ASEE's 123rd Annual • Conference & Exposition • New Orleans, LA • June 26-29, 2016

Paper ID #16136

Investigating How Design Concepts Evolve in Engineering Students

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Abstract

A critical aspect to engineering practice is the ability to design solutions to ill-structured problems. Prior research has shown that such solutions are highly effective when they are evaluated in relation to multiple design concepts. However, prior research has also shown that engineering students tend to fixate on their initial design ideas rather than base their solutions on the integration of many diverse concepts. One recently developed method to overcome the problems of fixation is 77 Design Heuristics. This method for generating design concepts comes in the form of 77 cards, each with a different cognitive prompt for generating a solution (e.g., reduce material, flatten). By using the cards, engineers and engineering students are able to expand their horizons of possible solutions to challenging design problems.

Using a first-year engineering course, we integrated the 77 Design Heuristics cards to document how these students develop final concepts in relation to their initial ideas. We analyzed 12 first-year engineering students, distributed across 3 different design teams. Our findings demonstrate key influences that did foster idea fluency (Theme 1: Influence of 77 Cards on Early Design Concepts) but also ways that students remained attached to particular concepts throughout their design process (Theme 2: Resilient Concepts after Concept Generation).

Introduction

Engineering students will potentially encounter a breadth of challenging and ill-structured problems in their future careers[1,2]. The National Academy of Engineering's Grand Challenges describe a series of problems that deeply integrate social and technical forms of problem-solving[3]. For example, problems such as "prevent nuclear terror," "provide energy from fusion," and "restore and improve urban infrastructure" are timely challenges that deeply interact with a social context.

Societal problems like those listed in the Grand Challenges, and the multiple sub-problems that compose them, are associated with solutions that are not yet apparent. Solving these problems will require engineers to think flexibly, building upon lots of design ideas to develop a final solution. Yet, as they learn engineering design, students often lack strategies that could help them generate multiple solutions[4]. As outlined by Crismond & Adams[5], beginning designers can enact a pattern of idea scarcity, starting "their design work with very few or even just one idea, which they may not want to discard, add to, or revise" (p. 755).

How, then, might we prepare students for the challenging landscape of these complicated problems? While the answer to this question might be multi-faceted, the ability to solve ill-structured problems, in part, lies in how students learn to generate multiple ideas in design. With this overarching goal, our investigation qualitatively examines how first-year engineering students responded to an instructional tool, 77 Design Heuristics, which encourage the exploration of a variety of conceptual solutions during ideation. In the following section, we review existing literature on fixation and how others have proposed to promote idea fluency. We then discuss methods and findings of our particular investigation, which extend this literature and suggest insight into future research.

Literature Review: Fixation and Concept Generation Strategies

A common aspect of engineering design processes involves generating multiple and varied solutions for a design problem within a team or individual setting. In an ideal world, this ideation phase would result in multiple design concepts that are varied in nature. Such diverse design concepts would then create the opportunity for a wide variety of possible innovative solutions. With a diverse set of potential concepts, novel and innovative solutions are more likely to ensue[6,7].

However, novice designers tend to develop predominantly one idea early on in the design process[8]. They enact a practice of *fixation*, or the tendency to become focused on specific options early in the design process, consequently limiting the variety of designs considered[9-11]. Fixation can occur from an idea being inspired from an existing product, initial idea, or the designer's previous experience. In Jansson & Smith's (1991) study, designers were shown an initial example of an unsatisfactory product and then made aware of its flaws. These designers produced solutions inferior to those who had not seen the initial example. Additionally, Linsey et al. (2010) discussed how designers might have a cognitive inability to break away from known products or example solutions. A number of other studies have investigated fixation[9-12], and together, they describe the existence of this persistent limitation among beginning designers.

Without strategies to generate concepts, designers are often limited by existing solutions and their initial ideas. Indeed, previous studies have demonstrated that beginning designers tend to not generate more concepts that are different from ones' initial ideas[9,13]. Additionally, novice designers can develop a sense of attachment to initial design concepts and hang onto concepts even when they realize they may be extremely difficult to pursue or have major flaws[14, 15].

To overcome fixation, theorists have proposed a range of concept generation techniques and approaches[16,17]. Yilmaz and her colleagues categorize some idea generation techniques in terms of:

1) the facilitation of idea flow (e.g., brainstorming[18] and brainwriting[19])

2) the stimulation of initial idea formation (e.g., analogical thinking[20], morphological analysis[21], and Synectics[22])
3) the transformation of ideas into more or better ideas (e.g., lateral thinking[23]), conceptual combination[24], SCAMPER[25], and TRIZ[26,27].

Other published tools include IDEO™ Method Cards[28], which focus on understanding a product's users, and "Whack Pack" cards[29] intended to help designers break out of habitual views by providing general techniques and decision-making advice.

However, despite the number of techniques that may be used to overcome fixation, many of these strategies lack published empirical validity in the context of engineering design. Indeed, in Smith's systematic compilation of over 170 concept generation techniques, he concluded, "Of the hundreds of existing methods, only brainstorming has been subjected to a substantial battery of performance tests. Moreover, these assessments have generally been inconclusive in their results" (p. 129)[16]. In sum, fixation is a pervasive obstacle for students as they learn engineering design. While a number of strategies exist to overcome this cognitive limitation, few of these strategies are empirically validated in an engineering design context.

Background: 77 Design Heuristics

The 77 Design Heuristics are a set of cognitive shortcuts that help designers explore a variety of solutions during ideation[4, 30-35]. This tool comprises 77 illustrated cards that are used to promote fluency in concept generation. Each card includes a specific design prompt, along with a graphical representation and descriptive text. In addition, on the reverse of each card, two existing product examples are provided where the specific heuristic is evident. An example of a *Design Heuristic* is 'Apply an existing mechanism in a new way'. The card associated with this heuristic prompts the designer to take an existing product or component and incorporate it to function differently in the final product. For example, in designing a generator, the engineer may take an existing mechanism like a bicycle and apply it as a power source. This one design heuristic can be applied repeatedly to generate other concepts (e.g., using a water bottle to squirt water and turn a wheel). The set of cards are intended to guide engineers and engineering students in generating non-obvious ideas that are different from one other, providing a larger set of diverse ideas to choose from later in design[38].

The Design Heuristic strategies were empirically-derived from three data sources. These sources include: 1) analysis of over 400 award-winning products[32]; 2) over 200 sketches of a long-term household design project by an experienced industrial designer[31,37]; and 3) protocol studies of approximately 50 industrial and engineering professional designers and students[30, 31, 34, 36, 37].

Empirical studies of novice, experienced, and professional designers have demonstrated the efficacy of 77 Design Heuristics as a tool to cultivate idea generation. This empirically-developed tool has been studied in several contexts and engineering courses, and few of these settings have been documented in prior research[35-37].

Research Context and Questions

While 77 Design Heuristics has been established as an empirically validated way of supporting students in generating design concepts, research is ongoing to determine how this technique is applied in various institutional settings. Thus, in this paper, we describe a study that examines how first-year engineering students learn to generate new concepts using the 77 Design Heuristic tool. The knowledge claims from this study provide suggestive direction for future research. However, we substantiate these claims with evidence that was discovered through a robust methodology.

Research Context:

In the context of an introductory engineering design course, we used the 77 Design Heuristics as a way to instill idea fluency in students. The course was within an engineering program at a private, liberal-arts university, and only first-year engineering students were enrolled in the class. In the semester that data was collected, 25 first-year students were enrolled in this course.

Throughout the entire academic semester, the students were divided into seven design teams in order to partner with a local Habitat for Humanity chapter to generate solutions for seven design problems that the chapter had identified at the local Re-Store (e.g., designing displays for donated televisions, lights, or mattresses). The Habitat for Humanity Re-Store sells donated goods in order to raise funds for building houses for economically disadvantaged individuals. However, it is mostly staffed by volunteers and there are few resources available to address long-term needs within the store.

In the middle of the semester, at approximately the eighth week, the students were introduced to the 77 Design Heuristics, and then each student was tasked with generating a minimum of 20 different solutions to their design problems. In order to develop these solutions, each team with 3-4 students shared a deck of the 77 cards. And each individual member was required to use the cards as prompts to develop the 20 ideas. The students individually each sketched their concepts and wrote down the number of the associated card that prompted the idea. The design teams then discussed and negotiated these early concepts (approximately 60-80 per team) in order to generate three to five conceptual solutions to evaluate against one another for the final design concept.

Research Questions:

The students performed the assigned task as required, though our focus in this study was to determine how they responded to the 77 Design Heuristics. Specifically, we sought to answer the following research questions:

RQ1: How do students represent design concepts when prompted by *Design Heuristics* cards?
RQ2: How do design concepts evolve within individual students?
RQ3: How are design concepts negotiated in a team?

In RQ1, we sought to explore the patterned responses of students when they were presented with the 77 Design Heuristics cards. In RQ2, we sought to analyze how initial ideas developed into final design concepts. In RQ3, we wanted to capture how external influences from other students affected the final design concepts. This external influence does not include influence generated from the *Design Heuristics* cards and is generally only recorded when mention of team cooperation was present.

Methods

We conducted qualitative research to answer our research questions. Specifically, we studied the design records of 12 first-year engineering students that were separated into three teams (4 students each). Of the seven project teams in the class, the three teams that we studied collectively had generated the most documentation, enabling us to find credible insights based on our research questions. Drawing from their individual design notebooks and team documents as data, we conducted a thematic analysis in order to identify patterns of design-thinking across the participant sample. The study was approved by Harding University's IRB.

Data Collection

We gathered design records from three separate teams of four students each (n = 12). Throughout this paper, we refer to the teams as Hardware Team, Mattress Team, and Lighting Team. Each team was assigned the task of creating displays in the store for the corresponding product. We collected two sources of data: design notebooks and team design documents.

Design Notebooks: In order to record the students' design concepts, each student wrote in a designated notebook. The students were asked in these notebooks to record their reflections, ideas, and thought processes. In the notebooks, individual students documented their early concepts in response to the 77 *Design Heuristic*s Cards, as described above. Throughout the entire semester, they also documented their own thinking in these notebooks, including very early concepts that they developed when the projects were first assigned, before they were precisely in the phase of generating concepts.

Team Design Documents: Each of the three teams submitted a design document that was more polished than the team members' individual notebooks. While the evolution of design thinking could better be seen in the notebook, the team design document gave insight into the final solutions that were chosen by each of the three teams. Analyzing this document provided insight into how early design concepts were ultimately retained, abandoned, or modified by the entire team.

Data Analysis

To analyze the data, we conducted a thematic analysis on the 12 students across 3 design teams[38, 40, 41]. Braun and Clark described thematic analysis as "a method for identifying, analyzing and reporting patterns (themes) within data" (p. 79)[38]. This method of analysis is distinguished from other types of similar qualitative methods, such as grounded theory, in that "thematic analysis is not wedded to any pre-existing theoretical framework, and therefore it can be used within different theoretical frameworks (although not all) and can be used to do different things within them" (p. 81) [38]. Thus, in this investigation, we used thematic analysis as a way to understand patterned responses of students who use 77 *Design Heuristics* cards.

Further, we approached this study inductively, allowing the participant data to speak for itself rather than looking to confirm any existing theoretical frameworks. This approach aligned with Braun & Clark's understanding of inductive thematic analysis: "Inductive analysis is . . . a process of coding the data *without* trying to fit it into a pre-existing coding frame, or the researcher's analytic preconceptions" (p. 83)[38]. By approaching the data inductively, we were not informed by existing theory *a priori*. Indeed, although we have discussed prior literature on fixation and concept generation, we suspended developing our own understandings of this research in order to fully attend to what we might learn from the data.

Each notebook was recorded electronically in order to analyze the data using Atlas TI software. This software allowed us to develop codes and track patterns and themes that were present in the data. We began the analysis by the first authors' thoroughly annotated, descriptive and conceptual comments in three of the design notebooks. After these design notebooks had been thoroughly annotated by the first author, the author team developed a concise list of codes to apply throughout the remaining data set. Throughout analysis of the remaining notebooks, with multiple discussions among the author team, these codes developed into the list provided on

Table 1. After this set of codes had been established, the first author revisited his analysis to all the data sources and applied these codes.

We regarded our codes as filters to the large amounts of textual and visual data because they organized sections of text or images around common descriptions, as noted in Table 1 below[39]. By using them, we were able to interpret and describe how the early, individual concepts evolved throughout the semester. We were also able to examine how these concepts were negotiated within teams. After the documents had been coded, we discussed important relationships among the codes to condense the findings to two significant themes. Findings discuss how early design concepts evolved to the final proposed solutions (RQ1 & RQ2) and how these concepts were negotiated within teams (RQ3).

Table 1: The list of codes with their descriptions

Codes	**Description**
Common Team Initial Concept	Excerpts or images that describe a concept that was common among the whole team
DH Cards Had Direct Influence on Final Drawing	Excerpts or images that describe a distinct influence that a *Design Heuristics* card had on the final drawing
Drawing – Early	Excerpts or images that describe the early design drawings
Drawing – Final	Excerpts or images that describe the final design drawings
First Concept	Excerpts or images that describe the first concept generated
Human-Integrated Drawings	Excerpts or images that describe the drawings that integrated people in the design concept
Indirect Response to the Card	Excerpts or images that describe a particular drawing based on the cards that were not expected during our research
Prioritized Customer Needs	Excerpts or images that describe a segment where the student prioritized the customer in the design
Realizing Reality of Design	Excerpts or images that describe a segment where the student is brought to the realization of a drawing, whether it be positive or negative
Resilient Concept	Excerpts or images that describe a concept that continued to resurface throughout the semester
Spoke with Team Member	Excerpts or images that describe communication between team members that might have influenced certain drawings

Findings

By conducting an inductive thematic analysis across the data set, we were able to track the progression of design concepts in individual students. The data gave us insight into how each student and team came to decide on their final concept. In our analysis, we found two important themes: 1) Influence of 77 Cards on Early Design Concepts, and 2) Resilient Concepts after Concept Generation. Each theme addresses a certain characteristic that sheds light on how these particular students formed design concepts. Before we describe these two themes, we begin this section by describing the dominant initial concepts that were held by each team. In portraying these initial concepts, we can better explain in the theme descriptions how these initial ideas were challenged by 77 *Design Heuristics* (or other factors) or how they remained present throughout the entire conceptual design.

Initial Design Concepts. After they were assigned the design problems for each team, several students began to individually develop initial design concepts for their project. These students sketched out such solutions unprompted by the instructor and had done so approximately 5-7 weeks before they were introduced to ideating with the 77 Cards.

For example, Hardware Team's task was to construct an apparatus that could display small hardware items. When directed towards this problem, Jessica began sketching two rotating displays for the parts, as can be seen in Figure 1 and Figure 2. In Figure 1, Jessica added wheels to the design, noting it as movable and describing its rotating functionality "like a bicycle wheel/chain". Similarly in Figure 2, Jessica retained these features while displaying the design in a vertical manner.

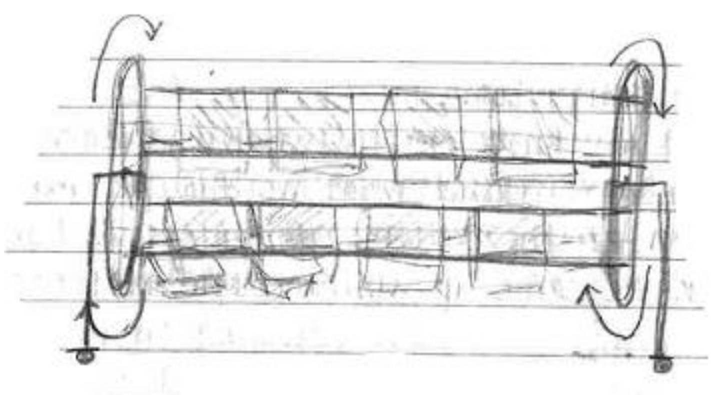

Figure 1: Horizontal rotating initial concept drawn by Jessica

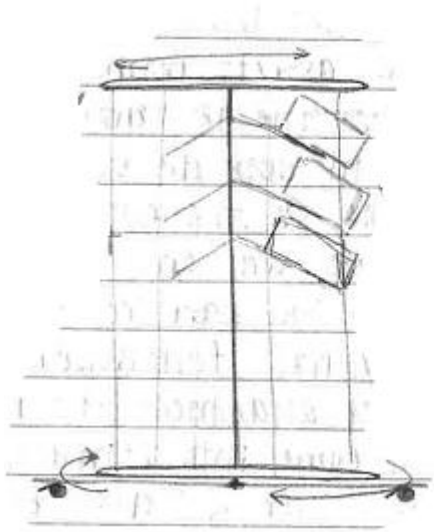

Figure 2: Vertical rotating design by Jessica

The other members of Hardware Team also developed their initial ideas. Daniel's early design concepts were very similar to Jessica's, resembling Figure 1 and Figure 2. The other two members Frank and Travis, however, contributed more conventional shelf ideas. Frank, for example, drew a movable shelf that had wheels on it to provide movement, shown in Figure 3.

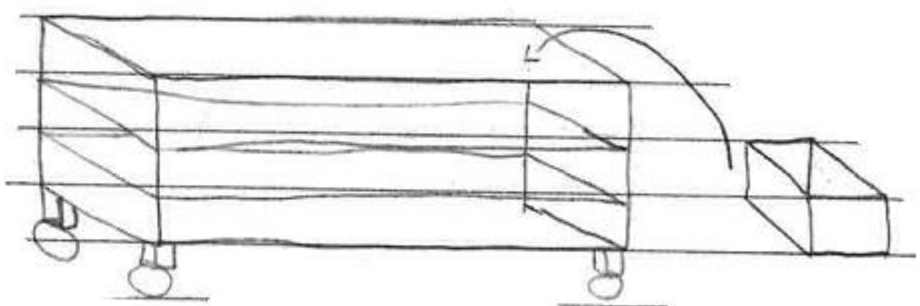

Figure 3: Conventional shelf design drawn by Frank

Mattress Team's task was to construct a mechanism that could display mattresses. When he initially received the problem, Matthew immediately began coming up with potential designs for a particular apparatus. As shown in Figure 4, Matthew illustrated his desire to have the mattresses stacked within the mechanism. He depicted two basic ideas for a mattress display apparatus, both of which organize the mattresses through stacking.

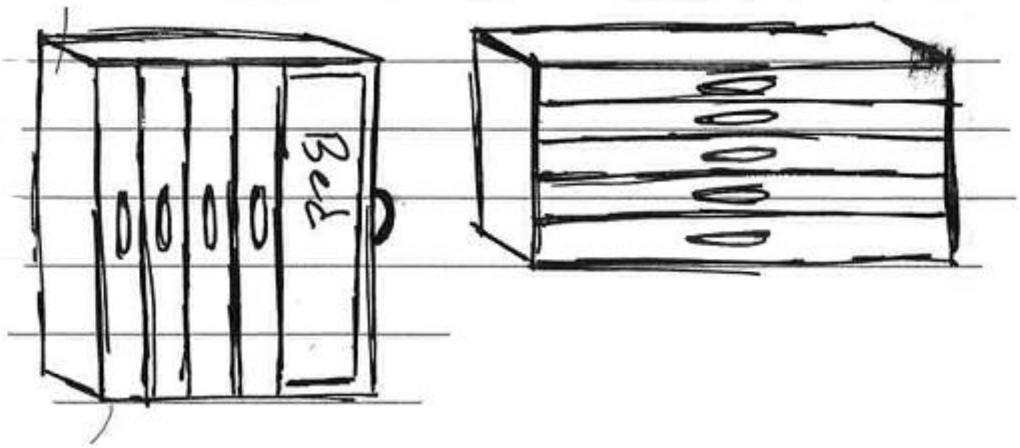

Figure 4: Vertical and horizontal displays of the mattresses by Matthew

In similar fashion, Tom created his first design concept by sketching a display that would allow the user to vertically stack mattresses within the display (Figure 5). While this apparatus was somewhat unique from Matthew, both individuals tended to focus on a single function of the display, that is, how mattresses would be stored.

Figure 5: Curved mattress apparatus drawn by Tom

Lighting Team's task was to create a display for lights that were donated to the ReStore in a way that store customers could see the donated lights hung and illuminated. In order to accomplish this, David's initial concept was to use PVC pipe hanging from the air and distribute light from above. In his sketch (Figure 6), the pipes would be a platform from which the donated lights would be displayed. As seen below, his initial solution focuses on the singular function of hanging lights.

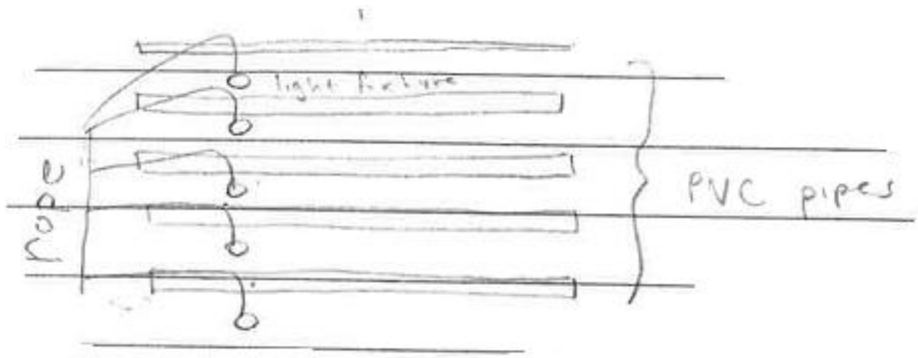

Figure 6: Initial lighting display concept by David

In summary, students from each of the three teams immediately began to sketch out initial ideas once they were given the problem. Although this sketching was done before they had developed requirements and specifications for each of these projects, these initial design concepts provide substantial information about the students' initial assumptions of their design problems. As we have discussed, these initial ideas tended to be centered on a single function (e.g., stacking mattresses, shelving hardware, hanging lights) and did not consider other functions that we might expect in a display for donated goods (e.g., space optimization, usability from staff who would stock the display).

Theme 1: Influence of 77 Cards on Early Design Concepts. Beginning with an understanding of how students developed their initial concepts, we began to analyze their notebooks in order to see how their design concepts were differentiated and developed. In the semester, students began to generate multiple and varied ideas to their design problems. This seemed to especially occur after they were instructed to generate multiple design concepts using the 77 Cards. In addition to the cards, we found that much influence on design ideas were drawn from negotiations within the teams.

For example, in the case of Lighting Team, Tim represented a concept that he inferred from Design Heuristic card 43 ("Make Multifunctional"). This card encourages users to "identify a secondary, complimentary function for the product and create a new form to accomplish both functions"[42]. Using this prompt, Tim created the drawing that can be seen in Figure 7. As seen below, this drawing is very similar to the final design concept for the team (Figure 8). Although Tim engaged at least 20 *Design Heuristics* cards, this particular prompt appeared to powerfully disrupt the momentum of early thinking on this project, which tended to fixate on a narrow solution of how lights would be hung from a raised platform.

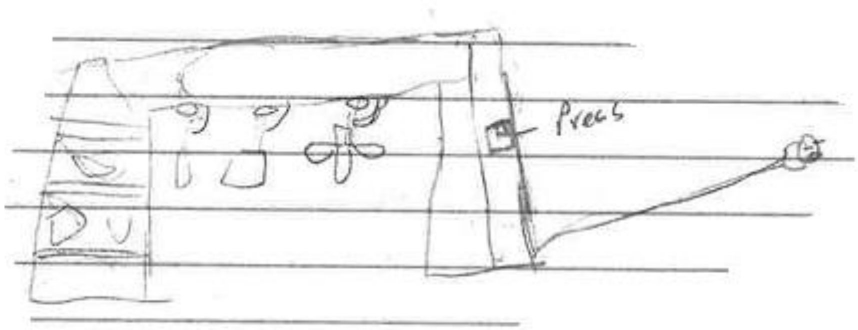

Figure 7: Lighting display inspired by Design Heuristic card #43 drawn by Tim

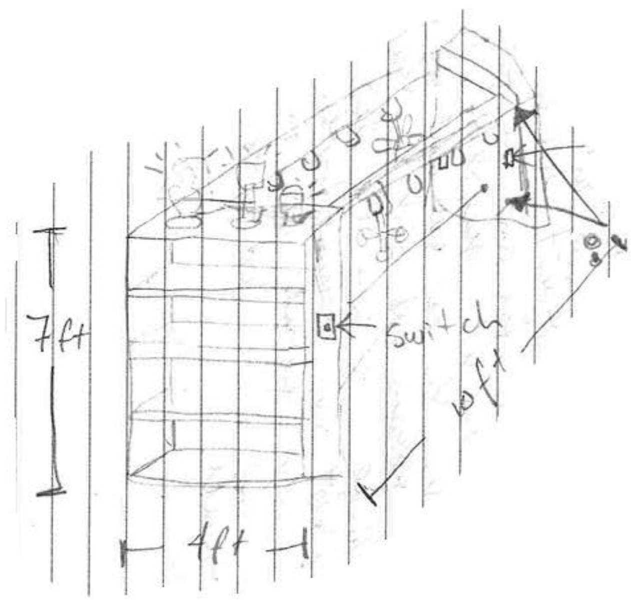

Figure 8: The final concept for the Lighting Team

For the Mattress Team, the Design Heuristic cards helped Matthew create a concept for the mattress display. As seen in Figure 9, Matthew sketched multiple design concepts that were all related to a vertical mattress display on wheels. This set of drawings does show some fixation on a general solution to vertically display mattresses. Yet, these drawings also show Matthew's ability to more deeply develop his solution, focusing on multiple functions as prompted by some of the 77 cards. Similarly, Toby demonstrated that he was influenced by prompting from the *Design Heuristics* card with the strategy of "Repeat". Figure 10 depicts how Toby interpreted this prompt, which caused him to develop a mattress display with an open top.

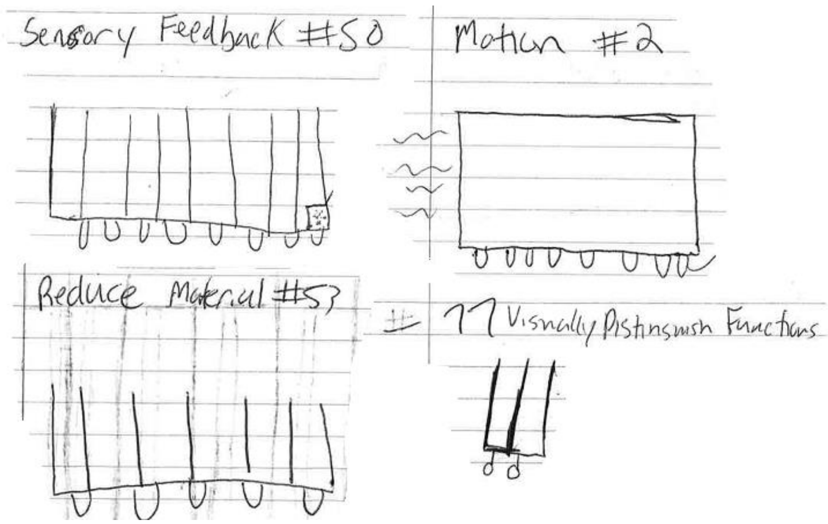

Figure 9: Design Heuristic influenced drawings of the mattress repeated by Matthew

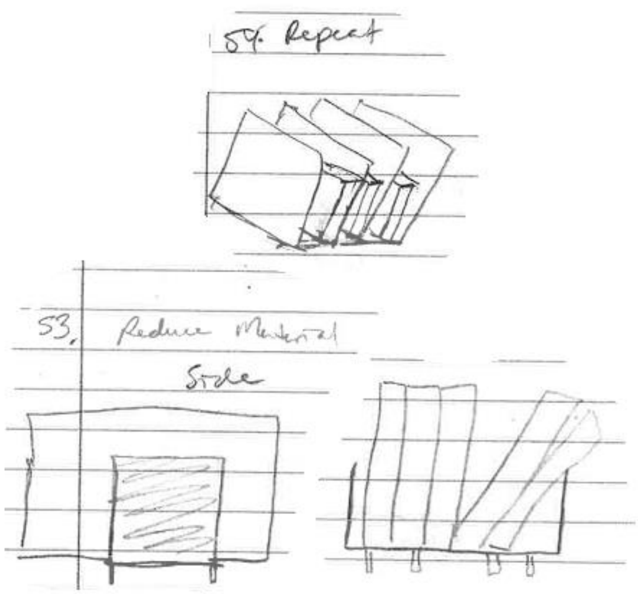

Figure 10: Design Heuristic influenced designs repeated by Toby

This overall design, to vertically stack mattresses on a mobile platform, became the foundation for the Mattress Team's final concept, and enabled the team to consider reducing material (e.g., by removing the top of the apparatus) and more fully engage the requirements of the problem by incorporating mobility as a function of the solution.

Although the previous examples described how the cards' supported students in building final solutions on a platform of diverse ideas, the same phenomenon did not occur with the Hardware Team. For example, though Jessica developed a defined initial concept of a rotating display for hardware, she generated multiple, diverse design concepts in order to develop the hardware display (Figure 11). Although the concepts were quite diverse, features of these early concepts did not appear in the team's final solution.

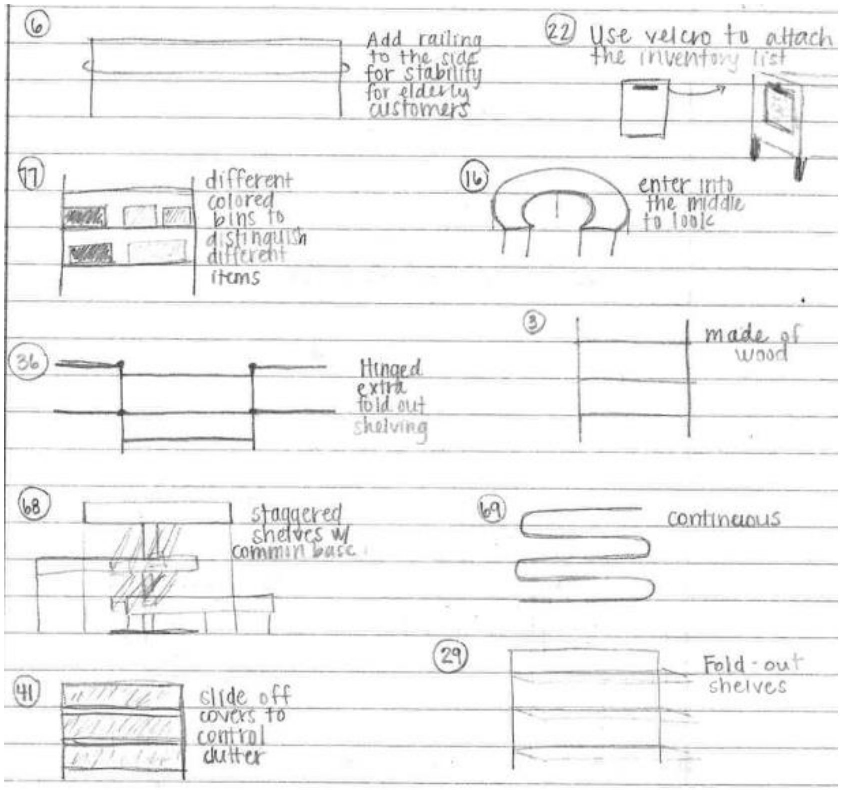

Figure 11: A sample of the design ideas influenced by the Design Heuristic cards drawn by Jessica

One reason for not integrating the diversity of these designs could be the influence developed from her teammates. When she communicated with her team, they discussed some of the shortcomings of their early design concepts designs. Jessica commented on the differing focuses between her and her teammates:

> My main focus with my idea was on the customers, but my teammates' focus was on the volunteers, [the store manager], and ease of use. We can see the challenges that this display has: functionality v. simplicity, having to consider and meet the needs of all people who will come into contact with our design and use it for different purposes, and making it versatile.

Her newfound attention to simplicity seemed to cause her to disregard the many ideas that she developed by using the 77 cards. Notably, most of the designs in Figure 11 involved complex features that might be difficult to implement (e.g., multiple hinges, rounded structures). As a result, Jessica reverted back to her initial concept which eventually endured until the end of the semester. This drawing can be seen in Figure 12.

Figure 12: Renewed shelf concept after team discussion drawn by Jessica

Theme 2: Resilient Concepts after Concept Generation. While the students were mostly successful in generating many diverse concepts, their final solutions tended to fixate on relatively few early concepts. Some of these concepts were generated through the 77 Cards, and some were initial ideas. We defined these as *resilient concepts*, or conceptual solutions that continued to resurface in design records throughout the semester. These concepts were seemingly unaffected by any external influence. These ideas were drawn by students who largely did not alter their designs. We documented these trends by marking the concepts that were generally repeated throughout the students' notebooks.

For example, Hardware Team mainly focused on two major design concepts: rotating shelves and slanted shelves. The appeal to both, as documented by Jessica, was that "the lower rows will be more visible to the customers and volunteers" (see Figure 13). However, as noted, both designs were created at the beginning of the semester. Thus, ideas generated with the 77 *Design Heuristics* cards appeared to have little effect on the final design.

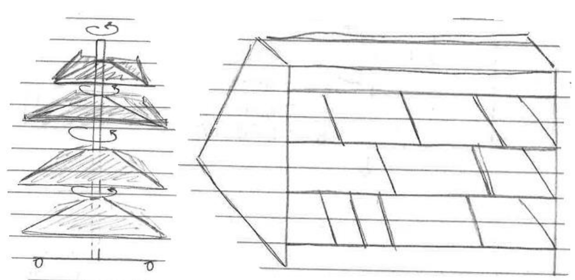

Figure 13: Initial design concepts that remained resilient throughout the semester by Jessica

The final concept that the Hardware Team developed can be seen in Figure 14. As stated in the previous section, the team was motivated to make the slanted shelf decision because of its inherent simplicity.

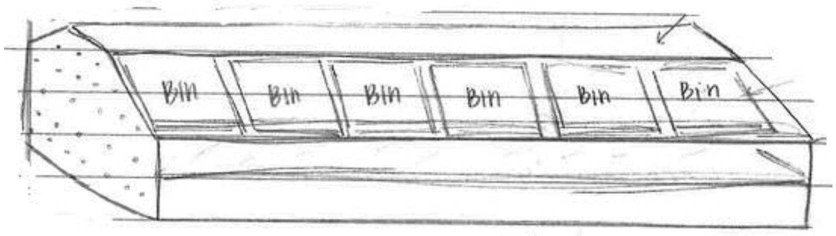

Figure 14: The final concept for the Hardware Team

Mattress Team's resilient concept related to the vertical stacking of the mattresses. This vertical stacking appeared in the initial concepts as documented by Matthew (Figure 4) and Tom (Figure 5). However, throughout the semester, though the 77 *Design Heuristic*s cards cultivated diversity of design concepts, the concepts all seemed to be framed around a common way to store the mattresses vertically (see Figures 9 and 10). The final drawing of the Mattress Team's display depicts how this overall structure pervaded throughout the concept generation phase. The inclination to stack the mattresses vertically throughout the semester demonstrate how the team was eventually unable to separate this approach for storing mattresses from other potential options.

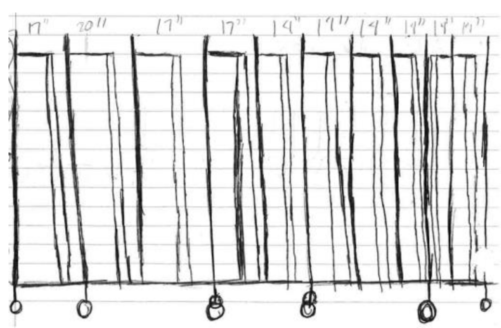

Figure 15: The final concept for the Mattress Team drawn

In summary, even though the results of the Hardware Team and the Mattress Team were deeply connected to resilient concepts that were formed earlier in the semester, this does not necessarily discount the effectiveness of the final design. However, as shown, in the cases of these two teams, students appeared to have difficulty integrating the diversity of concepts into an innovative final solution.

Discussion

The findings of this study are not intended to lead to grand knowledge claims. However, they do provide insight into how engineering educators and students might effectively employ concept generation techniques, especially the 77 *Design Heuristics*. This investigation extends prior research that demonstrates the effectiveness of the *Design Heuristics* cards in generating multiple and diverse conceptual solutions. In the two themes, we carefully walked through individual cases to demonstrate how students were able to generate multiple, varied concepts when using the cards as a way to prompt their thinking.

Yet, while the students were able to generate multiple concepts, our study revealed that, in some cases, they tended to ignore their robust foundations of early design concepts in developing their final solution. Rather than integrating multiple features of these diverse ideas, they tended to base their final solutions off of resilient concepts. What might this finding mean for design educators?

We suggest one possible explanation that can be explored in future research. First, it might be that fluency in generating design concepts is a separate skill from integrating features of these design concepts into a final solution. While students were able to develop a thorough foundation of ideas for their design projects, some tended to retreat to earlier patterns of fixation in developing final solutions—even if they had temporarily broken this fixation through *Design Heuristics* cards.

In future offerings of this course, informed by this investigation, the instruction team at this particular university will more carefully support students in how they *integrate* features of early design concepts. In the semester this study was conducted, the students only had received general instruction to develop a final design concept that was based on earlier design concepts. It would appear that these students would have benefited from guidance on *using* these early concepts after they had generated them.

As discussed earlier, prior research has suggested that fixation is overcome by strategies to generate multiple, diverse ideas. But informed by the findings of this small-scale study, we suggest that design instructors incorporate the *use* of early design concepts, not only generation of these concepts. In absence of this instruction, beginning designers might not fully understand how to leverage multiple concepts in order to develop a new solution, and patterns of fixation may simply be redirected to a few new ideas rather than the initial concepts.

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