A Case-Study Analysis of Design Heuristics in an Upper-Level Design Course

Abstract
This work reports on a case study in which we followed the design processes of eight student design teams enrolled in a semester-long upper-level design course involving a new ideation tool, "Design Heuristics." We observed how students formulated concepts and implemented ideas using the Design Heuristics tool in their ongoing projects. Our analysis revealed that all teams carried their heuristic-inspired concepts to their latter stage designs, with seven teams carrying their heuristic-inspired concepts to their final designs and prototypes. As all eight teams studied were working on different design problems, our findings demonstrate the utility and practicality of Design Heuristics across various design contexts. In addition, we found patterns in the design teams' general approaches to the design process, including synthesis, transformation, and abstraction. Seven of the eight teams showed some evidence of concept synthesis in their design processes, but often struggled in synthesizing multiple concepts together. Additionally, all teams seemed to directly transfer their ideas, concepts, or prototypes from one phase of the design process to another without abstraction (the use of a heuristic in an unanticipated way as a prompt to think of something new), while only three teams showed evidence of abstract transformation to develop their ideas across design process phases (such as from an early design phase to a later one). Our findings provide pedagogical recommendations for using the Design Heuristics tool in design classes and suggest opportunities for further research related to concept generation, development, and synthesis throughout the design process.

Introduction
Successful concept generation has been identified as the source of successful innovations[1,2], but engineering students often struggle to generate multiple and diverse ideas to fully explore the solution space[3,4]. This challenge is due, in part, to a lack of instruction on systematic approaches to idea generation and innovative thinking[5,6,7,8]. Instructors might encourage students to "brainstorm" to generate ideas[9], but may not know or provide their students with specific instructions about how to do so. This lack of formal idea generation instruction leaves students to their own devices, and therefore, novice designers often fail to employ specific design strategies as they initiate and develop concept ideas[4].

Existing research has uncovered two specific cognitive challenges associated with concept generation in engineering: (1) engineers form an early attachment to their initial ideas and stop considering alternatives[10]; and (2) engineers are unable to break away from known examples or solutions[11]. Ullman et al.[10] found that engineers tended not to explore multiple ideas and instead only pursued a single proposed design they quickly settled upon. Ball et al.[12] found that engineers tended to adhere to their original idea, even if this solution had serious flaws. The first cognitive difficulty, as identified above, has been termed "fixation," because the designer fixates on and persistently pursues an initial idea instead of spending time and effort searching for a better alternative[11]. The second cognitive difficulty is also a form of fixation – fixation on an existing example – and was highlighted in Jansson and Smith's[13] work where designers were shown an existing example of an unsatisfactory product and were made aware of its flaws. When they were asked to design an alternative solution, the designers frequently included elements of the provided example, along with the example's flaws. Therefore, these designers performed more poorly than the control group of designers who had not seen the initial example. This research shows that, without an intervention, designers are often blocked by their own initial ideas as well as any other existing ideas related to the design task. As a result, designers tend to stop short of generating a diverse set of novel concepts.

Several methods for concept generation have been published and used in design courses; however, only one has been systematically derived from engineering design and designers' processes and empirically validated in scientific studies—Design Heuristics. Design Heuristics were developed through analyses of innovative product designs and protocol studies with expert industrial designers and engineers[14,15,16,17]. Additional studies verified their success in guiding solution space exploration by both student and expert engineers, and industrial designers[18,19,20,21]. The 77 distinct Design Heuristics are packaged as easy-to-use prompts to guide the generation of new concepts. Each Design Heuristic can be used in multiple ways to initiate a new concept or to transform an existing concept. Design Heuristics provide specific strategies that can produce multiple, diverse, and creative concepts for any type of product design problem[22].

While Design Heuristics have been rigorously derived from and validated for individual ideation, their impact on student teams throughout a design process has not been researched. This paper presents a study of how eight student teams in an upper-level design course applied Design Heuristics throughout their design processes. We examine the relationship between Design Heuristic use in early design phases to student design team outcomes, and the applicability of Design Heuristics across different problem contexts. Our analysis also searched for patterns in the design teams' general approaches to the design process, including patterns of synthesis, transformation, and abstraction, and how these approaches affected concept development.

Design Heuristics

Design Heuristics are strategies to encourage a wide exploration of a variety of ideas during the ideation phase[15,16,23]. In psychology, a cognitive heuristic is a "rule of thumb" used to make a decision or judgment[24]. Cognitive heuristics do not necessarily lead to definite or explicit solutions; instead, they describe specific methods to make "best guesses" at potential solutions. Psychological research has shown that the efficient use of domain-specific heuristics distinguishes experts from novices; experts use cognitive heuristics constantly and effectively, while novices do not[25]. Applying the idea of cognitive heuristics within the domain of product design, research with designers and engineers resulted in a specific set of 77 "rules of thumb" for design, called Design Heuristics. The Design Heuristics have been empirically demonstrated as effective in helping designers generate possible conceptual solutions to address their design problems[19,20,26]. Design Heuristics can be applied multiple times during ideation and in various combinations to produce a wide range of novel concepts. They guide designers and engineers to generate non-obvious, distinct ideas, therefore producing a larger set of diverse ideas from which to choose[17]. A complete list of the empirically-derived Design Heuristics is shown in Figure 1 below.

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

Figure 1. The 77 Design Heuristics

To support their use in classroom and design settings, each Design Heuristic strategy was explained on a 4 x 6 paper card. On the front of the card, a descriptive title and action prompt provide specific instructions on how to use the heuristic to modify an existing idea or to build a new idea. An abstract image is included to depict the heuristic graphically. On the back of the card, two examples of existing products are shown: one from a variety of consumer products, and a second from a single type of consumer product (a seating device). The use of these two examples shows that each heuristic can be applied to both a wide range of products and to the same product category repeatedly. An example of a Design Heuristic card is shown below in Figure 2.

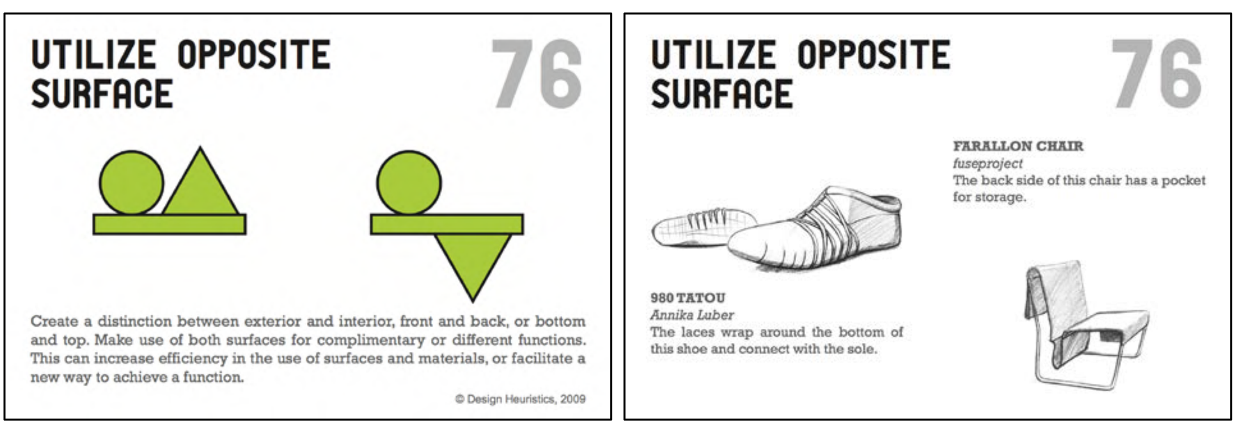

Figure 2. Heuristic Card Example: ***Utilize Opposite Surface***

Several studies were performed to assess the Design Heuristics cards for their effectiveness. The first of these studies introduced the Design Heuristics to first-year engineering students in an educational session[19,26]. After analyzing the concepts they generated for a given design task, the results showed that concepts guided by the Design Heuristics were more original than concepts that were not inspired by Design Heuristics. The concepts created without Design Heuristics were less developed and were often replications of known ideas, or minor changes to existing products. The concepts created using Design Heuristics resulted in more developed, creative designs. In another study, separate instructional sessions on Design Heuristic use were provided to two groups of first-year engineering students, teaching the Design Heuristics as (1) a concept generation technique and (2) a concept transformation technique[18]. The results showed that while both techniques yielded design improvements, the concepts created following the generative instructional session had higher variation. Design Heuristics in both techniques helped students elaborate their concepts, generate new ideas, and further develop previous ideas.

To validate the effect of Design Heuristics on non-engineering students, a study was conducted with sophomore industrial design students[20]. In this study, students were given a design task and a set of twelve Design Heuristics cards, and were asked to generate design concepts using the heuristics. The results indicated that Design Heuristics helped the students to generate diverse and highly creative concepts. Another study assessed the efficacy of Design Heuristics with professional engineering designers during a small group innovation workshop with professional engineers from a manufacturing company[21]. The designers successfully applied the heuristic cards to their existing products, and they reported that the cards stimulated novel thinking even though the designers had been working in the same design domain for many years. The results of these studies demonstrated that both engineering and design students (novices) and professionals can successfully learn to use the Design Heuristics within a short time period, and that their use supports creative and diverse ideation.

Research Methods

This study sought to extend the research on the impact of Design Heuristic use by investigating how student design teams used them throughout their design processes. This study was guided by the following research questions:

1. What evidence of Design Heuristics use during a heuristic-guided ideation session can be seen in later team designs?
2. How do Design Heuristics contribute to the practicality and overall quality of designs across different contexts?
3. What are the impacts of Design Heuristics on solutions generated by design teams?

Participants

Eleven student design teams enrolled in an upper-level design course at a large Midwestern university participated in the study. Three teams were excluded from this analysis: one team's final design was inaccessible to us, and two teams changed their design problem for unknown reasons mid-process, rendering their initial ideation irrelevant. The reason the student teams changed their design topics was not explored and is outside the scope of this study. The student design teams were cross-disciplinary, and composed of students from engineering, art and design, and design science disciplines. While over eighty percent of design team members were mechanical engineers, we still consider the teams to be cross-disciplinary due to the presence of non-mechanical engineers. Table 1 lists the academic discipline and student status of participants.

Table 1: Academic background of students enrolled in course

	Art and Design	Mechanical Engineering	Materials Science and Engineering	Electrical Engineering	Computer Science and Engineering	Design Science	Total
Undergraduate	3	22	0	0	0	0	25
Graduate	0	13	1	1	1	2	18
Total	3	35	1	1	1	2	**43**

The eight student project teams analyzed had between three and five members each. Each team chose their own project topic based on their interests. Table 2 shows the topic for each team.

Table 2: Description of project topics explored by design teams enrolled in course

Team	Topic
A	Automated two-part-cocktail mixer
B	Aerobic exercise device and mobility piece for children with Duchenne Muscular Dystrophy
C	Heel-actuated bass drum pedal
D	Shoulder wearable athletic gear
E	Integrated home entertainment system
F	Wind turbine for use in resource-limited settings
G	Computer mouse for people with hand- and upper-limb-disabilities
H	Ergonomic computer mouse

Data Collection

In the early part of the semester, students spent a class session learning and applying the Design Heuristics. They were then asked to use the cards in the preliminary concept generation phase of their design projects. In this concept generation session, students were first given time to ideate individually. They were then given time to ideate as a team while still using the Design Heuristics. We collected preliminary concepts from both the individual and team ideation portions of the session. Additionally, we collected their designs throughout the semester (with explanations and justifications for their decisions) in the form of reports. This data collection took place three times: (1) at the Proposal, (2) at the Progress Report, and (3) at the Final Report milestones of the course. Using the data collected during the initial ideation session and at these three stages, we created “timelines” detailing each team’s design process progression. For these timelines, we pulled out several specific pieces of information given in the teams’ reports:

1. Problem statement or abstract
2. Current design solutions
3. Concept generation after initial ideation session
4. Concept selection
5. Alpha prototype (version 1 prototype)
6. Beta prototype (version 2 prototype)
7. Final design or Beta+ prototype (improved Beta prototype)

Data Analysis

We analyzed the timelines for evidence of heuristic use and explored how heuristic-inspired ideas evolved throughout students' design processes. Specifically, we sought to uncover patterns in the degree of heuristic use, the synthesis of the concepts present at various phases in the design process, and the nature of transformation in moving from one design phase to another. When analyzing the nature of transformation, we defined "abstraction" as using a Design Heuristic not as anticipated, but instead as a prompt to think of something new. For example, a direct application of the heuristic *Add motion* would be to motorize a toy car so the car can be driven around, while an abstraction of the same heuristic would be to add graphics onto the toy car to give it the appearance of being in motion. While the prompt was about adding physical motion, the heuristic was used instead as a jumping off point to develop the concept in an unanticipated way.

Findings

During the initial ideation session using Design Heuristics, each individual generated an average of 3.7 concepts, and each team generated an average of 3.3 concepts. Most of the team-generated concepts were not the same as the individually generated concepts; each team generated 2.6 concepts during the team ideation session that were not the same as those generated during the individual ideation session. However, many of these individual and team concepts were not used in any further concept development. In our analyses presented here, we show only the concepts that were used in further concept development in order to demonstrate the process of transforming and changing concepts from the initial ideation to the final design stage.

Evidence of Design Heuristics throughout the design process

Our analysis revealed that all eight teams showed evidence of heuristic use in at least one of their concepts following the initial heuristic-driven ideation session. Of these, seven teams showed clear evidence of heuristic use in their final designs and prototypes.

For example, Team H demonstrated heuristic use throughout their design process (Figure 3). The team's goal was to develop a low cost ergonomic mouse. One team member generated Concept 1 during the initial heuristic-driven ideation session. He/she used *Allow user to reorient* to create a mouse that can be oriented into two stable states. The team then generated another heuristic-driven concept (Concept 2), which used the heuristics *Adjust function through movement* and *Twist* together. This concept used moveable buttons to shift between left, right, and middle positions to best meet the user's needs. The mouse could also change, or "twist," orientations. The team then synthesized their initial individual concept with the initial team concept into a new team concept (Concept 3) that maintained the functions and characteristics driven by the heuristics observed in the initial concepts. The team's alpha prototype (Concept 4) and beta prototype (Concept 5) were clearly motivated by this synthesized team concept (Concept 3). The final design (Concept 6) is a computer rendering of the design concept, and shows elements of *Adjust function through movement*, *Allow user to reorient*, and *Twist* in the same form as they appeared in the previous concepts and prototypes. This final concept was a computer mouse that is stable when oriented either an angle of 45 or 135 degrees, illustrating evidence of three unique Design Heuristics.

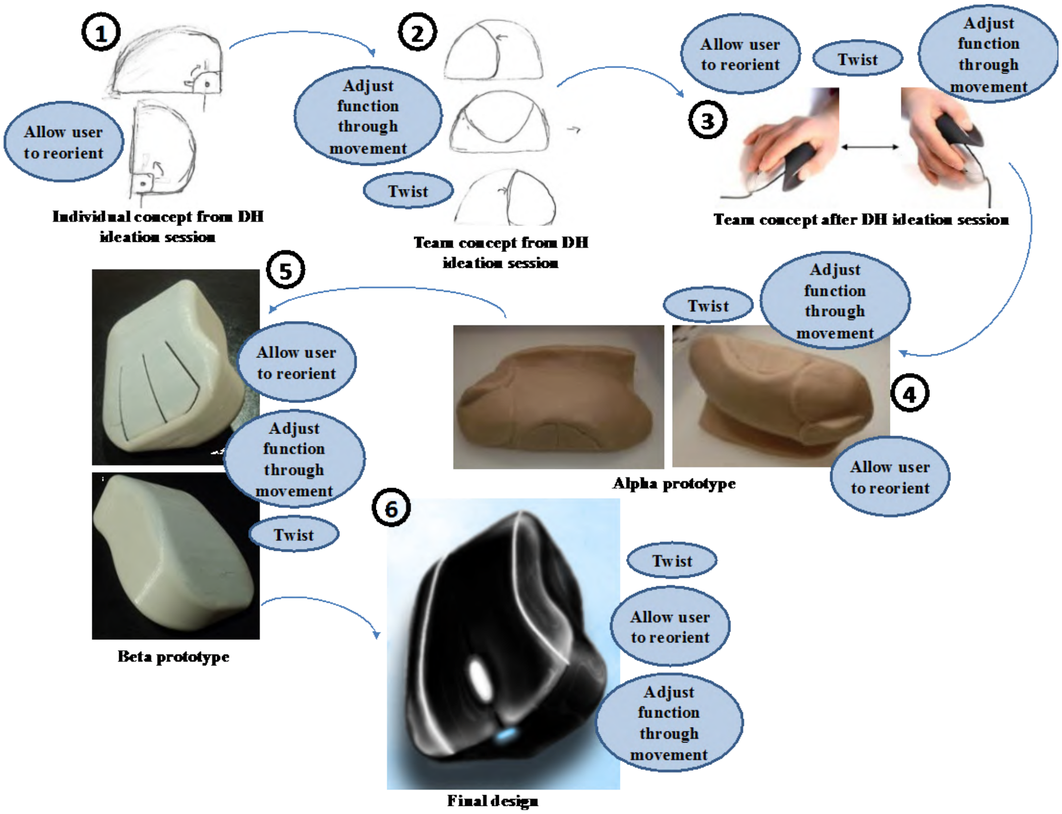

Figure 3: Team H design process

Team C approached the use of Design Heuristics differently (Figure 4). We observed heuristic use in their intermediate designs, but not in their final solutions. Team C's task was to design a heel-actuated bass drum pedal. One of the concepts generated during the initial individual ideation session (Concept 1a) inspired one of the team's initial concepts (Concept 2), which in turn inspired another team concept generated after the heuristic-driven session (Concept 3a). All three concepts used the *Adjust function through movement* heuristic, as demonstrated by the folding nature of the drum pedal. The team's final design (Concept 6) was traced to a different individual concept (Concept 1b), and did not show evidence of heuristic use. Following the initial ideation session, the team generated a concept (Concept 3b) based on Concept 1b. The alpha and beta prototypes (Concepts 4 and 5) were iterations of this concept, leading to the final design (Concept 6). Unlike Concepts 1a, 2, and 3, Concepts 1b, 3b, 4, 5, and 6 did not include a folding element, which would have allowed the drum pedal to serve as both toe-actuated and heel-actuated. While the team did not share their reasons for choosing 1b over 1a, they may have been motivated by the relative mechanical simplicity offered with Concepts 1b.

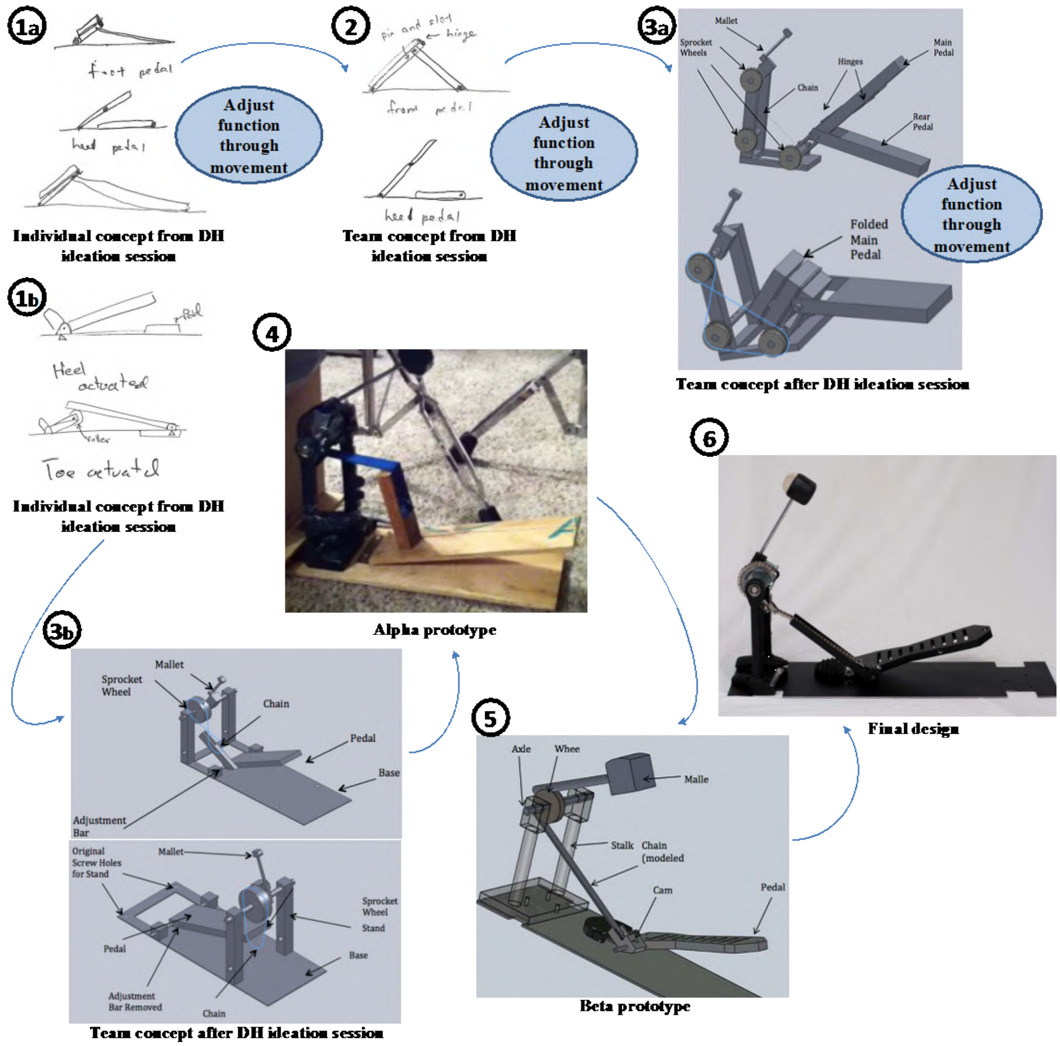

Figure 4: Team C design process

Design process approaches: Synthesis, direct transfer, and abstract transformation

When analyzing the general design processes of the design teams, we discovered three specific patterns in concept development: synthesis, direct transfer, and abstract transformation. Synthesis refers to the combination of several elements of different concepts into a new concept. Direct transfer refers to the transition of ideas, concepts, or prototypes from one phase of the design process without abstraction directly to another phase. Abstract transformation, or abstraction, refers to the non-straightforward development of ideas, concepts, or prototypes from an early design phase to a later one. Abstract transformation occurred when a team or team member used a Design Heuristic in an unanticipated way to prompt a new idea.

Seven of the eight teams were found to synthesize their concepts during the design process. They combined characteristics of multiple concepts together to form a new concept. All eight teams directly transferred their ideas, concepts, or prototypes from one phase of the design process to another without any abstraction. Only three teams showed evidence of abstract transformation when moving their ideas, concepts, or prototypes from one phase to another.

For example, Team F synthesized and directly transferred their concepts throughout their design process (Figure 5). Their task was to design a low-cost wind turbine, specifically for use in resource-constrained settings. One of the initial individual concepts (Concept 1a) generated during the heuristic-driven ideation session used *Apply existing mechanism in a new way* by analogizing the new concept of a wind turbine to an ancient Greek water-pumping wheel. This individually generated concept inspired one of the team concepts (Concept 2) that applied the same heuristic with minor changes to create a wind turbine with four triangular blades. The alpha prototype (Concept 3) was clearly based on Concept 2, as it keeps the same form and function. Concept 3 used fabric and supports to create a four-bladed turbine reminiscent of a Greek water-pumping wheel. The beta prototype (Concept 4) included a functional electrical circuit and an integrated motor for electricity generated, but otherwise kept the same elements as the alpha prototype. The final design (Concept 5) synthesized the beta prototype with a previous individual concept generated using the heuristic *Animate* (Concept 1b). The final design was “animated” by the integration of the team’s logo into the turbine blades, therefore creating an abstraction of the “waving billboard” originally developed during the individual ideation session.

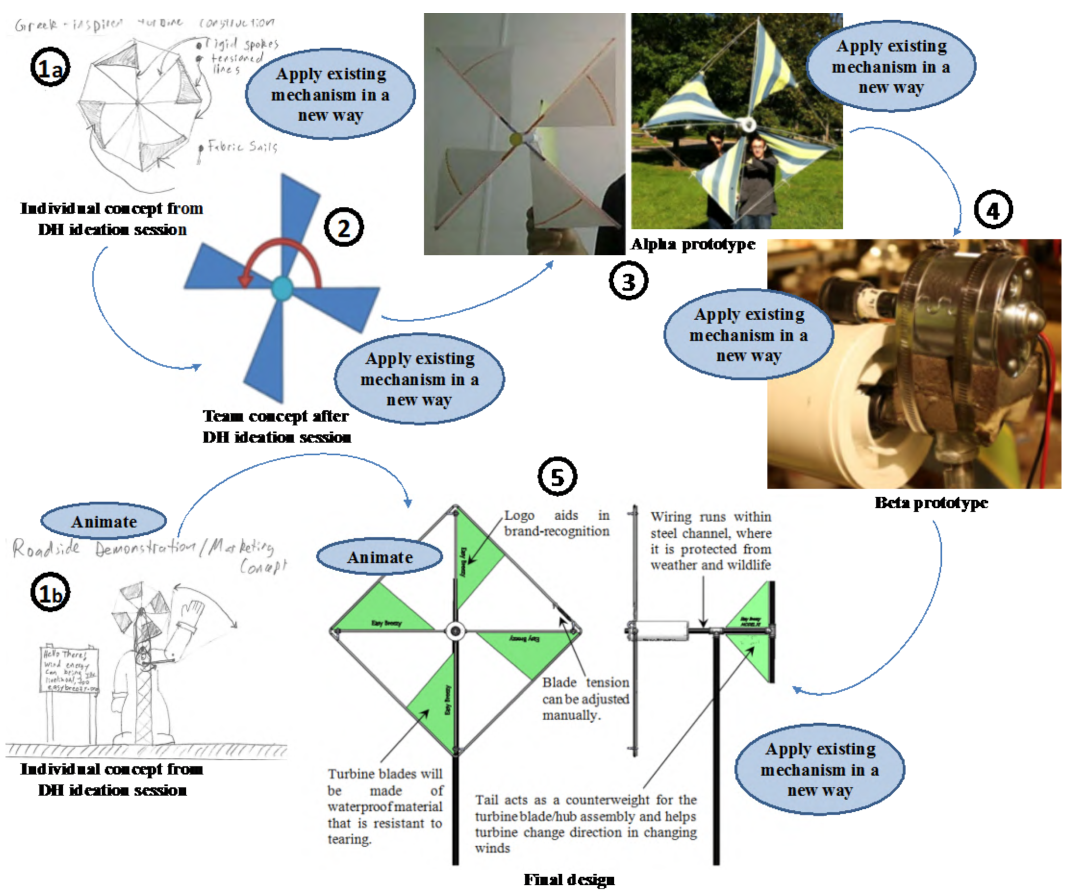

Figure 5: Team F design process

In contrast to Team F, Team D did not synthesize concepts in their design process, and instead demonstrated only direct transfer of concepts with small variations across stages of design (Figure 6). The team’s goal was to design shoulder-wearable athletic gear to serve the purpose of both a performance-enhancing compression shirt and a backpack for runners. The team used *Unify* in all of their concepts, beginning with an individual concept generated during the heuristic-driven ideation session (Concept 1). The shoulder pack concept was "unified" with the runner's body. This initial concept was then minimally altered, and was carried into the team's initial concept (Concept 2), the team's concept generated following the initial ideation session (Concept 3), the alpha prototype (Concept 4), the beta prototype (Concept 5), and the final design (Concept 6).

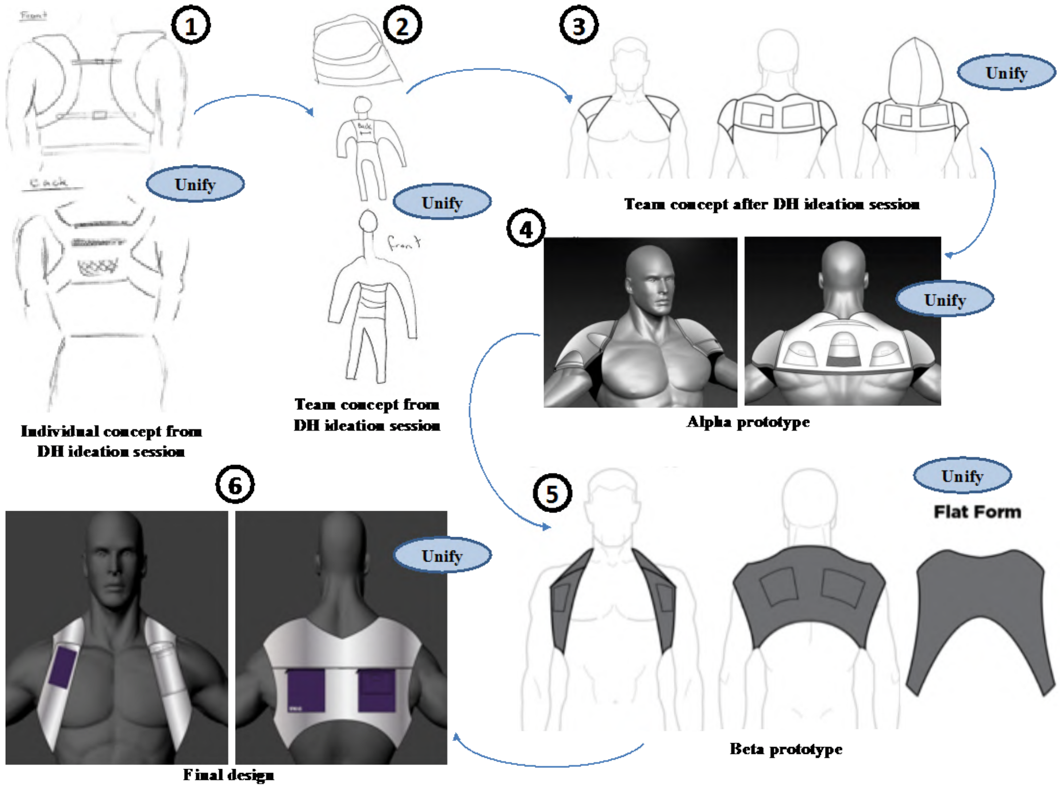

Figure 6: Team D design process

Team B, whose goal was to design an aerobic exercise device for children with Duchenne Muscular Dystrophy (DMD), demonstrated synthesis, direct transfer, and abstract transformation in their design process (Figure 7). The team members used heuristics in their initial individual concept generation phase. One of these individual concepts (Concept 1a) used *Animate* to develop an "approachable and recognizable" look for the device. The second individual concept (Concept 1b) used *Change surface properties* to integrate soft material into the device as a cover. Neither of these individually generated concepts was used in the development of the alpha prototype (Concept 2) or the beta prototype (Concept 3). The beta+ prototype (Concept 4) synthesized the wooden scooter shape of the beta prototype with Concepts 1a and 1b. The first of these synthesized concepts (Concept 1a) – an abstraction of *Animate* – was synthesized into the beta+ prototype by transforming the original idea of creating a device in the shape of something approachable and recognizable, and instead created a device with *images* of something approachable and recognizable – in this case, Mickey Mouse. The second of these synthesized concepts (Concept 1b) – which used *Change surface properties* – included a soft cover on the face of the device to increase the user's comfort.

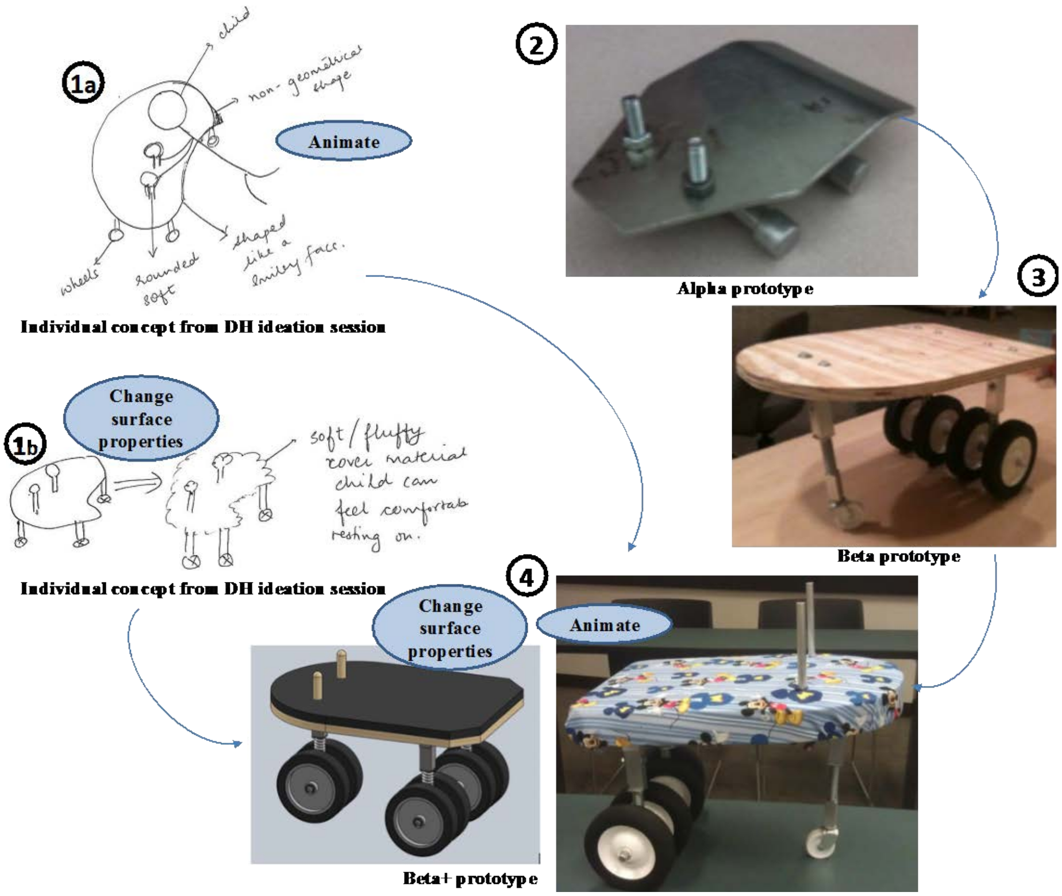

Figure 7: Team B design process

Summary of Findings

Our analysis of the design teams' processes highlighted the use of Design Heuristics as a tool to aid in concept development. All but one of the design teams displayed evidence of heuristics in their final designs based on an initial heuristic-driven ideation session. The one design team (Team C) that did not display evidence of heuristics in their final design demonstrated heuristic use in their intermediate designs. The teams took a variety of paths to end up at their final designs, but seven of the eight teams still incorporated heuristics into the final stage of their design processes. Tables 3 and 4 summarize the evidence of each team's design process patterns.

Table 3: Evidence of heuristic-driven synthesis in team's design processes

Team	Heuristic-Driven Initial Concept *Synthesis into Team Concepts*	Heuristic-Driven Initial Concept *Synthesis into Later Stages*
A	Yes	Yes
B	No	Yes
C	No	Yes
D	No	No
E	No	Yes
F	No	Yes
G	Yes	No
H	Yes	Yes

Table 4: Evidence of heuristic-driven direct transfer and abstract transformation in team's design processes

Team	Heuristic-Driven Initial Concept *Direct Transfer*	Heuristic-Driven Initial Concept *Abstract Transformation*
A	Yes	No
B	Yes	Yes
C	Yes	No
D	Yes	No
E	No	Yes
F	Yes	No
G	Yes	No
H	Yes	Yes

This summary supports the conclusion that the Design Heuristics introduced in the initial ideation stage had a continuing influence in the design process over time.

Discussion

The analysis of eight cross-disciplinary design teams in our study revealed differing patterns in individual and team ideation with Design Heuristics. The majority of team-generated concepts were not the same as the individual concepts, which means that most of the teams did not simply reuse their individually generated concepts: they worked with the Design Heuristics tool as a group to develop new and different concepts. The teams took several different approaches to the team ideation portion of the Design Heuristics session: some teams distilled or synthesized their individual concepts into new concepts, while other teams came up with completely new and seemingly unrelated concepts. Each team then considered both the individual and team generated initial concepts as they moved forward in their design processes.

Evidence of heuristic-driven concepts in all phases of design provides confirmation that heuristics support practical design outcomes. The teams built several prototypes of their concepts, and each prototype maintained the concept functions and features prompted by the heuristics. This finding is especially important because students tend to struggle to take a creative idea to a final product. Thus, the Design Heuristics not only support creativity[14], but also support practical and useful design outcomes.

Because all eight teams studied were working on different design problems they chose themselves, the findings also support the claim that heuristics are applicable in a variety of design contexts. While not every team integrated the Design Heuristics into their final concepts, all of the teams successfully used heuristics in the initial ideation session and in at least one additional design stage. This demonstrates the broad applicability of the Design Heuristics for product design.

Seven teams showed evidence of synthesis in their design processes. This synthesis, however, was very straightforward and was a simple "sum of the parts" solution, keeping the essence of their original heuristic-driven concepts the same. Student teams may benefit from training on how to effectively synthesize by composing a solution based on several sub-concepts. The final concept may then be more creative and more successful than the simple sum of the individual sub-concepts. Synthesis of concepts could provide an opportunity for designers and design teams to revisit their original concepts or their original conception of the Design Heuristics. All eight teams displayed evidence of direct transfer of their concepts through the steps in their process, whereas only three teams transformed their concepts during these steps. Because direct transfer does not alter ideas, it does not, by nature, allow for additional explorations. Transformation, on the other hand, requires further abstraction of the original idea. Therefore, transformation may result in the exploration of more creative and successful outcomes.

The prevalence of direct transfer in this study suggests that student design teams may prefer design processes that are less advantageous to their design outcomes. Teams who showed evidence of transformation, however, revisited their original ideas of what each Design Heuristic card meant, and recast it to have a novel meaning within their concepts. This may have allowed for increased variation and introduction of novel ideas further into the design process. We believe that if design teams were to employ, in particular, more synthesis and transformation of ideas, their outcomes would be more creative and successful.

The findings of this study complement the validation studies of Design Heuristics[18,19,20,21]. Design Heuristics have been previously evaluated for efficacy and effectiveness when used by individuals. This study demonstrated the effectiveness of Design Heuristics as a tool for cross-disciplinary design teams to use in the development of a final design deliverable.

This work contributes to our understanding of idea development throughout a semester-long design project. Many ideation studies focus on immediate success in ideation[11,19,27,28], but there is a need to understand what happens after this early ideation phase. Novices tend to complete design phases only once in a linear order, while more informed designers tend to improve and iterate on ideas, often making changes and shifts in ideas multiple times through feedback, prototype building, and various levels of testing[29]. This study demonstrated that student design teams tended to move linearly through their design processes without synthesizing or integrating ideas from earlier phases. Only two of the teams (Team B and Team F) iterated back and forth between design concepts developed at different design process stages. This is consistent with studies on design fixation[13]. The value of synthesis in idea development is supported by Goldschmidt and Tatsa's[30] work showing the largest number of "links," or the most synthesis, resulted in the most successful and creative outcomes.

Several implications arise from this study. One pedagogical suggestion is to encourage design teams to use Design Heuristics at the beginning of their design processes, and at several other points throughout their concept development process. Design Heuristics can result in more novel and diverse design outcomes[18,19,20,26,31,32] and, therefore, encouraging design teams to use Design Heuristics in their initial ideation process and throughout their idea refinement can support the quality of the final design outcome. Instructors may support this by encouraging design teams to revisit the Design Heuristics cards after their initial ideation process.

Students seemed to struggle to make larger transformations during concept development, and often carried their initial designs through their entire design process. We hypothesize that if students were to have the opportunity to use the Design Heuristics at least one more time during the design process, their designs might be more apt to evolve, and the Design Heuristics could reveal to them some further opportunities for iteration. Finally, as fixation has shown to be a challenge for designers[17], Design Heuristics can be used to combat fixation on existing products or first ideas by promoting the generation of multiple, diverse concepts throughout the design process.

Limitations and Future Work

This paper presents a qualitative analysis of eight student teams in an upper-level design course working on different design projects. The goal of qualitative work is transferability to similar settings and therefore our study was not designed to provide generalized findings across the board, but to understand the ways Design Heuristics were used and carried through the design processes of upper-level student design teams. The analysis presented does not consider how the relative success of each team was influenced by the use, or failure to use, of Design Heuristics. We also did not consider what effect the Design Heuristics instructional protocol had on each student's choice to use Design Heuristics instead of brainstorming their own ideas.

In sum, this study exposed a gap in the current understanding of how design teams work together to synthesize, transform, and develop their initial concepts as they move through the design process. Remaining questions include:

- What approaches do teams use to develop their initial concepts using Design Heuristics?
- Which of these approaches, if any, result in more practical and creative design outcomes?
- Is there a protocol that can be created to train teams to work successfully with Design Heuristics?
- In which stage of the design process are Design Heuristics the most useful? When do they lead to more creative, practical, useful solutions?
- How can we improve the integration and implementation of Design Heuristics into design courses?

Future work may allow for the exploration of these questions.

Conclusions

This study contributed to our understanding of how cross-disciplinary design teams build on concepts developed during an initial ideation session using the Design Heuristics tool. Study outcomes revealed that Design Heuristics support practical ideation, where ideas developed initially were often incorporated into the final design prototypes. Additionally, heuristics proved useful across multiple and diverse problem contexts. Finally, it was apparent that student teams tended to favor straightforward approaches to the design process. The teams tended to synthesize and transfer their concepts from one design process phase to another in a straightforward manner instead of employing abstraction. Students may benefit from building skills to successfully iterate on their ideas and to bring multiple ideas together. Design Heuristics can be a successful strategy to support design teams in creating successful design outcomes, and further work is needed to explore how Design Heuristics can best be used in design processes.

References

[1] Brophy, D.R. (2001). Comparing the attributes, activities, and performance of divergent, convergent, and combination thinkers. *Creativity Research Journal*, 13(3&4): p. 439-455.

[2] Liu, Y.C., Bligh, T., & Chakrabarti, A. (2003). Towards an 'ideal' approach for concept generation. *Design Studies*, 24(4): p. 341-355. 1323251

[3] Cross, N. (2001). Design cognition: Results from protocol and other empirical studies of design activity. *Design knowing and learning: Cognition in design education*, *7*, 9-103.

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

[5] Grasso, D., Burkins, M. B., Helble, J. J., & Martinelli, D. (2008). Dispelling the myths of holistic engineering. *PE Magazine*.

[6] Klukken, P. G., Parsons, J. R., & Columbus, P. J. (1997). The creative experience in engineering practice: Implications for engineering education. *Journal of Engineering Education*, *86*(2), 133-138.

[7] Pappas, J., & Pappas, E. (2003). Creative thinking, creative problem-solving, and inventive design in the engineering curriculum: A review. In *Proceedings of the 2003 American Society for Engineering Education Annual Conference*.

[8] Richards, L. G. (1998). Stimulating creativity: teaching engineers to be innovators. In *Frontiers in Education Conference, 1998. FIE'98. 28th Annual* (Vol. 3, pp. 1034-1039). IEEE.

[9] Osborn, A. (1957). Applied imagination: Principles and procedures of creative problem-solving, NY: Scribner.

[10] Ullman, D. G., Dietterich, T. G., & Stauffer, L. A. (1988). A model of the mechanical design process based on empirical data. *Artificial Intelligence in Engineering Design and Manufacturing*, *2*(1), 33-52.

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

[12] Ball, L. J., Evans, J. S. B., & Dennis, I. (1994). Cognitive processes in engineering design: A longitudinal study. *Ergonomics*, *37*(11), 1753-1786.

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

[14] 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.

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

[16] Yilmaz, S. & Seifert, C.M. (2010). Cognitive heuristics in design ideation. in *International Design Conference*. Cavtat, Croatia.

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

[18] 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, in *Annual Conference of American Society of Engineering Education*. San Antonio, Texas.

[19] 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.

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

[21] Yilmaz, S., Daly, S., 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*, 1-15.

[22] Daly, S., Yilmaz, S., Seifert, C., & Gonzalez, R. (2010). Cognitive Heuristics Use in Engineering Design Ideation. In *American Society for Engineering Education*. American Society for Engineering Education.

[23] Yilmaz, S., & Seifert, C. M. (2009). Cognitive heuristics employed by design experts: A case study. In *Proceedings of the 4th International Conference of International Association of Society of Design Research (IASDR '09)*. Seoul, Korea.

[24] Nisbett, R. E., & Ross, L. (1980). *Human inference: Strategies and shortcomings of social judgment*. Englewood Cliffs, NJ: Prentice-Hall.

[25] Klein, G. A. (1998). *Sources of power: How people make decisions*. MIT press.

[26] Daly, S. R., Christian, J. L., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2011). Teaching design ideation. In *American Society for Engineering Education*. American Society for Engineering Education.

[27] Genco, N., Hölttä-Otto, K., & Seepersad, C. C. (2012). An experimental investigation of the innovation capabilities of undergraduate engineering students. *Journal of Engineering Education*, 101(1), 60-81.

[28] Benami, O., & Jin, Y. (2002). Creative stimulation in conceptual design. *Proceedings of ASME DETC/CIE, Montreal, QC, Canada, DETC2002/DTM-34023*, 2(1).

[29] Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, 101(4), 738-797.

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

[31] Yilmaz, S., J.L. Christian, S.R. Daly, C.M. Seifert, and R. Gonzalez. Idea generation in collaborative settings using design heuristics. in *International Conference on Engineering Design (ICED)*. 2011. Copenhagen, Denmark.

[32] Design Heuristics: Strategies to Inspire Ideas. (2014). *Design Heuristics, LLC*. Retrieved November 14, 2013, from www.designheuristics.com.