Teaching Design Innovation Skills: *Design Heuristics* Pedagogy for Creating, Developing, and Combining Ideas

Shanna Daly[1], Seda Yilmaz[2] Colleen Seifert[3], Keelin Leahy[4]

[1] University of Michigan, 2350 Hayward Avenue, Ann Arbor, MI 48109

srdaly@umich.edu

[2] Iowa State University

seda@iastate.edu

[1] University of Michigan, 530 Church Street; Ann Arbor, MI 48109

seifert@umich.edu

[2] University of Limerick

leelin.leahy@ul.ie

Abstract. Successful ideation that explores a variety of diverse ideas is hard to achieve. Various design tools can support ideation success. In this chapter, we discuss the Design Heuristics ideation tool for product design, including research that guided the development of the tools, a variety of lessons and structures that use Design Heuristics to foster ideation, and research on these approaches. Specifically, we describe how the tool can be used for initial ideation, idea development, generation of subcomponent ideas, and within design teams. The tool has been shown to support ideation across experience levels and disciplines.

Keywords: design pedagogy; idea generation; innovation tools

1 Introduction

Students and practitioners across disciplines often face unstructured, ambiguous design problems without strategies in hand to assist them in developing innovative ideas. Even experienced designers attempting to generate original designs often fall into the same trap: While the first idea or two may come easily, it is often difficult to generate more ideas, especially ideas that are different from one another. This is simply a result of how we think: What comes to mind first are the most obvious ideas that are similar to existing solutions (see Figure 1). As a result, designers often become "fixated," limiting their consideration of alternative possibilities when developing ideas, also referred to 'set in', 'blinkered', or 'blinded' by initial ideas (Crilly, 2015). Engineering students frequently struggle to generate solutions without basing their ideas on existing solutions (Ahmed, Wallace, & Blessing, 2003; Ball, Evans, & Dennis, 1994).

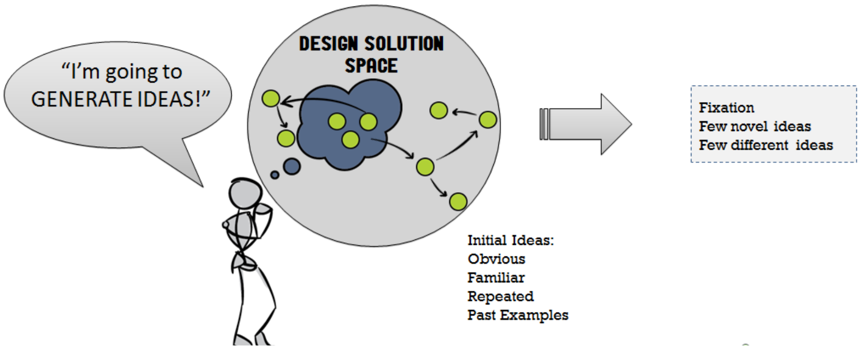

Figure 1. The problem: A designer may generate only a few ideas from the space of possible solutions.

To help design students and practitioners alike learn ways to generate novel ideas beyond the obvious and familiar, we introduce an empirically-derived cognitive tool, called *Design Heuristics (CITE)*. *Design Heuristics* are a recent advance in design education based on research evidence. Studies of designers working on many different design problems uncovered the strategies designers used to help them create a new and different idea. *Design Heuristics* capture these "lessons learned" on how to create more, and more varied ideas. Based on the "best practices" of product designers, *Design Heuristics* give students a "jump start" into successful idea generation.

In this chapter, we describe the *Design Heuristics* tool – the "77 Cards" – and the pedagogy for conducting training sessions on their use. The lessons include (1) idea initiation, (2) idea development, (3) subcomponent design, and (4) team ideation. These lessons provide a comprehensive understanding of how and when to use *Design Heuristics*, and how to teach them to students from a wide range of design backgrounds. The pedagogy is supported by empirical studies with student designers following the lesson plans in classroom settings. Based on these studies, beginning through senior design students find using the *Design Heuristics* an easy and productive method to help them create innovative ideas.

2 What are *Design Heuristics?*

Design Heuristics are “prompts” that encourage exploration of a variety of ideas during ideation (Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Seifert, Gonzalez, Yilmaz, & Daly, 2015; Yilmaz, Daly, Seifert, & Gonzalez, 2014; Yilmaz & Seifert, 2011; Yilmaz, Seifert, Daly, & Gonzalez, 2016a, 2016b). As defined in psychology, a cognitive heuristic is a simple “rule of thumb” used to generate a judgment or decision (Cross, 2011; Lawson, 1980). Cognitive heuristics are not guaranteed to lead to a determinate solution, or to serve as a search algorithm; rather, they describe specific methods for "best guesses" at potential solutions (Pearl, 1984). Research in cognitive psychology shows that experts use cognitive heuristics constantly and effectively, and their efficient use of domain-specific heuristics distinguishes them from novices (Klein, 1998). *Design Heuristics* include a specific set of 77 “rules of thumb” that have been shown to help designers and engineers generate possible solutions (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2012; Kramer, Daly, Yilmaz, & Seifert, 2014; Yilmaz, Daly, Christian, Seifert, & Gonzalez, 2013).

The complete list of 77 *Design Heuristics* has been published in a summary article (Yilmaz et al., 2016) and as a set of illustrations on a 5 x 7 paper cards (Design Heuristics, Inc., 2012). On the front of each card, a descriptive title and action prompt provides specific instructions on how to modify an existing idea or build a new idea, and a graphical image depicts the heuristic visually. On the back of the card, two existing product examples are shown, one from a variety of consumer products and a second of the same type of object (a seating unit) where each heuristic has been applied. This example demonstrates that each heuristic can be applied to a given products, and that heuristics are evident in existing commercial designs. A sample card is shown in Figure 2.

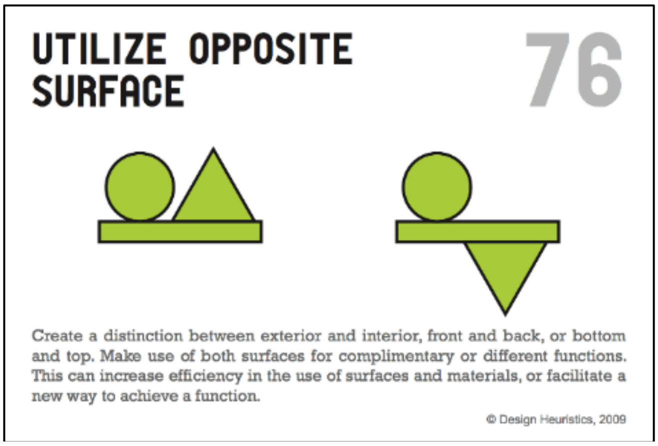

Figure 2. Front of a *Design Heuristics* Card (#76): Utilize opposite surface, presenting a written description of the heuristic and a graphical depiction on the front. (Courtesy of Design Heuristics, Inc.)

How do designers use *Design Heuristics* to create new designs? Consider this scenario: You are tasked with generating initial ideas for a new product line of children's footwear. After coming up with some ideas involving placing features from animal on the shoes (tiger stripes, zebra stripes), you consider applying the *Design Heuristics* in Figure 4 to your designs. How might the prompt, "Use Opposite Surface," be considered within your existing ideas? The opposite surface of the shoes (the bottom) might also serve as a space to add more animal features to your ideas (see Figure 3).

Figure 3. Children's shoes incorporating the *Design Heuristic, Use Opposite Surface*.

When used to introduce variations to an idea, can the *Design Heuristic*, "use opposite surface," result in better designs? Examples of product designs where each heuristic is evident help to explain how to apply the heuristics and provide evidence of their use by professional designers. "Use opposite surface" can be observed in a different shoe design where the underside of the shoe is employed to both tighten and stabilize the lacing. In the second example, the area under the back of the chair is used to provide additional storage. The differing uses of "opposite surface" seen in these two examples illustrate that the same heuristic can be applied to more than one area, feature, or aspect of a design (see Figure 4) because the way the heuristic is applied is nondeterministic (Author, 2010), allowing for a variety of ways to use the heuristic in a single design. In this way, a single heuristic can be applied repeated in the same design, each time resulting in a different idea variation.

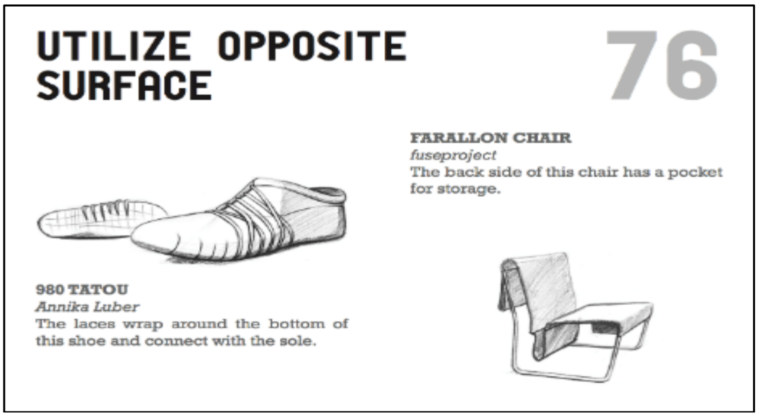

Figure 4. Back of a *Design Heuristics* Card (#76): Utilize opposite surface, presenting examples of two consumer products where the heuristic is evident. (Courtesy of Design Heuristics, Inc.)

Where do *Design Heuristics* come from, and how do they aid in generating designs? *Design Heuristics* were empirically derived from three data sources (Yilmaz et al., 2016b): 1) behavioral studies of student and expert designing new concepts for products (Daly, Christian, Yilmaz, Seifert, & Gonzalez, 2011; Daly, Yilmaz, et al., 2012; Yilmaz, Daly, Seifert, & Gonzalez, 2013); 2) analyses of idea developments from existing products that resulted in award-winning concepts (Yilmaz & Seifert, 2010; Yilmaz et al., 2016a); 3) a case study of a long-term project by a professional designer (Yilmaz & Seifert, 2009; Yilmaz & Seifert, 2011).

The research project began with an analysis of a large set of highly varied designs from a juried competition for award-winning products. These 400 products were created by different designers working on independent design problems, and these designs were independently identified as especially innovative. Analysis of these designs identified their major elements and key features, along with their functionality, form, and user-interaction features. This analysis resulted in the identification of 39 heuristics (Yilmaz et al., 2016a), with specific heuristics observed repeatedly across products and designers. Next, a case study (Yilmaz & Seifert, 2011) followed a very experienced industrial designer who had created a series of over 200 product design concepts for creating a universal access bathroom in existing homes. The designs were analyzed in sequence, and transitions between concepts were examined. The results identified 34 of the same heuristics as in the product analysis, with an additional 25 capturing changes that occurred repeatedly over the set of designs.

In a third set of empirical studies, a think-aloud protocol technique was used to explore how student and practicing designers in both engineering and industrial design settings generated and transformed concepts during a concept generation session (Daly, Yilmaz, et al., 2012; Yilmaz, Daly, Seifert, et al., 2013; Yilmaz, Daly, Seifert, & Gonzalez, 2015). We created an open-ended design task identified by the Grand Challenges in Engineering of the 21st Century (Duderstadt, 2008; Engineering, 2004a). We chose to offer minimal criteria, and asked them to “design a solar cooking device” that was portable and suitable for use by families in low resources areas. Each designer created as many concepts for this problem as possible in a 25-minute session. We then analyzed how each designer created their concept set, and how concept in sequence flowed from one into another. The protocols were systematically coded for the presence of candidate heuristics, and we found evidence for the use of 60 heuristics in this study.

Accumulating evidence across these three studies resulted in 77 unique *Design Heuristics* (Yilmaz et al., 2016), listed in Figure 5. An important feature of this compilation of heuristics across studies is that each heuristic was observed multiple times (at least four) in different products and product concepts, and all were observed in solutions from more than one designer.

1	Add levels	27	Cover or wrap	53	Reduce material
2	Add motion	28	Create service	54	Repeat
3	Add natural features	29	Create system	55	Repurpose packaging
4	Add to existing product	30	Divide continuous surface	56	Roll
5	Adjust function by movement	31	Elevate or lower	57	Rotate
6	Adjust functions for users	32	Expand or collapse	58	Scale up or down
7	Align components on center	33	Expose interior	59	Separate functions
8	Allow user to assemble	34	Extend surface	60	Simplify
9	Allow user to customize	35	Flatten	61	Slide
10	Allow user to rearrange	36	Fold	62	Stack
11	Allow user to reorient	37	Hollow out	63	Substitute mechanism
12	Animate	38	Impose hierarchy on functions	64	Synthesize functions
13	Apply mechanism in new way	39	Incorporate environment	65	Telescope
14	Attach independent functions	40	Incorporate user input	66	Twist
15	Attach product to user	41	Layer	67	Unify
16	Bend	42	Make components attach/detach	68	Use common base
17	Build user community	43	Make multifunctional	69	Use continuous material
18	Change direction of access	44	Make product recyclable	70	Use different energy source
19	Change flexibility	45	Merge surfaces	71	Use human-generated power
20	Change geometry	46	Mimic natural mechanisms	72	Use multiple components in one
21	Change product lifetime	47	Mirror or array	73	Use packaging as component
22	Change surface properties	48	Nest	74	Use repurposed or recycled
23	Compartmentalize	49	Offer optional components	75	Utilize inner space
24	Contextualize	50	Provide sensory feedback	76	Utilize opposite surface
25	Convert 2-D to 3-D object	51	Reconfigure	77	Visually distinguish functions
26	Convert for second function	52	Redefine joints		

Figure 4. Descriptive Titles for the 77 *Design Heuristics* observed in empirical studies presented in alphabetical order.

After identifying the 77 *Design Heuristics,* we created an instructional tool to allow designers to access the heuristics during a work session, and to keep the cards for use on later tasks. We conducted workshops with educators at national design and engineering conferences, and established an online dissemination platform on www.designheuristics.com, where instructors can view videos of the Design Heuristics pedagogy, download the research papers, and order printed decks of the Design Heuristics cards. *Design Heuristics* have been in use by over 500 educators, practitioners, and students in over 300 classrooms in 97 different universities, high schools, and industries, and in 163 different locations spanning countries around the world since their introduction five years ago.

To examine their efficacy in instruction, we have conducted further empirical studies. Using classroom and practice settings, we have conducted training sessions on *Design Heuristics* followed by idea generation sessions and surveys of trainees. Across these studies, we have found that training on the use of *Design Heuristics* can be accomplished in a ten-minute session; that even beginning designers can use these heuristics to generate more, and more varied, ideas; and that students and practitioners find them easy to use and productive in assisting their design process.

3 How Effective are *Design Heuristics* in Ideation*?*

Following the identification of the 77 *Design Heuristics*, we tested their efficacy in both engineering and industrial design classrooms (Author, 2012; Author, 2011a, 2011b, 2012; Author, 2014; Author, 2014; Author, 2015; Author, 2011b, 2012; Author, 2013; Author, 2015) and with professional engineers working on consumer products (Author, 2011a; Author, 2013). An important contribution of these heuristics is their efficacy in communicating new concept generation principles to designers. Ideally, these heuristics distill knowledge of precedents in product design into generative constraints that are easy to learn and apply. By adding these heuristics to the process of generating concepts in the early phases of design, the variety and novelty of the resulting designs may be enhanced. The training created to assist designers in using the cards includes a short (10 min.) introduction to ideation, an introduction to the *Design Heuristics* and how they were developed, and practice using a few example cards on a design task.

The studies showed that both engineering and design students and experts can learn to use the *Design Heuristics* cards with a short instructional session, and then go on to successfully create their own novel and diverse ideas (Author, 2011a, 2011b; Author, 2012; Author, 2011a, 2012; Author, 2013). One study tested 48 first-year engineering students in an 80-minute classroom session. The students were each given a different subset of 12 *Design Heuristics* and were asked to create concepts for a portable solar oven. Of the 161 designs generated, 55% showed evidence of *Design Heuristics* (Author, 2012). The concepts resulting from the application of *Design Heuristics* were rated by trained coders as more creative (averaging 3.6 on a 7-point scale) than those without heuristics (averaging 2.7).

Another study of twenty second-year industrial design students resulted in 59 new design concepts with the heuristics and 19 concepts without heuristics, in an 80-minute class (Yilmaz, Christian, Daly, Seifert, & Gonzalez, 2012). The average creativity score of the concepts with evident heuristics was 3.7 (on a 7-point scale), and 2.3 without heuristics. Students were also observed applying multiple heuristics to find alternative concepts, leading to more complex and developed solutions, as shown in Figure 56. The first design is a packaging box doubling its function as a stand for the magnifying cube and metal bowl, using a combination of heuristics, including repurpose packaging, Reverse the direction, and Make components multifunctional. The second design is a set of square pieces of mirrors sewn together, rolled and used to concentrate sunlight, using the heuristics: Mirror and Roll.

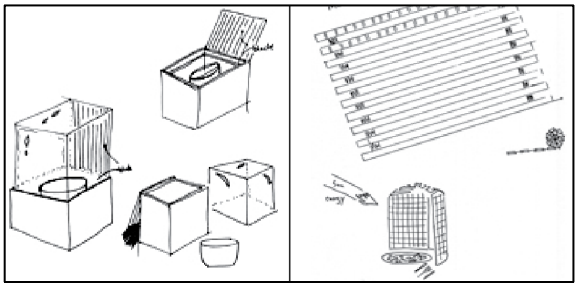

Figure 5. An Industrial Design student's concept for a solar oven. The design combines the heuristic, *Mirror*, with another, *Roll*, to produce an array of mirrors that are rolled around a focal point to concentrate sunlight.

In addition, the studies demonstrated that *Design Heuristics* can help to introduce variations to designs in a non-deterministic manner (Author, 2010). As a tool to aid designers, *Design Heuristics* appear to scaffold the metacognitive development of early engineering students (Author, 2012; Author, 2014), and facilitate the generation of novel concepts even in experienced designers (Author, 2013). The results indicate that concepts generated using *Design Heuristics* resulted in more creative designs and facilitated greater variety in designs (Author, 2012; Author, 2012; Author, 2013).

In sum, the empirical evidence shows that using *Design Heuristics* was associated with more original and creative concepts, resulting in better candidate concepts to choose from. Designers found the cards easy to use following a just short introduction. These studies documented the use of every card in the set of 77 in multiple design problems by multiple individual designers, showing that they capture knowledge about creating designs that is helpful to a wide range of designers working on a wide range of design problems.

Now that their efficacy has been demonstrated, we turned to devising lesson plans for training designers on the use of *Design Heuristics* in educational settings. We developed multiple lessons that leverage *Design Heuristics* to facilitate idea generation and development. *Design Heuristics* have been incorporated into student instruction, to from pre-engineering, to undergraduate, to graduate students, as well as in professional training of engineers and industrial designers. Across these studies, we have identified four lesson plans for training in *Design Heuristics* that fit naturally into contexts typically found in design education. These lesson plans include 1) Idea Initiation, 2) Idea Development, 3) Subcomponent Design, and 4) Team Design.

4 Lesson Plan 1: *Design Heuristics* in Initiating Ideas

The formation of initial ideas is a generative process (Finke et al. 2004b) characterized by creating ideas "from scratch." In the lesson plan for *Design Heuristics* in idea initiation, students were asked to use *Design Heuristics* cards to prompt their generation of new ideas. Our goal is to help even novice students experience a flow of ideas to produce many candidates; in practice, even experienced designers become "stuck" or "fixated" when trying to generate many, different ideas. The cognitive prompts provided by *Design Heuristics* make it possible for designers to move through an ideation session generating a steady flow of new ideas. This lesson plan emphasizes developing skills to continue generating new and different ideas and allows students to experience success in following the "best practices" of considering multiple candidate ideas.

Extensive testing has occurred comparing *Design Heuristics* to other idea generation approaches. In one study, 102 first-year engineering students were introduced to one of three different ideation techniques— Design Heuristics, Morphological Analysis, or Individual Brainstorming—and asked to generate solutions to a given design problem, in 25-minute sessions (Daly, Seifert, Yilmaz, & Gonzalez, 2016). Using an adapted version of the consensual assessment technique (Amabile, 1982), all concepts were rated for creativity, elaboration, and practicality, and all participants' concept sets were rated for quantity and diversity. All three techniques produced creative concepts averaging near the scale midpoint. The elaboration of the concepts, however, was significantly higher with *Design Heuristics* and Morphological Analysis techniques, and the practicality was significantly higher with Design Heuristics, suggesting that *Design Heuristics* facilitate more detailed and practical outcomes.

To determine whether use of *Design Heuristics* would improve idea generation for more advanced students, a further study examined how engineering students make use of *Design Heuristics* in their senior capstone projects. This study traced the changes in initial concepts based on Design Heuristics, and followed their evolution throughout the course (Kramer et al., 2014; Kramer et al., 2015). Analysis revealed that all eight teams carried their heuristic-inspired concepts to their latter stage designs, with seven teams carrying their heuristic-inspired concepts through their final prototypes. As all the teams were working on different, team-specific open-ended design problems, these findings demonstrate the utility and practicality of *Design Heuristics* across various design problems. These studies found that *Design Heuristics* can be successfully used to initiate new ideas by engineering students in senior-year project-based courses and can facilitate producing positive outcomes for idea generation. These findings demonstrate the utility and practicality of *Design Heuristics* across eight independent design problems selected by the teams.

While these studies focused on the process of idea initiation for individual designers, *Design Heuristics* can be used in multiple ways to assist ideation. For example, they can be used to support individual designers as well as within team design settings. In the following sections, we describe multiple lesson plans for using *Design Heuristics* to support idea development, design of subcomponents, and team ideation, as well as research studies supporting each plan.

5 Lesson Plan 2: *Design Heuristics* in Developing Initial Ideas

In the idea development lesson plan, students are asked to generate their own initial ideas, and then to apply *Design Heuristics* to add more ideas to their existing ones. In this way, the fixation arising from the presence of prior examples can be overridden by transforming typical initial ideas into novel ones. The goal of this lesson is that a single idea can be the source of interesting novel ideas through developments suggested by the Design Heuristics. Students learn how to break free of stereotypical first ideas by adding their own, novel changes to create new ideas.

During idea development, students can apply the same Design Heuristic card to prompt multiple developments of an idea. For example, Figure 6 represents a student who was designing ways to cook food using solar energy. She used the same heuristic, Change Geometry, twice to develop new versions of an original concept: first one from a narrow horizontal rectangle to a wider vertical one, and second one from a rectangle to a pyramid.

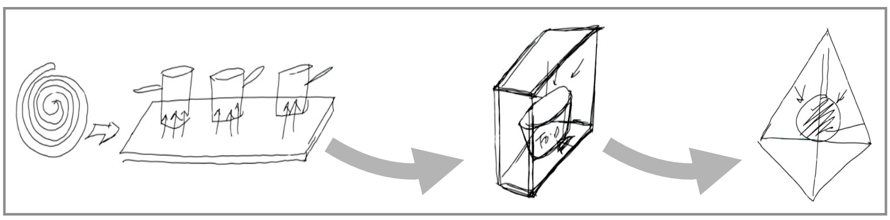

Figure 6. Transforming an initial concept twice using the same heuristic

Alternatively, different heuristics can be used to transform an initial idea to multiple new ideas. Figure 7 represents an example of this where the designer began by attaching two existing components to each other -- a magnifying glass and a griddle -- to create a surface with focused sunlight. In her second concept, she transformed the magnifying glass to a square magnifying glass attached to the griddle. In the following concept, she made the lens height adjustable, and, in the fourth concept, she added sides to it to maintain the heat more effectively. She then considered portability by adding a rigid handle, which was changed to a flexible handle. The final concept also included an attachment that held utensils and a spout for draining fluids from the cooking surface.

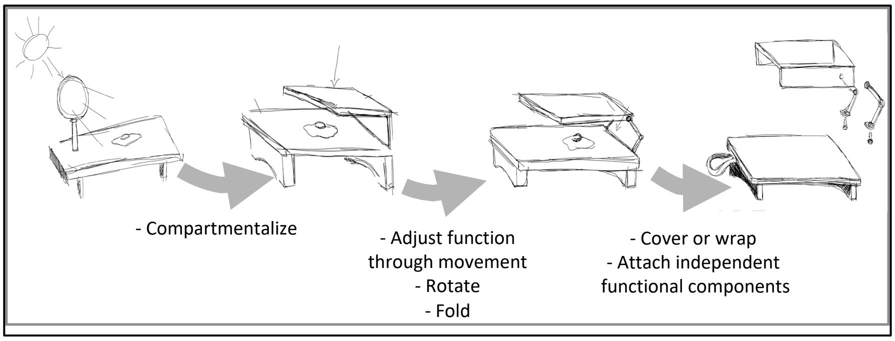

Figure 7. Transforming an initial concept with serial application of multiple different heuristics

These examples demonstrate how one concept is transformed with serial application of single heuristics; for example, five cards can be serially and separately applied to an original idea to produce five different potential solutions not considered before. In addition, students can try applying the same card multiple times to create more ideas; that is, "rotate" can be repeatedly applied to different areas or directions within the original idea. While the card provides a clear prompt to guide in the generation of ideas, the designer must also select how and how much to apply each heuristic. In an early study of designers using the heuristics, we discovered that designers often developed more designs by applying multiple heuristics within a single new idea (Daly, et al., 2012). Finally, students can change the heuristic they are considering and the existing design where they choose to apply it, resulting in an idea production session maximizing the variation in designs serving as a base and in heuristics applied. This Lesson Plan is structured for the student as:

1- Pull a card at random.
2- Generate a solution by transforming an existing concept.
3- Shuffle the cards and randomly pull another.
4- Apply the card to the same or another of your existing solution.

An organizing framework, the concept tree, can be added to the idea development process to organize and reflect on the relationships between ideas. As shown in Figure 8, concept trees map the relationships among candidate ideas. In an alternative lesson plan for idea development, the use of *Design Heuristics* is combined with the structure of a concept tree. The instructor begins the lesson by setting a goal for the number of branching ideas to generate (we recommend at least 10), and students select what they believe to be the best of their original ideas to further develop. Alternatively, the instructor can recommend an idea from the student's set (especially one a student is fixated on). Students then build off the original idea, developing subsequent ideas by applying *Design Heuristics* cards (one or more) to each of the resulting ideas to create more branching ideas. They continue to use the last concept as the base idea and repeat the process of developing each idea using Design Heuristics in repeated iterations, culminating in alternative concepts.

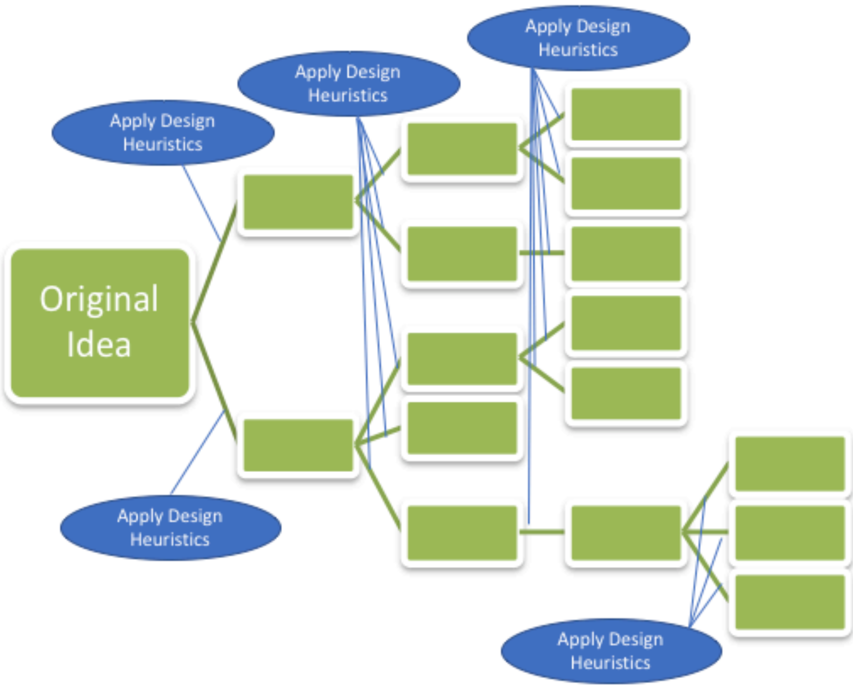

Figure 8. Concept tree generated using repeated applications of *Design Heuristics* to develop an existing idea into transformed ideas

After the ideation phase, the class can discuss the variations in developed concepts based on the original ideas. This lesson plan helps to make variations within concepts prominent and highlights how designs can be transformed during development to lead to differing outcomes. Another key point is for students to recognize there are still more characteristics that can be varied or further iterated upon if they continued developing these ideas, even if they base all of their new designs on the same original concept.

In a classroom study on pedagogy for using *Design Heuristics* to transform existing ideas, senior engineering students created initial concepts, and then used *Design Heuristics* to transform these concepts into alternative solutions, resulting in more variety to choose and develop (Leahy et al., 2018a). For some concepts, students applied a single heuristic, and in other cases, they applied multiple heuristics for the same transformed concept. The concept sets generated were analyzed, and eight types of developments were identified, including the enhancement of aesthetics, features, functions, settings, materials, sizes, organizations, and usability.

The outcomes of this pedagogy study showed that heuristics facilitated exploration of possible concepts in diverse ways, resulting in variations in designs to achieve the desired functions, as well changes in aesthetics and usability. *Design Heuristics* did not lead students to follow the same trajectory of development, suggesting the heuristics provide direction for concept development without prescribing a particular way to implement that feature within a design. As a result, students pursued deeper explorations of alternative concept designs by pushing their initial idea through further development. *Design Heuristics* supported students' idea development by providing on-point suggestions about ways to iterate on their initial concepts to lead to variations in ideas. As a result, students explored alternative concepts by producing iterations on their early designs and were more likely to select these more-developed concepts as their most creative, unique, and favoured designs.

6 Lesson Plan 3: *Design Heuristics* in Subcomponent Design

This lesson builds on a curricular goal in most engineering design courses; namely, re-designing products using incremental changes to improve product components. In industry, this allows companies to continue production while simultaneously bringing new-generation products to the market. However, when students are trained to analyze components, they are not given instructions on how and when to separate designs into components and tackle design issues independently. This lesson is framed around the differences in designing an entire product versus making modifications to its components. In this lesson, students decompose existing products, redesign individual components using Design Heuristics, and suggest new versions of the product based on combinations of the redesigned components. This lesson teaches students to generate ideas through decomposition and recombination.

The lesson plan involves asking students to follow a sequence of steps implemented as pages within an idea generation workbook. The steps included:

1. complete a functional decomposition of a design problem into its subfunctions (the time required to do this varies greatly with the complexity of the problem).
2. generate ideas for the subfunctions using the *Design Heuristics* cards, focusing on generating as many alternatives for these subcomponents as possible.
3. create whole concepts by recombining selected subcomponent ideas.

In a classroom study investigating pedagogy for subcomponent design using *Design Heuristics*, industrial design students were asked to apply the Functional Decomposition method to a given problem, then apply *Design Heuristics* to the individual components identified, and then to reconstruct the concepts into a "whole" solution. The initial functional consideration of the problem space allowed the students to productively generate diverse concepts using the heuristics, within a focused design space by using a selected function as an explicit constraint. Students also used *Design Heuristics* in distinct ways reflecting their growing understanding of the range of concepts that might exist within a solution space, suggesting the application of *Design Heuristics* for exploratory, iterative, reframing, and synthetic activities (Gray, Yilmaz, Daly, Seifert, & Gonzalez, 2015).

Figure 9 shows an example of a process for an industrial design student's ideation addressing the design problem focusing on food preservation and storage. The student created a concept for a product with a "living" pop-out flexible hinge (using #12: "animate") in the ideation stage to facilitate placement in a dishwasher. In the iteration stage, he added rubber nibs to further aid in cleaning (using #22: "change surface properties"); and in the recombination stage, he added similar nibs to flexible parts from another earlier concept, improving grip and discoverability of functionality (using #22: "change surface properties"; #29: "create system"; #73: "use packaging as a functional component").

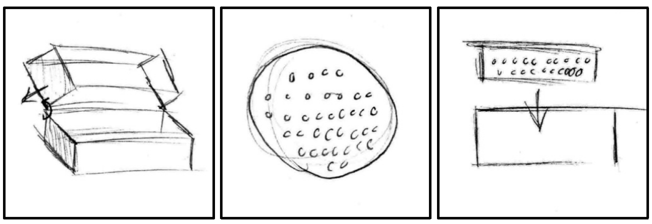

Figure 9. Evolution of an industrial design student's concepts from subcomponent design to the recombination of the concepts into a whole concept.

Idea Generation for Subcomponent allows students to also leverage the use of another ideation method, Morphological Analysis, alongside of the Design Heuristics. Students create a chart as they would if they were doing morphological analysis. They write subfunctions in the first column and then ideas generated using the *Design Heuristics* for each subfunction along the row. The ideas should be drawn and described, the table cells will be sized accordingly. Students themselves create combinations using their charts, and the draw the resulting idea based on the combination. The morphological chart allows students to see how many different ideas are possible.

In a study with engineering students, this lesson plan was conducted in a classroom with upper level engineering design students. The results revealed that nesting the use of *Design Heuristics* within Morphological Analysis promoted students' abilities to elaborate on features and consider additional aspects of the context as compared to their initial ideas (Leahy et al., 2018b). Morphological Analysis facilitated the decomposition of complex artifacts into separable functions, and *Design Heuristics* facilitated the generation and exploration of multiple, diverse ideas. Both tools also support elaboration on designs. Students were able to combine the two tools of Morphological Analysis and *Design Heuristics* within a relatively short period of training and use. Additionally, students reported that combining these tools was relatively easy.

A second variation of the Lesson Plan for Subcomponent Design encourages hands-on discovery of subcomponents through the physical dissection of an existing product. First, instructors ask teams to carefully dissect an existing product, sorting the components into categories or types. Then, each team member is asked to select a single component (or set of components). Students use the *Design Heuristics* to generate ideas for their component(s). Finally, the teams combine their subcomponent ideas to generate whole ideas for the product.

Lesson Plan 3 for Subcomponent Design draws students' attention to important subgoals within a design and allows them to consider ideas that work well for a given subfunction. This "local focus" for design allows the designer to optimize the features of the subcomponent designs to maximize function. Then, the recombination stage draws the students' attention to the tradeoffs in design that may be necessary to fit a subcomponent's design into a whole concept. For example, a solar oven design may include a local focus on retaining heat in the cooking surface, suggesting a solid metal cooktop; however, when recombined into the portable solar oven concept, the cooktop may be altered to address the need for a lighter weight design. Lesson Plan 3 works to provide practice in designing for local and global design goals.

7 Lesson Plan 4: *Design Heuristics* in Team Ideation

Many design activities involve teamwork, especially as the complexity of the design problem increases. The team approach requires benefitting from the knowledge, expertise, and contributions of all members while avoiding conflict resulting from differences in perspectives. Research has shown both positive (Sutton & Hargadon, 1996) and negative (Diehl & Stroebe, 1987) impacts on ideation outcomes from working in team settings. In some cases, as a team develops more concepts, the quality of the concepts created by a team improves (Rowatt, Nesselroade, Beggan, & Allison, 1997), and the team helps in selecting the best among multiple ideas.

In a field study, we investigated whether a *Design Heuristics* pedagogy may support a team ideation process. The team consisted of professional engineers as they worked collaboratively on concepts for their company's existing product line (Yilmaz, Christian, Daly, Seifert, & Gonzalez, 2011; Yilmaz, Daly, Christian, et al., 2013). The engineers met in a 4-hour "innovation workshop" facilitated by an external consultant meeting over a two-day period. During ideation, the team worked together to generate multiple ideas by reviewing one heuristic card at a time. The individuals "called out" their ideas for new concepts and added on to the ideas of others while recording their designs on easel pads. and calling out and building on "called out" ideas from others. An example from the audio transcription of their interactions includes the following segment:

Engineer 1: "Consider whether they are purchased separately or included with the product, and where they will be stored when not in use." (reading aloud from card # 49: Offer optional components)

Engineer 2: "I mean, we have talked about the existence of a couple of interfaces that could make that quite interesting. One is your skateboard interface, right? So anything that's pulled by a device, it could be fertilizers or other things that people want to do in the same process."

Engineer 3: "Or even a brush to clean your driveway when there's a lot of sand or something in the spring."

This transcription of their workshop session illustrates how discussing *Design Heuristics* facilitated the generation of novel concepts even for the existing product line they had been working on for many years. The team members at times used a prompt from the cards to initiate new whole ideas, generate new ideas for subcomponent designs, and to transform their ideas for both whole and subcomponent ideas by applying the heuristic. Additionally, the team used the heuristics to better define existing needs within their product line so as to better explore the "real problem" by identifying novel views of their existing design problems. These professional engineers later completed individual surveys about their experiences with the workshop. The engineers stated that the heuristic cards forced them to stay on track and helped them focus one direction of idea generation at a time. They also reported that using the heuristic cards helped them to further explore the problem space – what are real needs to be addressed? – as well as innovative solutions they had never before considered despite years of work on these design problems.

Based on this study, we identified a lesson plan for using *Design Heuristics* in a team ideation session. The alternative versions of the plans are included to suggest ways of varying teamwork using the *Design Heuristics* during ideation. These alternatives allow the instructor to focus on the needs of the teams and their stage of the early design process, along with allowing variations for repeated ideation sessions. The four alternative lesson plans are the Team Workshop, Idea Rotation, Card Rotation, and Team Jigsaw lesson plans.

"Team Workshop"

Following this "workshop" model of *Design Heuristics* training, a group ideation lesson can be set up in a design group with one individual taking on the role of a facilitator. The facilitator brings each individual card to the attention of the team by reading the card aloud and explaining the example products illustrating each heuristic. Once everybody on the team agrees, they begin applying the heuristic to their existing problem while discussing ways to apply it. The group maintains a focus on that particular heuristic card with the help of the facilitator. When the team exhausts all the ideas they can generate through applications with that card, the facilitator moves to the next heuristic. This workshop model appears to work well when the team is very familiar with the design problem and is comfortable building collaborative ideas with each other.

"Idea Rotation"

Another approach to group lessons using *Design Heuristics* combines training with *Design Heuristics* and responding to team members' ideas. A common difficulty with group ideation methods is production blocking, where team members must wait while others present ideas before presenting their own (CITE). At the same time, the advantage of the team work session is the exchange of ideas leading to new concepts created "across" individual designers. To accomplish both of these goals, a variant of the Brainwriting technique (CITE) can be employed to combine the prompting of ideas using *Design Heuristics* with build on others' ideas. In "Idea Rotation" procedure, each student in the team is given a single, different *Design Heuristic*, and they study the card to become the local "expert" on that one prompt. After generating their own design solutions working individually for a given time interval (i.e., between five and ten minutes), the team members pass their concept on to another group member and receives someone else's without any verbal conversation. Then, each team member creates a new concept by applying their assigned heuristic to the design created by someone else. After sharing the concepts across several team members holding different heuristics, the resulting concepts are elaborated and transformed into more distinctive and elaborated ideas.

"Card Rotation"

In a similar Brainwriting format, a team can begin with one heuristic card per member. After applying this first heuristic to initiate ideas for a set interval (e. g., five or ten minutes), the team member "passes on" their card and receives a new card from another member. Using the set of ideas they created, each team member then adds onto their ideas by using the received *Design Heuristic* to transform their ideas or to develop subcomponent designs. In this session, each student applies new heuristics to their ideas one after another and tries out new ways of developing their ideas with their own concept set. At the end of the session, the team members select which ideas to discuss with their team, and together they discuss how each differently applied the same set of heuristics to generate alternative ideas. The overlap in their use of the subset of *Design Heuristics* appears to facilitate discussion of the generation process and helps team members to identify the evolution of their ideas as well as the unique qualities they each contribute to the designs.

"Team Jigsaw"

Another example of a group lesson focuses on subcomponent design while allowing teams to work together in generating ideas. After creating a list of subfunctions as a group, the teams assign each subfunction to a single (or pair of) team members. Each team member then works to generate concepts to address their assigned subcomponent individually while applying *Design Heuristics*. After a longer interval (e.g., 20 or 30 minutes), the teams reform to confer about their ideas for subfunctions. Finally, the team then selects and combines the subcomponent designs to develop whole concept ideas. This method combines individual learning about ideation using *Design Heuristics* with the interdependent design structure of "real world" work teams. The team members are exposed to many different ideas generated by their members in a brief interval, and each can see the varied problem settings where team members successfully applied the *Design Heuristics*. Then, the team's combined ideas carry forward the distinct contribution of each individual team member while joining their ideas into a shared overall design.

There are several advantages to these lesson plans for training with *Design Heuristics* in a team setting. First, each individual experiences a time interval where they individually consider how to apply a given *Design Heuristic* to a specific problem. This effort takes them through the steps of understanding one heuristic and its examples, seeking ways to apply that heuristic to a problem, and generating ideas using the prompted approach, completing a standard (though shorter) lesson on how to use the heuristics. In addition, each individual is exposed to multiple heuristics either through their own longer work session or through reports from their teammates about their work sessions. Finally, each individual sees multiple ideas (their own or their teammate's) created using the same heuristic, allowing them to gain an appreciation of the generality of the *Design Heuristics*. To this, these team lesson plans add opportunities to appreciate ideas from other team members, exposing the individuals to many alternative ideas and providing a glimpse of how others came up with multiple ideas. The Lesson Plan 4: Team Ideation approach also accomplishes collaborative work on developing the team's ideas and includes the sharing and selection of viable ideas by all of the team members.

8 Discussion

The 77 *Design Heuristics* examined in these studies of idea generation lessons are the only set of strategies identified through systematic, empirical studies of design practices (Yilmaz et al., 2016a). These heuristics were observed in studies of award-winning products and in student and practicing designers' cognitive processes as they worked to solve design problems. The heuristics have also been documented in use across highly varied product design settings (Yilmaz et al., 2016b). The TRIZ method (Altschuller, 2005) is the only other approach to idea generation strategies has also analyzed successful product designs; however, there is limited evidence validating its effectiveness for practicing designers (Hernandez, Schmidt, & Okudan, 2013) or in classroom settings (but see Linsey et al., 2011). The empirical basis for the *Design Heuristics* ensures these strategies are tied to design practices and represent a varied set of heuristics captured across multiple problems and multiple designers (Yilmaz et al, 2016).

Given the empirical evidence presented above for the successful use of *Design Heuristics* through short instructional lessons, the success in teaching designers (both novice and experienced) to use these heuristics in creating new concepts and diverging from their fixated solutions is reliable and varied. Use of the heuristics was associated with more original and creative concepts, resulting in more elaborate and practical candidate concepts to choose from (Daly et al., 2012; Daly et al., 2016). These findings show that the *Design Heuristics* greatly enhance the design process for both novice and experienced designers, as well as improving the quality of their design outcomes.

One open question about *Design Heuristics* is how to decide which heuristic to apply in any given design context. The data from existing designs collected in these studies suggests the heuristics are applicable across many design problems. In studies with *Design Heuristics*, providing a subset of cards selected at random has produced improved outcomes (Daly, Christian, et al., 2012; Yilmaz et al., 2012; Yilmaz, Seifert, & Gonzalez, 2010) perhaps by focusing the designers on using a subset of cards within the short time interval provided. Not every heuristic is used each time it is considered, but the combination of an open-ended consideration of the heuristics with a smaller subset of heuristics in any one session appears to benefit designers.

The prompts provided by the *77 Design Heuristics* as an external representation through cards may be used to pace ideation sessions through card selection. The *Design Heuristics* cards can be shuffled to consider each when selected at random. In the studies testing their use in lessons, selecting a subset at random to consider during a single session was effective (Leahy, 2018a; 2018b). If more concepts are desired, more cards can be considered. However, it is possible that further research might identify cues to indicate when these heuristics are most relevant for application in a given problem. Using a criterion of efficacy, the studies on the Design Heuristic pedagogy (Daly, Christian, et al., 2012; Gray, Seifert, Yilmaz, Daly, & Gonzalez, 2015; Gray, Yilmaz, et al., 2015; Kotys-Schwartz et al., 2014; Kramer et al., 2014; Kramer et al., 2015) show that the set of 77 *Design Heuristics* captures design variations at a level useful in concept generation.

Another question is whether more such strategies may be uncovered in future research on design. Further analysis has shown that these same 77 *Design Heuristics* can each be applied in more technical mechanical engineering problems (Daly et al., 2018) In addition, a more specialized field of product design was examined in a study using patent awarded for microfluidics medical devices (Lee et al, 2018). Examining 235 patents, researchers found 36 design strategies in these technical devices, 19 of which (53%) were also observed among the 77 consumer product *Design Heuristics*. Future research on other design domains such as service, software, and apps may uncover the similarities and specialization in heuristics evident for each domain. Further, new design goals and solution contexts may give rise to new heuristics as the design field evolves over time. In addition, exploring design through diverse cultures may result in the identification of more heuristics less common in U.S. engineering and design schools. It is important to expand the observation and scientific study of designers within the many varied settings where design takes place, and to use this knowledge of common methods and practices as instructional resources for training designers in idea generation.

What is the best level of heuristic definition; that is, the level that provides helpful guidance while avoiding becoming overly specific and therefore less applicable across problems? Comparing approaches to heuristics in design, it appears there is a continuum from the very general to the very specific. Product design strategies may be captured through a large number of very specific heuristics; for example, the TRIZ method includes 39 design features (e.g., temperature, ease of repair) combined in a 39 x 39 matrix to suggest which of principles may be useful in devising a solution (Fogler & LeBlanc, 2008). Or, strategies may be captured more generally, resulting in a smaller number of more general ones; for example, the SCAMPER strategies (Eberle, 1995) include seven very general strategies; namely, substitute, combine, adapt, modify, put to other uses, eliminate, and rearrange/reverse. The benefits of a smaller set of more general heuristics is apparent: access to the set is easy. However, the application of these heuristics then requires more cognitive effort (e.g., Modify what? Eliminate what?).

Design Heuristics offer an intermediate level of description where the heuristic is already abstracted away from the concepts where they appeared. The relevant principle is provided at a level of description that facilitates implementing the heuristic in a new problem context. The needed information about how to create a new concept is readily available within the heuristic. Of course, many decisions must be made about how to apply the heuristic within a specific design, leading to possibility of reapplying the same heuristic to the same problem and creating a different concept, as was observed in the studies (Daly et al., 2012). Other researchers have documented the value of intermediate support structures including *bridging concepts* between empirically grounded theory and practical use (Dalsgaard & Dindler, 2014), and *strong concepts,* a form of intermediate knowledge describing core design ideas that are inherently generative (Höök & Löwgren, 2012).

Observing successful designs and extracting heuristic principles to generate ideas has been demonstrated as a successful technique in several other research programs. For example, TRIZ (Altshuller, 2005; Altshuller & Rodman, 1999; Hernandez, Schmidt, & Okudan, 2013; Savransky, 2000), transformative design heuristics (Singh et al., 2009; Singh et al., 2007; Skiles et al., 2006; J. Weaver, Wood, Crawford, & Jensen, 2010; J. M. Weaver, Wood, & Jensen, 2008), and other approaches (Cormier, Literman, & Lewis, 2011; Haldaman & Parkinson, 2010; Perez, Linsey, Tsenn, & Glier, 2011; Saunders, Seepersad, & Hölttä-Otto, 2011) all point to the usefulness of observational study. The methodology used in this approach added the collection of observations *during* the idea generation process. The generation of initial concepts while attempting to create multiple, different designs for consideration appears to give rise to patterns not evident in final designs. Consequently, it is important to observe designs created within a work session or project in order to capture the ways in which designers generate multiple concepts. Through systematic observation of many concepts created by multiple designers in varied design settings, we can attain a deeper understanding of the role of Design Heuristics.

These results provide evidence of an effective tool to aid designers in the early phases of design. Best practices in design suggest that generating as many concepts as possible will lead to better design process outcomes (Akin & Lin, 1995; Atman, Chimka, Bursic, & Nachtman, 1999; Liu, Bligh, & Chakrabarti, 2003); in addition, the generation of more and different designs will logically increase opportunities to consider novel and innovative designs, Training in the use of *Design Heuristics* stands to benefit both novice and practicing designers working on any product design task. When working on a design problem, becoming fixated on the initial ideas generated or on existing products inhibits the creation of new, different designs (Ball et al., 1994; Chrysikou & Weisberg, 2005; Crilly, 2015; Dong & Sarkar, 2011; Jansson & Smith, 1991; Linsey et al., 2010; Purcell & Gero, 1996; Sio, Kotovsky, & Cagan, 2015; Vasconcelos & Crilly, 2016; Viswanathan & Linsey, 2013; Youmans & Arciszewski, 2014). The use of *Design Heuristics* has been shown to facilitate idea generation by opening areas of the design space not previously explored. *Design Heuristics* help to identify new designs across design problems and designers, providing a set of general strategies for idea generation that also allow individuals to create original and differing designs through their use.

7 Conclusions

Research has documented a lack of systematic, empirically-validated instruction in design education. We have developed pedagogical approaches that leverage the empirically-driven and validated *Design Heuristics* tool to support skill development in idea initiation, idea development, subcomponent design, and group ideation. Using the tool in multiple ways helps instructors incorporate instruction on idea generation over sessions, allowing students to experience success and become confident of their ability to create many designs. For students, the *Design Heuristics* serve as a foundation for their increasing exploration of more innovative ideas in classrooms and in their future design tasks.

References

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., & Lin, C. (1995). Design protocol data and novel design decisions. *Design Studies, 16*, 211-236.

Altshuller, G. (2005). *40 Principles: TRIZ keys to technical innovation, extended edition*. Worchester, MA: Technical Innovation Center, Inc. .

Altshuller, G., & Rodman, S. (1999). *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity*. Worchester, MA: Technical Innovation Center.

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

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., Evans, J., & Dennis, I. (1994). Cognitive processes in engineering design: A longitudinal study. *Ergonomics, 37*(11), 1753-1786.

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.

Bleuze, T., Cioccib, M.-C., Detandb, J., & De Baetsc, P. (2014). Engineering meets creativity: A study on a creative tool to design new connections. *International Journal of Design Creativity and Innovation, 2*(4), 203-223.

Bonnardel, N. (2000). Towards understanding and supporting creativity in design: analogies in a constrained cognitive environment. *Knowledge-Based Systems, 13*, 505-513.

Casakin, H. (2004). Visual analogy as a cognitive strategy in the design process: Expert versus novice performance. *Journal of Design Research, 4*(2).

Christensen, B. T., & Schunn, C. D. (2007). The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design. *Memory & Cognition, 35*(1), 29-38.

Christian, J. L., Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2012). *Design Heuristics to Support Two Modes of Idea Generation: Initiating Ideas and Transitioning Among Concepts*. Paper presented at the Annual Conference of American Society of Engineering Education San Antonio, Texas.

Chrysikou, E. G., & Weisberg, R. W. (2005). Following the wrong footsteps: Fixation effects of pictorial examples in a design problem-solving task. *Journal of Experimental Psychology: Learning, Memory & Cognition, 31*(5), 1134-1148.

Cormier, P., Literman, B., & Lewis, K. (2011, August 28-31). *Empirically drived heuristics to assist designers with satisfying consumer variation in product design*. Paper presented at the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Washington, DC.

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies, 38*(May 2015), 54-91.

Cross, N. (2011). *Design Thinking: Understanding how designers think and work*. New York, NY: Berg.

Dalsgaard, P., & Dindler, C. (2014). *Between theory and practice: Bridging concepts in HCI research*. Paper presented at the Annual ACM Conference on Human Factors in Computing Systems, New York, NY.

Daly, S. R., Christian, J. L., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2011, June 26-29). *Teaching design ideation*. Paper presented at the American Society of Engineering Education, Vancouver.

Daly, S. R., Christian, J. L., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2012). Assessing Design Heuristics for idea generation in an introductory engineering course. *International Journal of Engineering Education, 28*(2), 1-11.

Daly, S. R., Seifert, C. M., Yilmaz, S., & Gonzalez, R. (2016). Comparing ideation techniques for beginning designers. *Journal of Mechanical Design, 138*(10), 101108.

Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2012). Design Heuristics in engineering concept generation. *Journal of Engineering Education, 101*(4), 601-629.

Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2010, June 20-23). *Cognitive heuristic use in engineering design ideation*. Paper presented at the American Society for Engineering Education Annual Conference (ASEE), Lousville, Kentucky.

Diehl, M., & Stroebe, W. (1987). Productivity loss in brainstorming groups: Toward the solution of a riddle. *Journal of Personality and Social Psychology, 53*(3), 497-509.

Dong, A., & Sarkar, S. (2011). Unfixing design fixation: From cause to computer simulation. *Journal of Creative Behavior, 45*(2), 147-159.

Duderstadt, J. (2008). Engineering for a changing world: A roadmap to the future of engineering practice, research, and education. Retrieved from http://milproj.dc.umich.edu/

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

Engineering, N. A. o. (2004a). The Engineer of 2020: visions of engineering in the new century. Retrieved from http://www.nap.edu/openbook.php?record_id=10999&page=R2

Engineering, N. A. o. (2004b). *The Engineer of 2020: Visions of Engineering in the New Century*. Washington, DC: National Academy Press.

Gray, C. M., Seifert, C. M., Yilmaz, S., Daly, S. R., & Gonzalez, R. (2015). What is the context of "Design Thinking"? Design Heuristics as conceptual repertoire. *International Journal of Engineering Education, 32*(2).

Gray, C. M., Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2015). *Supporting idea generation through functional decomposition: An alternative framing for Design Heuristics*. Paper presented at the International Conference on Engineering Design (ICED), Milan, IT.

Haldaman, J., & Parkinson, M. B. (2010). *Reconfigurable products and their means of reconfiguration*. Paper presented at the ASME INternational Design Engineering Technical Conferences and Computers and Information in Engineering Conference Las Vegas, Nevada.

Hernandez, N. V., Schmidt, L. C., & Okudan, G. E. (2013). Systematic ideation effectiveness study of TRIZ. *Journal of Mechanical Design, 135*(10), 101009.

Höök, K., & Löwgren, J. (2012). Strong concepts: Intermediate-level knowledge in interaction design research. *ACM Transactions on Computer-Human Interaction (TOCHI), 19*(3), 23.

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

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

Kolodner, J. (1993). *Case-based reasoning*. San Francisco, CA: Morgan Kaufmann Publishers Inc.

Kolodner, J. L. (1997). Educational implications of analogy: A view from case-based reasoning. *American Psychologist, 52*(1), 57.

Kotys-Schwartz, D., Daly, S. R., Yilmaz, S., Knight, D., & Polmear, M. (2014, June 16-18). *Evaluating the implementation of Design Heuristic cards in an industry-sponsored capstone design course*. . Paper presented at the Annual Conference of American Society of Engineering Education (ASEE), Indianapolis, IN.

Kramer, J., Daly, S. R., Yilmaz, S., & Seifert, C. M. (2014, June 16-18). *A case-study analysis of Design Heuristics in an upper-level cross-disciplinary design course*. . Paper presented at the Annual Conference of American Society of Engineering Education (ASEE) [Nominated for ASEE DEED Best Paper Award], Indianapolis, IN.

Kramer, J., Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2015). Investigating the impact of Design Heuristics on idea initiation and development. *Advances in Engineering Education, 4*(4).

Lawson, B. (1980). *How designers think: The design process demystified* London, UK: Architectural.

Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., & Schunn, C. D. (2010). A study of design fixation, its mitigation and perception in engineering design faculty. *Journal of Mechanical Design, 132*(4), 1-12.

Liu, Y. C., Bligh, T., & Chakrabarti, A. (2003). Towards an 'ideal' approach for concept generation. *Design Studies, 24*(4), 341-355.

Pearl, J. (1984). *Heuristics: Intelligent search strategies for computer problem solving*. Reading, MA: Addison-Wesley Pub. Co., Inc.

Perez, A., Linsey, J. S., Tsenn, J., & Glier, M. (2011, August 28-31). *Identifying Product Scaling Principles: A Step Towards Enhancing Biomimetic Design*. Paper presented at the ASME 2011 International Mechanical Engineering Congress and Exposition, Washington, DC.

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies, 17*(4), 363-383.

Rowatt, W. C., Nesselroade, K. P., Beggan, J. K., & Allison, S. T. (1997). Perceptions of brainstorming in groups: The quality over quantity hypothesis. *Journal of Creative Behavior, 31*(2), 131-150.

Saunders, M. N., Seepersad, C. C., & Hölttä-Otto, K. (2011). The characteristics of innovative mechanical products. *Journal of Mechanical Design, 133*, 021009-021001-021009.

Savransky, S. D. (2000). *Engineering of creativity: Introduction to TRIZ methodology of inventive problem solving*. Boca Raton: CRC Press.

Seifert, C. M., Gonzalez, R., Yilmaz, S., & Daly, S. R. (2015). Boosting creativity in idea generation using Design Heuristics *Product Development and Management Association (ed.), Design and Design Thinking: Essentials in the PDMA's New Product Development Series* (pp. 71-86): John Wiley and Sons.

Singh, V., Skiles, S. M., Krager, J. E., Wood, K., Jensen, D., & Sierakowski, R. (2009). Innovations in design through transformation: A fundamental study of transformation principles. *Journal of Mechanical Design, 131*(8), 081010-081011-081018.

Singh, V., Walther, B., Krager, J. E., Putnam, N., Koraishy, B., Wood, K. L., & Jensen, D. (2007, September 4-7). *Design for transformation: Theory, method and application*. Paper presented at the ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Las Vegas, Nevada.

Sio, U. N., Kotovsky, K., & Cagan, J. (2015). Fixation or inspiration? A meta-analytic review of the role of examples on design processes. *Design Studies, 39*(C), 70-99.

Skiles, S. M., Singh, V., Krager, J. E., Seepersad, C. C., Wood, K. L., & Jensen, D. (2006, September 10-13). *Adapted concept generation and computational techniques for the application of a transformer design theory*. Paper presented at the ASME 2006 International Design Engineering Technical

Conferences and Computers and Information in Engineering Conference, Philedelphia, PA.

Sutton, R. I., & Hargadon, A. (1996). Brainstorming groups in context: Effectiveness in a product. *Administrative Science Quarterly, 41*, 685-718.

Vasconcelos, L. A., & Crilly, N. (2016). Inspiration and fixation: Questions, methods, findings, and challenges. *Design Studies, 42*(January 2016), 1-32.

Visser, W. (1996). Two functions of analogical reasoning in design: a cognitive-psychology approach. *Design Studies, 17*(4), 417-434.

Viswanathan, V. K., & Linsey, J. S. (2013). Design fixation and its mitigation. *Journal of Mechanical Design, 135*(5), 051008.

Weaver, J., Wood, K., Crawford, R. H., & Jensen, D. (2010). Transformation design theory: A meta-analogical framework. *Journal of Computing and Information Science in Engineering, 10*(3), 031012.

Weaver, J. M., Wood, K. L., & Jensen, D. (2008). *Transformation facilitators: A quantitative analysis of reconfigurable products and their characteristics*. Paper presented at the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Brooklyn, NY.

Yilmaz, S., Christian, J. L., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2011). *Idea generation in collaborative settings using design heuristics*. Paper presented at the International Conference on Engineering Design (ICED), Copenhagen, Denmark.

Yilmaz, S., Christian, J. L., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2012). *How do Design Heuristics affect design outcomes in industrial design?* Paper presented at the International Design Conference, Dubrovnik, Croatia.

Yilmaz, S., Daly, S. R., Christian, J. L., Seifert, C. M., & Gonzalez, R. (2013). Can experienced designers learn from new tools? A case study of idea generation in a professional engineering team *International Journal of Design Creativity and Innovation, 2*(2), 82-96.

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2013). *Comparison of design approaches between engineers and industrial designers*. Paper presented at the International Conference on Engineering and Product Design Education, Dublin, Ireland.

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2014, June 16-18). *Design Heuristics as a tool to improve innovation*. Paper presented at the Annual Conference of American Society of Engineering Education (ASEE), Indianapolis, IN.

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2015). How do designers generate new ideas? Design Heuristics across two disciplines. *Design Science, 1*, 1-29.

Yilmaz, S., & Seifert, C. M. (2009, October 18-22). *Cognitive heuristics employed by design experts: A case study*. Paper presented at the 3rd Conference of

International Association of Society of Design Research, IASDR '09, Seoul, Korea.

Yilmaz, S., & Seifert, C. M. (2010, May 17-20). *Cognitive heuristics in design ideation*. Paper presented at the International Design Conference, Cavtat, Croatia.

Yilmaz, S., & Seifert, C. M. (2011). Creativity through design heuristics: A case study of expert product design. *Design Studies, 32*(4), 384-415.

Yilmaz, S., Seifert, C. M., Daly, S. R., & Gonzalez, R. (2016a). Design strategies in innovative products. *Journal of Mechanical Design, 138*(7).

Yilmaz, S., Seifert, C. M., Daly, S. R., & Gonzalez, R. (2016b). Evidence-based Design Heuristics for idea generation. *Design Studies, 46*, 95-124.

Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2010). Cognitive heuristics in design: Instructional strategies to increase creativity in idea generation. *Journal of Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 24*(3), 335-355.

Youmans, R. J., & Arciszewski, T. (2014). Design fixation: Classifications and modern methods of prevention. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 28*(02), 129-137.