively applying different design heuristics assists in creating different candidate concepts from this potential design space. We propose that expert designers employ design heuristics in order to enhance the variety, quality, and creativity of potential designs they generate during the ideation stage.

In a case study of an expert practitioner working on a two-year project, we examined the designer's work as captured in his progression of designs recorded on a scroll such that related designs appear in adjacent positions. By closely analyzing the progression of concepts in the scroll, a large number of different design heuristics were identified [31]. This designer appeared to have acquired design heuristics that could be applied to create multiple new concepts. The concept sketch in Fig. 1 illustrates one design heuristic from this study. In the retrospective interview, the designer commented, "… 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?" By "adding on" snap-on trays onto the bathtub for the needed functions, using the heuristic

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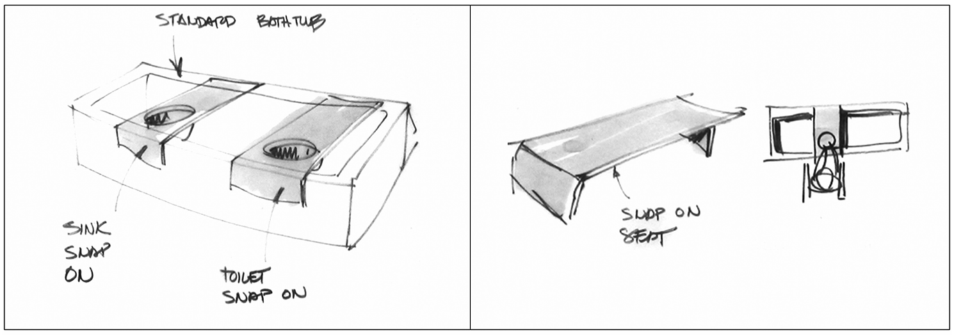


(*a*) (*b*)

Fig. 1 ((*a*) and (*b*)) An expert designer's concepts reflect the heuristic add-on, take out, or fold away components when not in use [31]

creates a novel design. This heuristic of "add-on, take out, or fold away components" can be readily applied to many product design contexts, and it is evident in many existing consumer products such as a Swiss Army knife. For the designer, it appeared to be a natural heuristic to apply as needed to generate new designs.

The analyses from this in-depth study of one designer revealed common patterns of design heuristic use across concepts. Over this large set of over 200 varied designs, specific heuristics were observed repeatedly even though applied in different concepts. Interestingly, these heuristics were implicit in the designer's thinking. In an interview, he described it as recognizing that he must have been thinking that when he created the design, but he did not recall consciously thinking about applying the heuristics [31]. As a very experienced designer, these rules of thumb about generating novel designs were well learned and highly accessible as evidenced by their frequent appearance in the concepts. While the cognitive process cannot be known from such studies, such as whether the designer is recalling other designs, design heuristics, or more general principles, it was possible to identify how the *concepts* differ from each other. From these descriptions, rules of thumb were captured and described in a manner that provides direction for intentionally introducing variation within designs. If these heuristics are then successively applied intentionally in new problems, the idea generation stage can be expanded to identify a larger, more varied set of candidate designs. The next step is to examine whether these design heuristics are evident in a diverse set of successful, innovative products.

2 Uncovering Design Strategies

Our goal is to investigate the design heuristics evident in innovative products through a systematic examination of the work of successful designers. A variety of idea generation tools and techniques have been proposed to help designers create new concepts, including brainstorming [11], brainwriting [32], morphological analysis [33,34], Synectics [35], lateral thinking [36], conceptual combination [37], SCAMPER [38], IDEO™ Method Cards [39], and holistic approaches [40]. These varied ideation techniques differ in their focus, specificity, and ease of use. These approaches offer general heuristics about creating designs; for example, the SCAMPER approach [38] defines seven general heuristics (*substitute*, *combine*, *adapt*, *modify*, *put to other uses*, *eliminate*, and *rearrange/reverse*). The heuristics proposed in Synectics [35], called "triggers," provide very general theme suggestions, including *parody, prevaricate, metamorphose*, and *mythologize* to change the setting or meaning of the product, or compare markets and other similar products. While often based on design experiences, these methods are not tied to a systematic analysis of innovations.

Other studies have examined protocols of designers at work and identified important cognitive strategies such as analogical thinking [41–44], where comparison is drawn from related examples and applied to a new design. Singh et al. [45] proposed an inductive extraction method to study analogies in nature, patents, and products. They identified three "transformation principles" and corresponding "facilitators" by studying key design features and functional elements in products and patents. For example, the principle, "expand/collapse," suggests transforming a design by changing the physical dimensions of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane or in three dimensions. Just as the puffer fish expands its body to ward off predators, a portable sports chair expands for sitting and collapses for storage or portability; in a patent, a bag expands from a towel to a tote bag. The transformation principles identified are specific to changing states in order to facilitate added functionality.

Another approach systematically considered the design innovations in a large body of existing product patents, called TRIZ [46,47]. The TRIZ approach was developed by analyzing past designs from mechanical engineering patents. The approach was to analyze existing patents to uncover how a novel contribution was made to an existing mechanical device. From the analysis, a technical matrix of 39 common engineering problems and 40 possible solution types were derived. The results were then translated into a method for identifying and resolving conflicts in the implementation of new designs. For example, in designing a soda can, a designer employing the TRIZ system may first analyze the technical contradictions caused by engineering parameters; specifically, the wall thickness of the can has to be rigid enough for stacking, yet cost-effective for manufacturing. Then, using the heuristic, "increase the degree of an object's segmentation," the can wall could be redesigned from flat to corrugated to increase durability. The TRIZ heuristics are focused on very specific engineering mechanisms (such as pneumatics), parameters, and related conflicts and tradeoffs, and as a result, are most useful for resolving problems that arise within a design later in the design process, once commitments have been made to implementation of concepts within specific materials.

Finally, Saunders et al. [48] investigated 197 award-winning products to identify the characteristics that distinguish these products from the competition. They found that award-winning products had multiple characteristics (an average of approximately two more characteristics than their competitors on retail shelves) contributing to their innovative designs. More than two-thirds enhanced user interactions and external interactions, half displayed innovative architectures, and one-third offered additional functions. Their analysis produced 13 "characteristics of innovation" ranging from "additional function," "modified size," "modified material flow" to "purchase cost." Their method of surveying award-winning products suggests that the analysis of many products is helpful in identifying important contributions to design.

Our present research started with the same method of collecting innovative product designs for systematic analysis to determine whether design heuristics would emerge. Using design competition awards as an index of quality, over 400 products were identified for the study. All were designs for differing products created by different designers. These products were analyzed separately

Table 1 Sources for products included in study

Source	Year	Organizing body
International Design Excellence Awards (IDEA)	2009	Industrial Designers Society of America
Red-Dot Product Design Awards	2009	12,000 submissions from 60 more than countries
iF Product Design Awards	2008	International expert jury
Good Design Awards	2008–2009	Awarded by jury through the Japan Industrial Design Promotion Organization
National Design Awards	2009	U.S. national awards by Smithsonian's Cooper-Hewitt National Design Museum
Deconstructing Product Design: Exploring the Form, Function, Usability, Sustainability, and Commercial Success of 100 Amazing Products	2009	William Lidwell and Gerry Manacsa by Rockport Publishers
Design Secrets: Products	2001	Industrial Designers Society of America by Rockport Publishers (50 products selected from IDEA competition winners)
Design Secrets: Products 2: 50 Real-Life Product Design Projects Uncovered (v. 2)	2006	Lynn Haller and Cheryl Dangel Cullen by Rockport Publishers (50 products selected from IDEA competition winners)
Process: 50 Product Designs from Concept to Manufacture	2008	Jennifer Hudson by Laurence King Publishers (50 contemporary domestic objects from around the world, both long-established and emerging designers)
1000 New Eco Designs and Where to Find Them	2009	Rebecca Proctor by Laurence King Publishers (1000 contemporary product designs chosen for esthetics and ecological value)

to identify design heuristics evident in the final product designs. This method of extracting heuristics by examining final products necessarily focuses on externally observable forms and appearances, along with the customer needs addressed. This method is similar to that of TRIZ [46,47], which is based on examinations of the internal architecture and the enabling engineering characteristics from patented mechanisms. We identified an extraction method (similar to Ref. [45]) for systematically analyzing the award-winning designs while comparing them to existing designs in the same product category; for example, what is it about this award-winning bicycle design that is different from a typical one? While this method may miss some heuristics, it allows the definition of other heuristics based solely on evidence from comparing the final product and its qualities that distinguish them as different from other existing products. We set out to analyze a large number of products so that the final set of designs included truly innovative products. The more varied the set of designs, the more likely they would lead us to a variety of potential design heuristics for innovation. Our central question was: "What are the heuristics that lead to award-winning designs?"

3 Method: Extracting Heuristics From Product Designs

We identified designs through existing, independent award competitions and published compendiums of well-known, successful products. The information available about each product included the product descriptions, design criteria, constraints, scenarios, and sometimes critiques provided by professional designers. The sources of the example designs we analyzed for this study are given in Table 1.

From these sources, we narrowed our selection using the following criteria: the product was (1) easy to understand through reading its description, (2) designed for the consumer market, (3) currently available in the marketplace, and (4) innovative in both its functionality and its interaction with the user. This left us with 400 products for a more detailed investigation. The information available about each product included a color photograph, product name, and a short description of its goals, functions, and features. An example product and its description can be seen in Fig. 2.[2]

Major elements and key features of the products were identified for functionality, form, user-interaction, and physical state. We then performed a content analysis of the needs, design criteria, and the design solution. After the products were analyzed, the ones with the same apparent design innovations were grouped, and then compared in order to explore the commonalities. A description of this extraction procedure is illustrated in Fig. 3.

In this extraction process, we first (step 1) randomly selected one of the products from our source list and (step 2) defined its functions, its key features, and what makes it unique. Then, (step 3) we hypothesized heuristics for each function and described how each component interacts with the other components and within the product as a whole. This investigation then led (step 4) to a set of heuristics that transform or manipulate basic functions or forms of the design components, such as repeating or flipping. We then (step 5) identified the design criteria that potentially were met by the product, such as adjustability and security. Once the heuristics were extracted and the criteria identified for one product, we then (step 6) identified at least two other products to serve as examples of the implemented heuristic that fit with the same criteria in their definitions. This step allowed us to explore whether we could identify the same heuristics from descriptions of other example products. We then applied steps 2–6 for each example product added for comparison in step 6. This process continued for each concept in our set of 400 products. As a final step (step 7), we identified different ways of implementing each heuristic by examining the ways the heuristics led to different concepts, ensuring they included flexible use.

First, a single coder (an experienced industrial designer) started the extraction process with an initial set of 21 heuristics in hand.

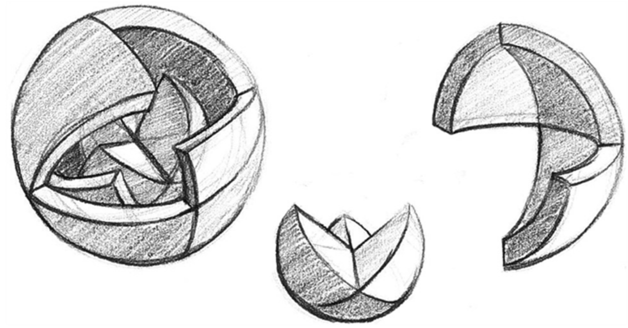


Fig. 2 Oblo puzzle

[2]http://www.idsa.org/oblo-puzzle

These were identified in a prior study investigating an expert designer's idea generation process that included 50 sequential concepts [29]. Each of the 400 products was examined at length and coded for the presence of specific heuristics, and each new heuristic extracted was added to the set as needed. At the final step (7), some of the observed heuristics were revised or combined, resulting in a master list of 40 heuristics [49]. All of the initial heuristics (21) from the prior study were also observed in this product analysis. The identification of new heuristics occurred regularly in the first 200 products analyzed, and then, the need to add new heuristics tapered off, indicating that the analysis had approached saturation with these product designs.

Each heuristic was then described in a concise statement that included the purpose of the heuristic and specified changes to a design. Because the identification of the heuristics was driven by their appearance in specific products, their descriptions vary in specificity and purpose. For example, some heuristics focus on "how," such as "hiding/collapsing/flattening," while others focus on goals for a product (such as "add portability"). Some natural relationships appeared between heuristics, and some offered a more complete definition than others. Rather than impose a consistent scheme upon the heuristics, we chose to use a data-driven approach and describe each as observed in the product analyses, and without reference to other heuristics in the set. Similarly, the analysis took no view of what was useful as a heuristic to an experienced or novice designer. Instead, the descriptions were written to capture the readily observed differences in the innovative product compared to other products.

Clearly, interpretation is necessary in order to derive a potential heuristic from the description of a finished product. The dataset did not include information on intermediate steps, competing concepts considered by the designers, nor a process trace of each designer's work. We worked solely from the concept drawings or photographs and descriptions provided; consequently, it is possible that a given designer may not agree with our characterization of heuristic derived from their work. The goal with the extraction process was to systematically perform the same analysis of each product and to describe the innovations in language close to the observations made of each product encountered.

The success of this extraction approach is determined by whether the proposed heuristic is observed by other raters in using the same information, whether it was possible to identify the heuristic as described within other product designs, and whether the heuristic is formulated so as to offer a strategy to be applied in creating novel designs. To evaluate the extraction process, two more coders independently examined the product set. They were provided with the list of 40 heuristics and all of the same product descriptions. Both of these coders were trained designers, one

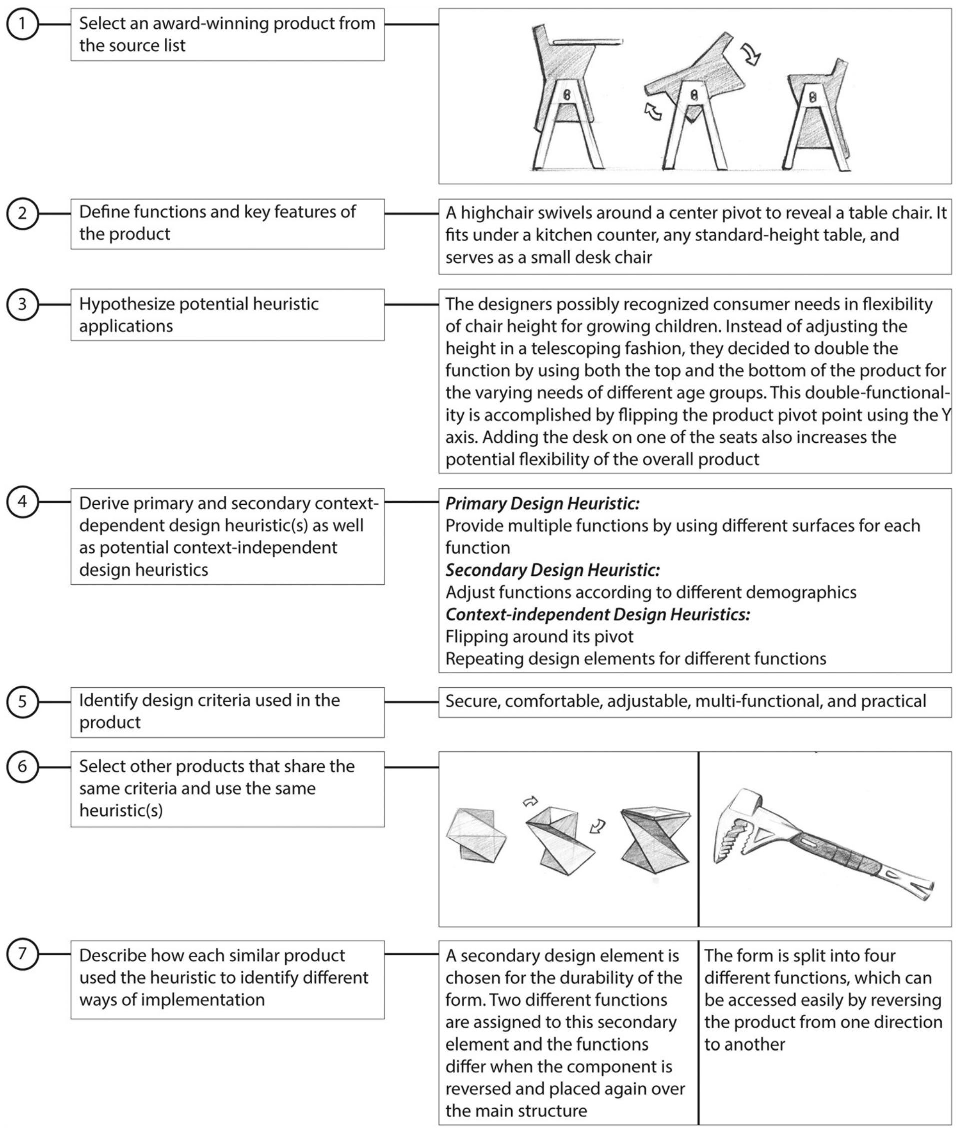


Fig. 3 Heuristic extraction process

with a Ph.D. in engineering and another with two undergraduate degrees in engineering and design. They recorded whether any heuristic was evident within each of the 400 designs. The initial inter-rater reliability between the two coders' judgments was above 80%. Any disagreement was resolved through discussion among all three coders in order to produce the final set of observed heuristics for the 400 products with 100% agreement among coders.

4 Results

The extraction process for the product design analysis successfully identified design heuristics in existing products. The process revealed multiple applications of individual heuristics in different products by different designers. In total, the analysis of the 400 products resulted in the observation of 40 different heuristics. In order to preserve the context of the heuristics' extraction from the award-winning products, we have intentionally avoided imposing a standard description or format onto the heuristics observed. Rather, we report the observations made from this set of 400 products, and the heuristics extracted from them.

4.1 Defining Design Heuristics. The changes in designs observed could be described at a very general, content-independent level, such as *addition*, *removal*, *distortion*, *orientation*, and *substitution*; this level of description is similar to approaches like Synectics [35] and SCAMPER [38]. However, the generality of these descriptions is problematic because they give little indication of *how* to apply the strategy. Thus, in defining design heuristics, we focused on a more specific description evident in the product examples in order to provide a clearer context for applying them to new design problems. As a result, the identified heuristics are more specialized and more varied, but they may also be more valuable as aids to designers. For example, twisting forms to create a playful look could also be described as "distortion" of the form. However, the added specificity of this heuristic (the playful look) is directly related to the design criteria observed in the product analyzed (designing a stool for a playground). In the set of 40 design heuristics, the nature of the specificity varies greatly and is derived from the observations of the specific products analyzed. The design heuristics also vary in that some add functionality, suggest use of fewer resources, save space, provide ideas about visual consistency, form relationships among the design elements, and emphasize design goals (adjust to different demographics). These more specific heuristics go beyond general descriptions to identify *why* a particular heuristic might be advantageous within a problem based on its occurrence in the innovative product example. Consider these five examples of the extracted heuristics and their resulting descriptions.

Heuristic example 1: Convert two-dimensional materials into three-dimensional. Change an object's dimensions with a change in boundary conditions. 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 can produce different functional outcomes.

Figure 4(*a*) shows a concept for a trashcan made out of rolled sheet plastic. Since it can be unrolled to be entirely flat, the design enhances the efficiency of transportation and storage. Figure 4(*b*) shows a lounge chair molded from a single flat sheet of transparent plastic. Both products convert a two-dimensional artifact into three dimensions during use.

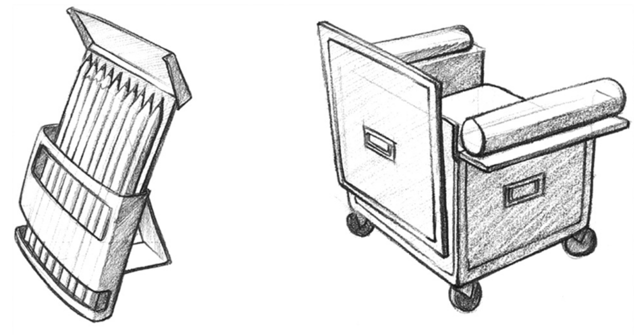
Heuristic example 2: Use packaging as a functional component within the product. Embed the packaging within the product, where the packaging performs a different function. Create a shell or cover for a component or the entire product using the package, and uncover it when it is used.

In Fig. 5(*a*), a set of colored pencils is stored inside a package that also serves as a stand for easy viewing during use. In Fig. 5(*b*), the chair is folded into a wooden box as its package, with wheels, while protecting interior cushions. Both products incorporate packaging as a feature of the product.

Heuristic example 3: Hide/collapse/flatten design elements not in use using by nesting. Place an object inside another object entirely or partially, wherein the internal geometry of the containing object is similar to the external geometry 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.

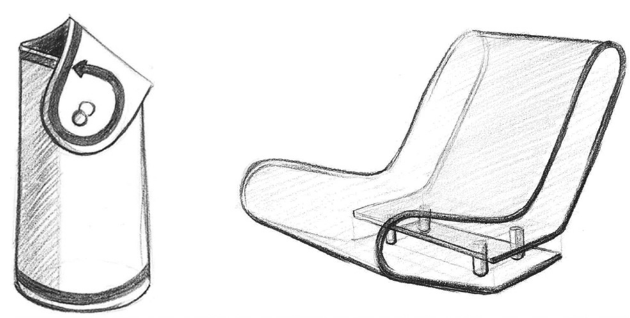
In Fig. 6(*a*), the two identical chairs can function together by nesting inside of each other. In Fig. 6(*b*), the different sized bowls and accessories are nested inside each other for compactness and saving space during storage.

Heuristic example 4: 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



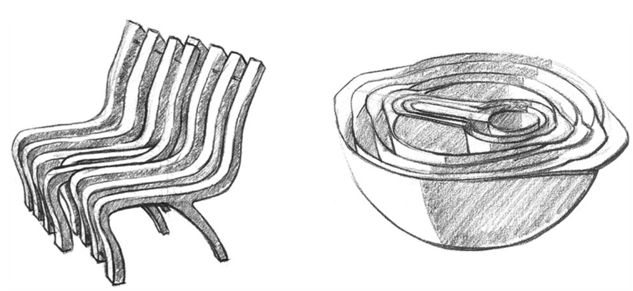
(*a*) (*b*)

Fig. 5 ((*a*) and (*b*)) Example designs for heuristic example 2 (use packaging as a functional component within the product)



(*a*) (*b*)

Fig. 4 ((*a*) and (*b*)) Example designs for heuristic example 1 (convert two-dimensional materials into three-dimensional)



(*a*) (*b*)

Fig. 6 ((*a*) and (*b*)) Example designs for heuristic example 3 (hide/collapse/flatten design elements not in use using by nesting)

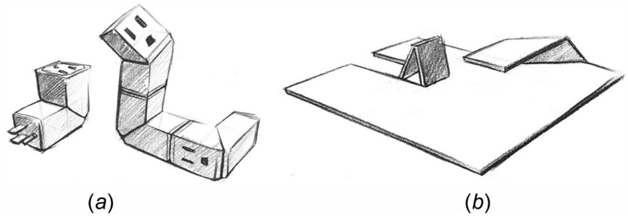


Fig. 7 ((*a*) and (*b*)) Example designs for heuristic example 4 (convert into modular units by repeating or splitting elements)

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 accomplish an overall function. In Fig. 7(*a*), the modules are electrical outlets that allow combinations to reach varied lengths and angles, and can be rotated 180 deg for easy access. They allow users to add or subtract sockets as needed. In Fig. 7(*b*), the user is given the option of configuring seating cushions on a platform to produce pleasing alternatives or raised and lowered sections and textures.

Heuristic example 5: Use same design element, color, and graphics for visual consistency. Arrange design elements within a product according to relationship, such as similarity, dependence, and proximity among them to create visual consistency. This can make the product more elegant and can be helpful in designing product families.

In Fig. 8(*a*), the set of two chairs and table fit together not in use. The armrests hug the tabletop, and the chair seats have an indent to fit the table leg. The size differs to communicate the two different functions. In Fig. 8(*b*), using the same geometrical form (a triangle) in various sizes for different functions creates visual consistency. This heuristic may result in more pleasing, easy to understand forms [50].

These five examples demonstrate that the design heuristics identified were observed in multiple products, and yet follow a more general principle that can be articulated and then applied in future designs. Each of the 40 identified heuristics was observed in at least four different products of the 400 in the database.

4.2 Forty Design Heuristics. Table 2 presents the 40 extracted design heuristics along with two different example products where each heuristic was also evident. Exactly how each heuristic is displayed differs based on the design problem, the context defined in the problem definition, and designers' preferences. Examples of other products where the heuristic was evident are meant solely to illustrate the apparent ready availability of heuristics in products. Each heuristic relates to specific features within the design problem and produces a new concept altered in a specific fashion. However, the same heuristic may be applied more than once in a given problem, such as applying the "visual consistency" heuristic to the seating area of a baby stroller, and applying it again to the external form. As a result, the identified design heuristics are applied within the specific problem context, and the selection of heuristic and how to apply it is not deterministic. As implied by the use of heuristic, they serve as rules of thumb that may or may not be useful within a given design. However, their use may allow a designer to create alternative concepts to consider that may not be obvious without the heuristic.

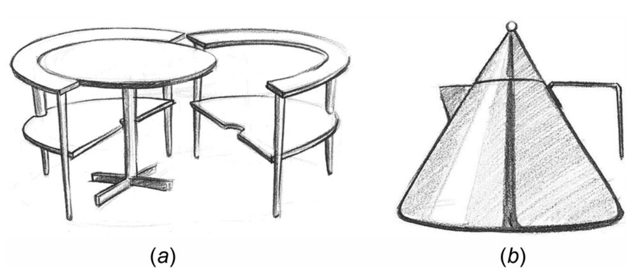


Fig. 8 ((*a*) and (*b*)) Example designs for heuristic example 5 (use same design element, color, and graphics for visual consistency)

The results of the product design analysis demonstrate a method for identifying design heuristics in existing products. The outcome of the content analysis was a set of 40 heuristics that were observed across 400 award-winning products from different designers. The observed heuristics cover a broad range of product functions, forms, materials, and interaction methods. The proposed heuristics offer the potential for application to other design problems and the creation of innovative concepts.

One limitation in our analysis of innovative products is that only one sample of 400 designs was included. This set of products likely taps a small proportion of the variety of innovation in product design and may be limited in the types of functions represented. For example, service-based products were not included in the study set. The 40 heuristics uncovered in this dataset are not likely to be exhaustive, as further the heuristics may be uncovered by considering different products. For example, sampling more products with a sustainability emphasis will likely uncover more heuristics involving ways to improve products. The extraction method also depends heavily on comparison of the target product to existing alternative products so that innovation can be identified. This method thus requires existing precedents since only the final concept for each product is included in the analysis. In addition, no reliability measure for the extraction process is provided here beyond the confirmation of observations by multiple coders. Clearly, interpretation is necessary to derive a potential heuristic from the description of a finished product.

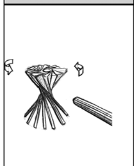
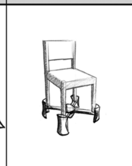
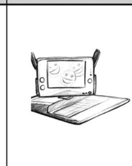
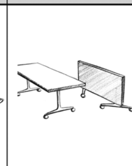
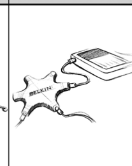
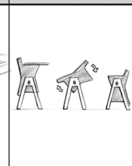
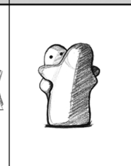
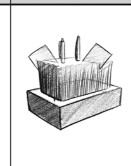
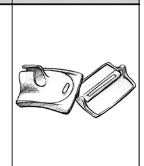
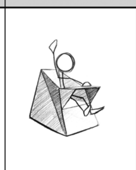
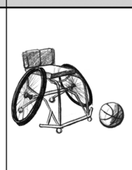
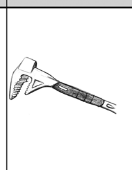
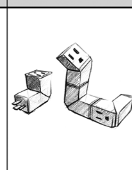
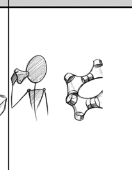
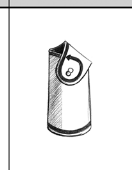
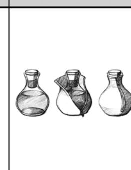
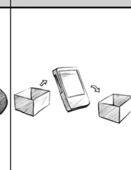
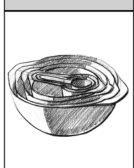
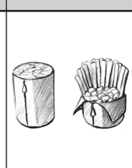
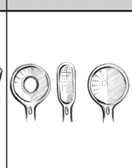
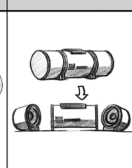
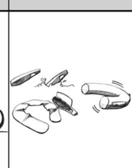
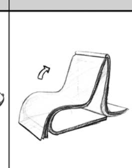
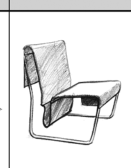
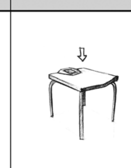
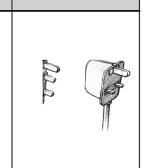
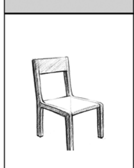
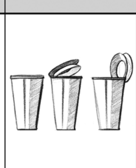
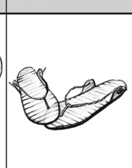
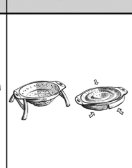
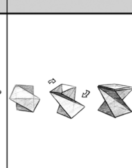
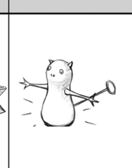
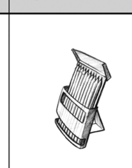
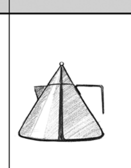
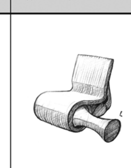
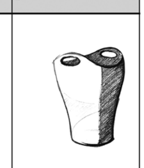
Some type of organization among heuristics is an ultimate goal of this research; however, imposing it prematurely poses some risk. Based on the product analysis method, we do not know what the designer experienced as they created the successful concepts. While it is likely that experienced designers have some heuristics brought to mind by the problem content, we do not yet have evidence to support such links. Similarly, it would be possible to consider the specific circumstances that promote the use of each given heuristic; however, doing so would require comparing many instances where the same heuristic is applied across design problems. Since that data are not available here, we chose to leave the heuristics descriptions as close to the observed examples as possible. The purpose of the present study was to uncover the specific heuristics evident in this product sample; so, the results are presented as the set of heuristics described as they were identified. Further refinement based on cognitive studies is an important direction for future research.

5 Exploratory Classroom Study

The purpose behind identifying design heuristics in innovative products was that the results should inform designers about how to achieve innovations in other products. We next examine whether the identified heuristics are useful for novice designers when generating new designs. Consider this example of using design heuristics to facilitate the ideation process. Figure 9 shows the application of four different heuristics to the problem: "Design a container to dispense a specific volume of liquid hand soap." Starting with an initial concept, the application of four different heuristics to the problem produces four different concepts for the product.

The application of each heuristic adds variety to the set of concepts generated, leading to a more diverse set of possible designs to consider. With each heuristic, additional features are explored beyond the basic criteria defined in the problem, and they each help to prompt new ways to achieve the basic criteria. For example, attaching the product on the faucet itself let the designer consider alternative ways of using the space around the faucet. This change also 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. Thus, the use of design heuristics is hypothesized to increase the diversity of concepts generated, and thus potentially lead to more creative solutions. Given that heuristic use was evident in the award-winning products, we wanted to test whether it was possible to observe correlations between use of heuristics and both creativity and diversity among novice designers.

Table 2 Forty design heuristics (1–40) identified in the content analysis of 400 innovative products

DESIGN HEURISTICS									
1. Add a portability feature to existing solutions	*2. Add motion to the product as a playful attribute (push/pull, etc.)*	*3. Add to existing product*	*4. Adjust functions according to different demographics*	*5. Adjust functions by moving the product's parts*	*6. Align components on the same base or around a center*	*7. Allow user to reorient*	*8. Animate product using human features for an approachable look*	*9. Apply an existing mechanism in a new way*	*10. Attach the product to the user*
									
This stool can be collapsed into a staff by twisting, providing compactness for storage and portability for carrying.	This alarm clock is designed to jump off a table and move. Two wheels on the sides allow it to roll while emitting a siren alarm.	This product attaches to an existing dining chair to turn it into a high chair for children. Using spring-loaded arms, it can securely hold any dining chair.	This laptop is designed for children living in developing countries. The size, colors, and interface all contribute to the playfulness of the product.	This design features a folding top that flips up or down, allowing the table to be used as room dividers.	This design allows for six audio devices to be shared at one time. All the components are collected in the center, and the six input jacks are placed around it.	This product provides three seating options. By turning the chair seat upside down, a baby seat becomes a toddler seat or recliner.	These shakers hug each other, abstracting human figures. The black and white colors also suggest balance and harmony.	This desk organizer uses brush bristles to hold pens, pencils, and business cards.	This vegetable peeler functions as an extension of the hand. It is slipped onto the finger like a ring.
11. Change physical approaches to the system	*12. Change product lifetime*	*13. Change the context of where the product will be used*	*14. Combine two or more functions by joining them*	*15. Convert into modular units by repeating or splitting elements*	*16. Convert the packaging into a product after the product is removed*	*17. Convert two-dimensional materials into three-dimensional*	*18. Cover or wrap*	*19. Create systems for returning to manufacturer after life cycle ends*	*20. Design communal activities to unite as a community*
									
The user approaches this chair from behind, and kneels on it, rather than sitting down on a standard office chair.	This feeding chair for toddlers is made from a single sheet of corrugated cardboard, coated with a food-safe layer. It is recyclable.	This hands-free braking and turning system allows athletes to maintain control without using their hands.	This product combines four tools into one solid piece. Both the top and the bottom of the handle are used for different functions.	This modular power strip enables users to add or subtract sockets as needed. The modules can also be rotated 180 degrees for easy access.	These Y-shaped bottles turn into a toy after use. They can be attached to each other in various configurations to make interesting sculptural forms.	This trash can is made out of a recycled sheet of plastic rolled around its center.	This fabric cover keeps tea hot and accentuates the sleek lines of the glass jar, as well as protecting the user's hands.	This phone is leased to the user with service, and is returned to the manufacturer after a year. Parts are replaced for reuse in later production.	This business card expresses the company's identity, and is manufactured with used packages collected by the company's staff.
21. Hide / Collapse / Flatten elements not in use by nesting	*22. Implement characteristics from nature within the product*	*23. Impose hierarchy on functions*	*24. Include user in the assembly or the customization of the product*	*25. Make the individual parts attachable and detachable*	*26. Make the product expandable in order to fit various sizes*	*27. Offer optional components*	*28. Provide multiple functions by using different surfaces for each*	*29. Provide sensory feedback to the user (tactile, verbal, visual, etc.)*	*30. Reduce the amount of material needed for the same function*
									
The different sized bowls and accessories are nested inside each other for compactness and saving storage space.	This task light uses "the great heron" as inspiration, and displays similar versatility in directional flexibility.	This chair can be manipulated into a cushy seat by following a set of steps: Unzip the cover, fold down some of the cushions, and then have a seat.	This collection offers three shower heads tailored for different consumer groups, allowing users to pick the head that fits to their preferences.	This tweeter and two bass speakers are assembled in a cylinder shape to protect the speakers while in transit.	This rescue stick inflates whenever it touches water. It is designed to be one-size-fits-all.	This chair is equipped with hundreds of colored sheets to fit any environment. Simply flip through the colors until you find one that suits you.	This dining chair contains hidden storage spaces and pockets by using a continuous fabric as part of the seat.	This stool doubles as a scale. Every time you sit down, the analog dial displays your weight.	The bulky traditional three-pinned plug is made portable by removing unnecessary material and adding folding wings.
31. Refocus on the core function of the product	*32. Remove the moving parts to minimize potential breakdowns*	*33. Replace materials with recycled ones*	*34. Replace solid material with flexible material for compactness*	*35. Twist forms to create a more playful look*	*36. Use human power as the energy source*	*37. Use packaging as a functional component within the product*	*38. Use same design element, color, graphics for visual consistency*	*39. Use the inner surface space of the product for different functions*	*40. Use the same material all throughout the product*
									
This dining chair represents the most simplistic solution to a chair: Four straight legs, a flat seat, and a rectangular back.	This trash can lid can be opened from all directions by gently lifting the edge because there are no fasteners.	These disposable shoes are made from recycled newsprint, and are completely biodegradable. This allows the product to be used in hospitals and salons.	The material of this colander is replaced with silicon in order to make it collapsible to save space in the cabinets.	This product is delivered to the user as a flat shape that can be twisted up into a rigid stool or side table.	This playful lamp is operated by pulling the attached cord repeatedly. Since human effort is required, it also enhances energy awareness.	A set of colored pencils is located inside a package that also serves as a stand during use.	Using the same geometrical form in various sizes for different functions creates visual consistency.	A stool fits in an inner space within the chair when not in use.	This trash can uses a continuous material for the basket and the handles.

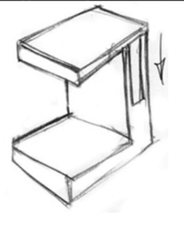
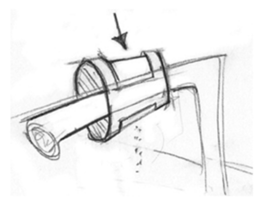
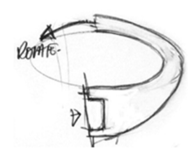
Heuristic 39: *Use the inner surface space of the product for different functions*	Heuristic 25: *Make the individual parts attachable and detachable.*	Heuristic 3: *Add to existing product.*	Heuristic 32: *Remove the moving parts to minimize potential breakdowns*
			
Top part is nested inside the main structure holding the soap. Soap is dispensed by a push-motion from the top. The central open space is used to place hand.	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 is attached to the faucet and slides. 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	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.

Fig. 9 Illustration of four different design heuristics applied to a new design problem, producing four different concepts

5.1 Study Method. In order to examine whether the identified heuristics can help novice designers, we conducted an exploratory, correlational study within an industrial design classroom. This provides access to design students who are learning about idea generation en route to becoming professional designers. Our guiding questions were as follows:

- Is heuristic use correlated with more creative designs?
- Is heuristic use correlated with more diverse set of concepts?

Twenty sophomore industrial design students between the ages of 18 and 24 (15 males and 5 females) taking an introductory course at a large Midwestern university participated in the study.

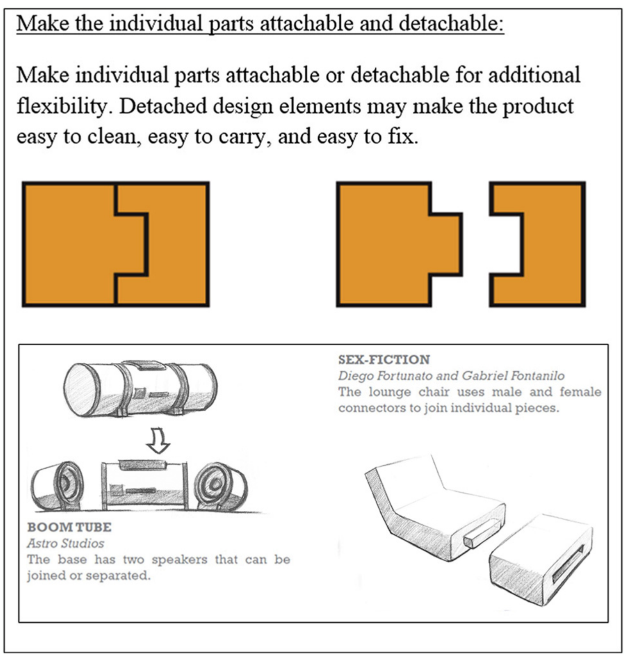


Fig. 10 An example heuristic, illustration, and product examples

The course covered the history, definition, scope, and basic principles of industrial design, including research, idea generation, visual communication, and sketch modeling. This class was the first the students took in the industrial design program after completing their freshmen year core program where they learned basic design principles. Students were considered "beginning designers" because they reported little or no previous experience in industrial design, but were enrolled in a professional training program.

The study was conducted within a classroom session. The design was correlational, so that all students were trained on the method and given opportunity to use it, and the product of their work was examined for evidence that they used the design heuristics method and, if so, the number of heuristics used. The session began with 15 min of instruction by the instructor on the use of design heuristics. Students were given the opportunity to ask questions. Each student was then supplied with a subset of 12 of the 40 design heuristics selected at random. Each heuristic card includes a title, written description, abstract illustration, and two photographic examples of existing products that illustrate the heuristic (see Fig. 10).

Then, the students were given an open-ended design task and were asked to generate as many concepts as possible within 25 min:

> 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. Please focus on conceptual designs. Please consider both the ways of capturing the light, and the structural variety of the concepts.

Since we wanted participants to spend their time on concept generation and not the feasibility of the concepts, we also provided information on the basic principles of transferring solar energy into thermal energy (by concentrating sunlight, converting light to heat, and trapping heat). While feasibility clearly is an important requirement, we are concerned with an earlier stage of the design process: idea generation. Students were instructed to

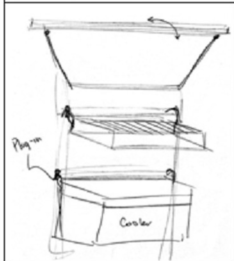
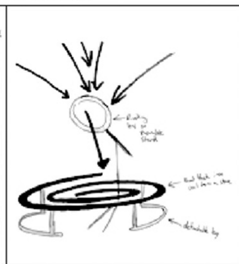
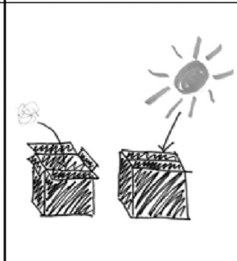
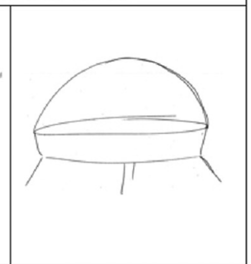
Heuristic Use Evident		Heuristic Use Not Evident	
			
Rack includes attachable grill, shelf, and cooler capturing the sunlight via solar panels.	A black iron coil on a stand is heated through focusing sunlight with a movable lens. All parts are detachable for easy storage.	Sun heats up the box which then heats up the food inside.	The dome form is used as a lid to retain sunlight inside.
25.Make individual parts attachable and detachable 27.Offer optional components	25. Make individual parts attachable and detachable		

Fig. 11 Example design solutions from student concepts in which heuristic use was evident versus not evident

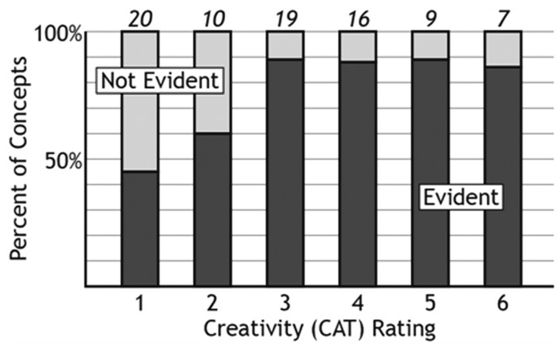


Fig. 12 Creativity (CAT) rating levels separated by evidence of heuristic use, with the number of concepts per rating is shown at the top

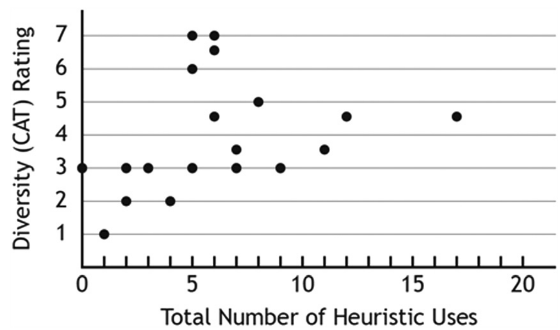


Fig. 14 Diversity ratings as a function of heuristic use

choose any of the design heuristics they wished from their packet of 12, and were told they could also combine heuristics in their concepts. While they were given instruction on using the heuristics, the students were free to propose any concepts they chose during the session. They were asked to sketch and label each of their designs on separate pages. After completing the task, they were also asked to write notes describing each concept, how they came to the idea, and which design heuristics, if any, they had used in generating each concept. This allowed us to collect information about how the participant viewed their use of heuristics, and this could be compared with the interpretation provided by the trained coders.

The main goal of this study was to understand how the use of design heuristics affected students' ideation processes. To answer

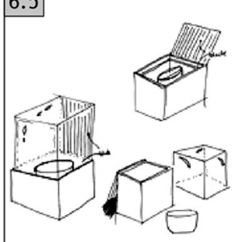
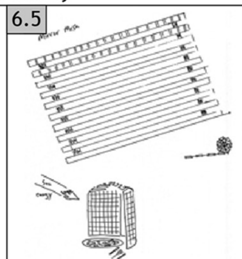
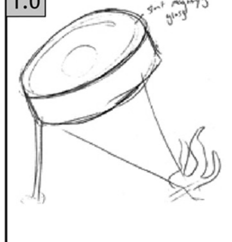
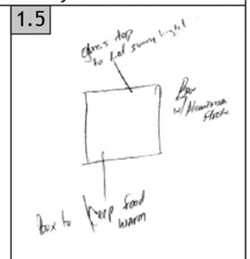
High Creativity		Low Creativity	
6.5	6.5	1.0	1.5
			
The packaging box doubles its function as a stand for the magnifying cube and metal bowl once it's turned upside down.	Square pieces of mirrors are sewn together, rolled and used to concentrate sunlight onto a specific area.	A giant magnifying glass is used to start fires to cook food.	A box with glass top and tin foil interior is used to retain heat.
14.Combine two or more functions by joining them 37.Use packaging as a functional component within the product	6. Align components on the same base or around a center 17.Convert two-dimensional materials into three-dimensional		

Fig. 13 Concept examples with high and low creativity scores

this question, we analyzed (1) the number of concepts generated, (2) the relative creativity of each concept, (3) the relative diversity, or variation, among the concepts within a given participant's set, and (4) coded the use of the 12 heuristics in the concepts they generated. Two coders trained in identifying design heuristics analyzed the concept sketches and written descriptions to determine which, if any, of the heuristics provided to a student were evident in that student's concepts. One coder had a background in engineering and art and design, and the other in industrial design. They also noted when the participant reported that he/she had used a heuristic for a specific design concept, and scored whether any of the subset was evident in the concepts. For example, if the heuristic was both observed by coders and claimed by the participant, then the heuristic was coded as "evident and claimed." The coders did not score for heuristics that were evident but not present in the 12 heuristics provided to that student.

Coding took place for two outcome criteria: the creativity of each concept and the diversity (differences among concepts) of each student's set of concepts. This involved a variation of the widely accepted consensual assessment technique (CAT) [51], where concepts were rated on a relative scale by two independent coders each using their own, implicit definition. These two coders had no prior experience with design heuristics and were seniors in a School of Art & Design with a specialization in industrial design. Each rated the individual concepts presented in a different, randomized order for creativity on a 1 (least creative) to 7 (most creative) Likert scale. The ratings were then averaged and rounded down. For diversity, the coders followed the same procedure, but rated the diversity on a seven-point scale while considering the whole set of concepts generated by each student. The correlation between coders was greater than 0.70 for both creativity and diversity scores. Because the emphasis of the study is the creation of new concepts, the feasibility of the resulting concepts was not assessed. The instructions encouraged the students to generate multiple concepts while avoiding technical questions of heat transfer and the feasibility of working solutions.

5.2 Study Results. In the allotted 25 min, the number of concepts generated by each student ranged from one to eight separate concepts, with an average of four. This is most likely due to the short time available for the concept generation session. Most likely, even those who chose to generate concepts without heuristics had not yet exhausted their own ideas by the end of the short task.

In total, 78 concepts were generated by the 20 students. Coders found design heuristics evident in the concepts from all but one of the 20 students (95%). Forty-two concepts (54%) showed evidence of one or more heuristics from the heuristics provided, with at least one also claimed by the student. In 17 (22%) concepts, students did not claim to use a heuristic from their set of 12; yet, the coders saw evidence of them. In these cases, the participant may have forgotten to make note of the heuristic use, or may have been unaware of its use. In another 13 (17%) concepts, students claimed heuristic use; yet, the coders saw no evidence for it. In 6 (8%) concepts, students did not claim heuristic use, nor was any evidence of use detected.

Figure 11 shows two design solutions in which heuristic used was both evident and claimed by the student, and another two solutions where heuristic use was neither evident nor claimed by the student. These examples demonstrate the impact of heuristics on the concepts generated, as those with evidence of heuristics appear more elaborated, structured, and novel. It is also evident from these examples that the heuristics were used to consider aspects beyond the primary function of collecting sunlight, suggesting a more developed construction of the problem. For example, one concept showed a magnifying glass to heat a black object, but use of the heuristic was also evident in that it addressed portability by making the parts detachable for easy storage.

We compared heuristic use to the average creativity ratings to identify what percentage of concepts within each creativity rating level showed any evidence of heuristic use (see Fig. 12). While there were fewer concepts that were scored as highly creative (five and over on the seven-point scale), those that received high scores included a higher proportion of heuristic-based concepts, while those with low creativity ratings included more concepts with no evidence of heuristic use.

On average, concepts with evidence of heuristic use were scored higher in creativity than the ones without heuristic use. The average creativity score of all 59 concepts with heuristic use was 3.7, whereas the average creativity score of the 19 concepts without heuristic use was 2.3. This difference is statistically significant, $t(79) = 3.4$, $p < 0.01$. Of the concepts that were scored *above* the scale midpoint, 88% had evidence of heuristic use. Of the concepts below the midpoint, only 65% had evidence of heuristic use. Figure 13 shows two concepts that were rated as very creative and two other examples that were rated as not creative.

The diversity of a set of concepts generated by each student was also be used to measure the ideation process. We hypothesized that students who used heuristics in their concepts would produce a more diverse set of concepts than those who chose not to use the heuristics in generating their concepts. To measure this, we counted the total number of times a student used any of the heuristics in their set, and plotted this count against the average diversity rating of each student's set of concepts (see Fig. 14).

From this graph, there appears to be a trend toward using more heuristics and a higher diversity score in ($r^2 = 0.31$). Further, there is a peak in the graph at five or six heuristics used, suggesting that within the short time frame, attempting to use about six heuristics resulted in a more diverse set of concepts. It is likely that applying a heuristic may take longer than generating one's own concept, but any time differences did not appear to benefit those who chose not to use the heuristics.

Figure 15 shows one example of a diverse set of concepts generated by a student. By shifting from one heuristic to another, he addressed the design criteria in three different ways: (C1) folded legs, (C2) detached components, and (C3) expanded body. Other students included sets involving minor modifications among the concepts, such as attachment of solar panels to existing products, combinations of existing concepts, or incremental changes to individual product components.

With different measures of idea generation (concept creativity and concept set diversity), we found that use of design heuristics had a positive impact. Concepts showing heuristics were rated as more creative, and the frequency of heuristic use was related to the rated diversity of an individual's concept set. This study suggests that novice designers can benefit from using design heuristics to generate multiple, creative ideas. Designers may acquire these heuristics based on experience with a variety of design

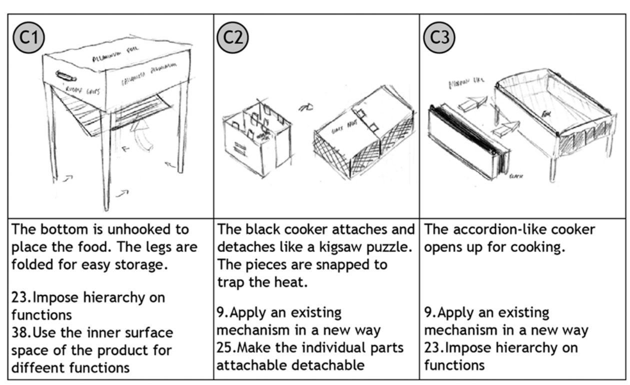


Fig. 15 An example set of diverse design solutions generated by one student

problems, and so may need no instruction on how to apply them in new problems.

This exploratory, correlational study has limitations to the findings. First, the design heuristics use was compared to concepts without heuristics created by the same individuals in a correlational design. An experimental design, where some participants are trained in the use of heuristics and a control group is not, is an important step required to make causal claims about the impact of design heuristics. Because the study was conducted in the classroom, the exploratory design allowed all students to benefit from the heuristics instruction, and the classroom study is the naturally situated context where instruction on idea generation takes place. In a different context using a different design task, we used an experimental manipulation with random assignment to use of design heuristics and found consistent results that design heuristics led to more creative concepts and a more diverse set of concepts [30]. Second, the problem selected in the present study was also more typical of engineering design and may have felt unfamiliar to the industrial design students in the study. Additionally, if the study is repeated with engineering students, the results may vary as industrial designers and engineers often approach problems differently. We did not evaluate the feasibility of designs for this study, and the instructions to the students explicitly asked them not to consider feasibility, though it may be an important outcome of heuristics instruction. Third, it is also possible that heuristics were not used in some concepts because it is more difficult than generating one's own ideas. That would result in stronger students using heuristics and producing better concepts. However, some students contributed concepts with heuristics and some without, contributing to both comparisons. Students' reports from the session about how they came to their ideas suggested that they did not find the heuristic method difficult, and only one student of the 20 did not use any heuristics in his/her concepts.

6 Discussion

Systematic observation of 400 consumer products allowed the extraction of 40 design heuristics evident across designers and products. This provides a sample of common cognitive heuristics used by expert designers as shown in their work product. The method of extracting heuristics from the work of designers may allow others to more quickly acquire these heuristics and make use of them in design, adding to the development of expertise in innovation. The design heuristics observed may serve as a "how to" guide for considering changes to designs that lead to more innovative concepts.

Our findings parallel those of Singh et al. [45]. Though their approach centered on principles for transformers, there are some similar principles identified in both studies. For example, their transformation called "Nesting and Shelling" captures aspects of the design heuristic, "hide/collapse/flatten elements not in use by nesting," and the transformation, "Inflate," can be considered similar to the design heuristic: "Make the product expandable in order to fit various sizes." However, we feel that the specificity of the description may be important in capturing the content of the heuristic while avoiding possible overgeneralization (as may occur in approaches like SCAMPER [38]). In addition, while the transformation approach emphasizes changes in states to improve functionality, design heuristics add changes on many other dimensions such as the visual qualities, user interactions, and interactions of products with each other.

Other research on novel products [48] used a similar methodology in examining key products identified as innovative. Their emphasis, however, was on characterizing how different the innovative products are, and the characteristics of the products as a group. In our study, we identified the heuristics the designer would use while generating concepts, and we described these heuristics from a how to point of view. Some of the features of innovative products identified by Saunders et al. [48] appeared in the present analysis as heuristics, including replace materials with recycled ones, replace solid material with flexible material for compactness, use the same material all through the product, and reduce the amount of material needed for the same function. Even though these features were identified as modified material flow as observed in the analysis of innovative products, the overlap in content suggests a verification of these findings but also extends them in important ways by increasing the number of identified features. First, the concepts with design heuristics were compared to concepts without heuristics created by the same individuals in a correlational design.

A similar approach to systematically analyzing examples of innovation and extracting heuristics was provided by TRIZ [47]. TRIZ provides a summary of heuristics derived from patents; as a result, their focus is much more specific to the tradeoffs and conflicts seen in the later implementation phases of design where issues such as material strength are brought to bear. In contrast, the design heuristics focus on the initial conceptual phases of design where feasibility is not a strong criterion. Instead, the emphasis is on exploring a wide variety of possible solutions so that innovative concepts may emerge for selection [2]. Design heuristics provide a method for generating multiple concepts in this initial stage and may prove helpful to designers who face the task of coming up with many designs while avoiding fixation on prior examples [13–16].

The main contribution of the study is the demonstration of an evidence-based approach to analyzing the content of design. By studying the award-winning products, we have uncovered some specific heuristics that successful designers appear to know about creating innovative ideas. In future research, the identification of design heuristics in other product sets may be possible, along with further description and characterization of the relationships among heuristics and the circumstances where they may be usefully applied. 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 to suggest as potentially relevant given the observed patterns. The results can then be incorporated into a computer tool that can take simple input about the design problem and propose appropriate design heuristics to apply. This tool would help the designer to organize the session's process, making use of heuristics found to be relevant in related problems. The availability of such a tool based on evidence from concepts by practicing designers would help to improve design instruction through successful use of design heuristics.

7 Conclusions

Designers develop idea generation skills to tackle real-world design issues. However, it is difficult for designers to recognize their own implicit cognitive strategies, making it challenging to share these idea generation methods with others or to train new designers. The product analysis presented here provides a collection of 40 design heuristics repeatedly observed in over 400 award-winning products. The design heuristics identified in this work offer a new method for students and practitioners to explore new design concepts. In order to generate a new idea, one can choose a heuristic, apply it to the current problem, and see where it leads [45]. We show that the use of design heuristics is correlated with more creative concepts and a more diverse set of concepts. Using design heuristics in engineering design may add to one's ability to generate multiple creative ideas to consider en route to innovation.

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