Teaching Design Ideation

Abstract

We developed a set of teachable design ideation strategies to support diversity in concept generation. These strategies, called “Design Heuristics,” are intended to facilitate the discovery of diverse concept ideas in the design of products. Design Heuristics were extracted from the work of students and professionals from engineering and industrial design. When applied to a new design problem, Design Heuristics serve as cognitive "shortcuts" for exploring the space of possible design solutions. In this study, we provided an educational session about Design Heuristics to 48 students in an introductory engineering course, and analyzed the design concepts they generated for a specific design task. The results showed that concepts guided by the Design Heuristics were more original than concepts that did not include their application. In a short intervention, some students were able to make use of the heuristics, and to generate original concepts. The findings demonstrate that Design Heuristics facilitate exploration of the design space beyond the “obvious” solutions.

Key Words: concept generation, design education, Design Heuristics

Introduction

A continuous challenge for engineering students is to generate innovative designs. Innovative outcomes can often be traced to success in idea generation, where diversity in the set of concepts considered provides multiple pathways to evaluate and pursue. More, and more varied, ideas increase the potential for a more successful outcome of the design process. However, engineering students often struggle to generate multiple ideas[1,2], and become attached to their first ideas, even when they realize those ideas have serious flaws or challenges[3,4,5]. Even students who are able suggest creative ideas have not learned specific strategies that would help them to explore the larger space of potential designs. This limits their ability to transform their initial creative solution into something potentially more successful, or to suggest more creative solutions.

For engineering educators, this presents an ongoing challenge: How can we teach creativity and innovation in engineering design courses? Defining innovation skills, and measuring the successful application of innovation skills, is challenging and complex[6]. As a result, this skill development is often left to the students by providing opportunities in courses (e.g., an open-ended project) rather than providing explicit instruction on creative processes or approaches[7,8]. While adequate time to practice and learn by experience is necessary, more explicit instruction on creative processes could help students develop stronger innovative design strategies.

One solution for these challenges is to provide students with a guide for concept generation. Many suggested procedures and tools exist[9]; however, many of them lack rigorous empirical research in their development and validation. The present study employed strategies in the

Design Heuristics approach that are grounded in research with advanced engineering designers and practitioners[10,11,12,13]. This study attempted to validate the use of Design Heuristics by novice (first year) engineering students to facilitate more successful concept generation.

Background

"Ideation," or idea generation, happens in many different ways. Sometimes, ideas come from previous experiences or examples of similar products. However these ideas may seem unoriginal because they are based on existing concepts[14,15,16]. Sometimes, new ideas form from analogies to existing products, nature, or abstract words or shapes[17,18,19,20,21]. An analogical approach facilitates less replication of existing artifacts and can limit fixation, however, products may still have abstract links to the idea source. Finke et al.[22] identifies two different ways that ideas are formed: *generative* (analogical transfer, association, retrieval, and synthesis) and *exploratory* (contextual shifting, functional inference, and hypothesis testing).

During the initial ideation phase, the likelihood of an innovative outcome increases when designers consider more, and more different possibilities. This is because generating multiple possible concepts or solutions increases the possibilities to consider during concept evaluation and selection, and thus a product that best meet the problem constraints[23]. Diverse idea generation is defined as visiting all feasible solutions in the "design space" (following Newell and Simon's[24] "problem space"). Some ideas in the design space are easy to find because they already exist, or involve simple combinations of known features or elements. But many ideas are difficult to generate because they are not obvious. Diverse idea generation provides multiple potential solution paths, and so may be the foundation for a successful outcome.

However, many designers, especially novices, find it challenging to think divergently, and to generate alternative ideas. Novice designers often face the challenges of successfully exploring the design space as well as creating original ideas[23]. They often replicate existing products or ideas with minor tweaks, but the product remains essentially the same. They may be trapped by the characteristics of an example solution or existing precedents[14,15,16]. Novice designers often "fixate" on their first ideas[3,4,5]. This limits exploration of the design space, and reduces the opportunity to consider other alternatives. Novice designers' attachment to initial ideas means that, since most are not successful, they are likely to fail. For many reasons, they do not want to, cannot see the need to, or are not able to consider other possibilities.

Existing Tools

Design experts often use transformations of their naturally-occurring ideas to develop novel solution concepts[10,11,12,13]. Thus, a variety of idea generation tools varying in their focus and specificity have been proposed to help explore design spaces. A sample of these tools include those that aim to: (1) facilitate the flow of ideas (e.g. brainstorming[25] and brainwriting[26]), (2) stimulate the formation of an initial idea, (e.g. analogical thinking[19,27], morphological analysis[28,29], and Synectics[30]), and (3) transform ideas into more or better ideas (e.g. lateral thinking[22], SCAMPER[31], TRIZ[32]). Other tools packaged for ideation include IDEO™ Method Cards[33], intended to help understand the target user, and "Whack Pack" cards[34], designed to transform habitual patterns by providing new information, techniques, and decision-making advice.

Some of these idea generation techniques lack specific strategies and actions that students can use to generate ideas. For example, while brainstorming includes guidelines such as, “suggest many ideas,” “do not evaluate ideas,” and “build off of others’ ideas,” it does not provide students with specifics for *developing* ideas[25]. SCAMPER[31] offers more specific information about how to transform ideas, but its set of general guidelines (e.g., "combine") may be difficult to apply to specific design problems. TRIZ[31] provides guidelines based on successful patents., however, its more specific strategies address refinements in mechanisms and design tradeoffs that occur later in the design process (the implementation phase). Some of these methods also require extensive training and practice (e.g. Synectics[30], TRIZ[32], and SIT[35], a modified TRIZ approach). Most importantly, these tools are not empirically driven, nor have they been tested for their impact on the success of ideation.

Design Heuristics

Design Heuristics have been proposed as a new method for generating novel ideas[10,11,12,13]. These heuristics are intended to capture patterns used in the design of products to introduce variation into a set of concepts. In psychology, a heuristic is defined as a simple, efficient rule used to generate a judgment or decision, especially for complex problems[36]. Behavioral research shows that experts use heuristics very effectively, and their efficient use of domain-specific heuristics distinguishes them from novices[37]. An important feature of all heuristics is that they are not guaranteed to lead to a determinate solution; rather, they lead to "best guesses," resulting in varied and creative solutions[38]. Rather than leading to a single solution, Design Heuristics are intended to be applied repeatedly, and together, to vary concepts and produce novelty and originality in designs.

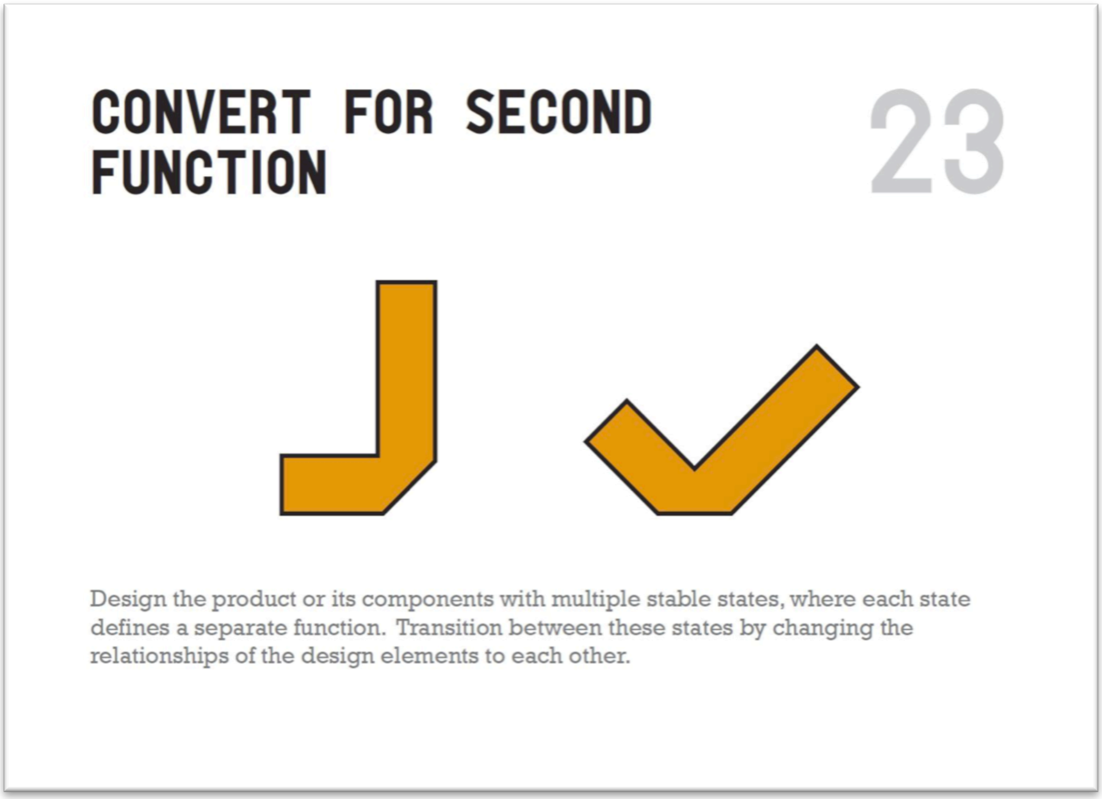
In previous studies, protocols from expert designers and award-winning products were examined to identify potential heuristics[10,11,12,13]. This research aimed to isolate design-related heuristics evident in behavioral patterns of advanced and expert designers. In one previous study, constant application of heuristic combinations was observed within an expert designer’s ideation process[10]. The study analyzed over fifty designs by a professional who was designing a shared structural unit for a universal access bathroom. In this set of quite varied designs, several specific heuristics were observed occurring together repeatedly. In a study of award-winning products, we identified transformations from existing products that resulted in creative product outcomes[11].

In another set of studies, we used a think-aloud protocol technique to explore how both student and expert designers generated and transformed concepts during an idea generation session[12,13]. With no instruction on heuristics, we studied how the designers naturally created concept sets and transformed ideas[10,11,12]. The protocols were coded for the presence of heuristics in the concepts. We found evidence for the use of 60 different Design Heuristics in concepts created for a single design problem. The rich variety and diverse solutions generated by these novices and experts testify to the potential for the use of Design Heuristics to create varied concepts.
This leads to the question of whether Design Heuristics can function as a viable tool to help designers generate varied concepts. Incorporating Design Heuristics into engineering education would help students in applying specific action prompts directly to their ideas. Practice with the use of heuristics may facilitate the generation of diverse ideas, and increase the possibility of an innovative solution. If successful, the incorporation of Design Heuristics into engineering education could fill an existing need for innovation in design.

Design Heuristics in Education

After analysis of these prior studies, we identified a merged collection of Design Heuristics totaling 77 separate strategies. We produced descriptions of the heuristics as action prompts that would suggest a specific strategy to use in idea generation. In addition, we created an abstract image to represent the strategy and selected two product examples that showed the application of each heuristic to an existing consumer product. We selected the first product example from a variety of different products, but the second example was always from the domain of chairs or seating to provide consistent applications across the set of heuristics.

This information was presented on a separate card for each design heuristic. The front of the card included the heuristic description and the abstract depiction, and the back displayed the two product examples of its use. Each card also showed a number (of the 77) and a descriptive title on both sides. Sample cards are shown in Figure 1 and Figure 2.



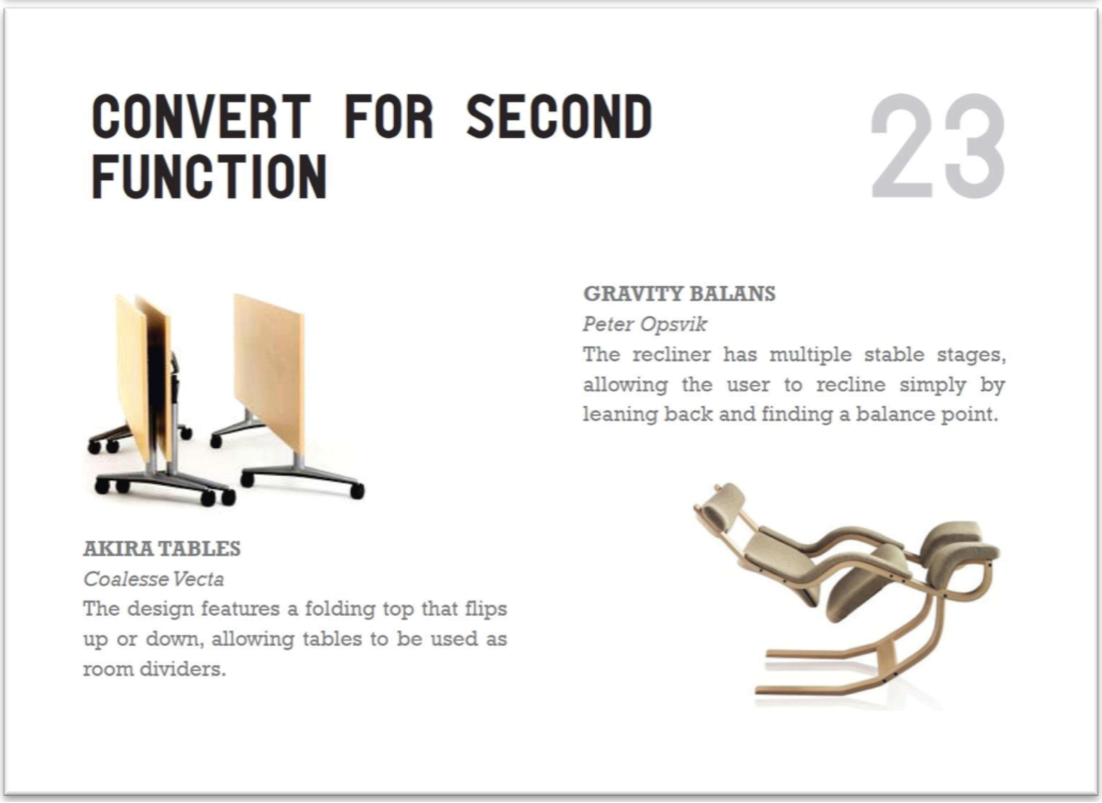
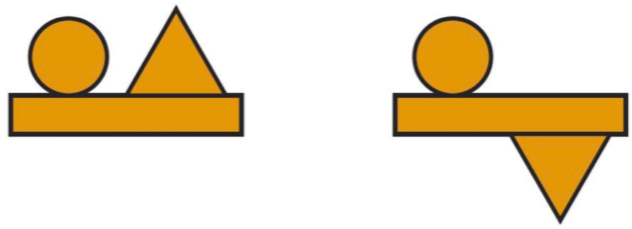


Figure 1. Heuristic Card Example: Convert for second function
Images: http://www.coalesse.com/products/223/4/Training/Akira, http://opsvik.no/index.asp

UTILIZE OPPOSITE SURFACE

77



Create a distinction between exterior and interior, front and back, or bottom and top. Make use of both surfaces for complimentary or different functions.

UTILIZE OPPOSITE SURFACE

77

980 TATOU

Annika Luber

With the laces extending towards the bottom, these shoes allow for better mobility and respond to unique movements.

FARALLON CHAIR

fuseproject

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

Figure 2. Heuristic Card Example: Utilize opposite surface

Images: www.idsa.org/content/content1/980-tatou-sport-shoe-le-parkour, http://www.fuseproject.com/category-3-product-19

Our premise is that the application of a heuristic provides a specific way to generate new ideas from scratch or transform existing ideas into new solutions. Each card provides a starting point for prompting the generation of a new concept, or transforming an existing concept. A single design heuristic can produce a wide variety of designs depending on how it is interpreted and applied within a problem.

Research Methods

This research sought to understand how the use of the Design Heuristics cards by novice engineering designers affected the outcomes of idea generation. In this study, we explored the ways that students used a sample set of the cards to generate design concepts. Our work was guided by the following research questions:

- How do novice designers apply the heuristics to idea generation?
- What impact does the application of heuristics have on proposed concept solutions?

Participants

One section of a large Introduction to Engineering course at a large midwestern university participated in the study. This semester-long course provides first-year students with an introduction to topics such as computer coding, Microsoft Excel, communication skills, and teamwork. They are given a guided design opportunity, in which they work on a team project while learning the stages of design. The class was selected because it included novice (first-year) engineering students in their first term. Forty-eight students (ages 17-19) participated in the study during one class session in the course. Thirty-nine students were male, nine were female.

Data Collection

Data collection took place approximately one third of the way in to the semester-long course. The students participated in an 80-minute class session on "concept generation." Prior to this session, students had not received any introduction to the topic. The session included 20 minutes of verbal instruction about Design Heuristics, followed by a 25-minute idea generation session for a specific design task and a 20-minute period in which we asked students to complete a worksheet describing the concepts they generated and their perceptions of their performance on the task. They then participated in a 15-minute discussion about how they could apply the heuristics on the cards to the design project for the course, which they would start in the following class period.

The verbal instruction at the beginning of the session focused on the structure of the Heuristic Cards, and how they could be applied to design problems. Three cards were provided as examples (*Bend, Synthesize functions*, and *Use packaging as a functional component*). First, we explained the details on the first card, with the two examples shown on the back of the card. For the second and third cards, we showed students the front side description first, and had them generate a concept by talking with another student for how they could apply the heuristic on the card to a traditional chair. This method helped students learn to generate a new concept using the heuristic; then, they could examine the example chair on the back of the card to see an alternative solution using the same heuristic. The purpose of this comparison was two-fold: first, to help guide students in the right direction if they did not understand how to apply the heuristic, and second, to show the students that there are multiple ways to apply the same heuristic. We encouraged the students to share their ideas with the class, and reinforced the notion that there are multiple good ideas in initial idea generation.

After this short introduction, each student received a set of 12 Heuristic Cards selected at random from the set of 77. The three sample cards used in the introduction were not included in the cards given to each student. The titles of each of the 77 Heuristic Cards are included in Figure 3.

Add features from nature
Add gradations
Add motion
Add to existing product
Adjust function through movement
Adjust functions for specific users
Align components around center
Allow user to assemble
Allow user to customize
Allow user to reconfigure
Animate
Apply existing mechanism in new way
Attach independent functional components
Attach product to user
Bend
Build user community
Change contact surface
Change direction of access
Change flexibility
Change geometry
Compartmentalize
Convert 2-D to 3-D
Convert for second function
Cover or remove joints
Cover or wrap
Create system
Distinguish functions visually
Divide continuous surface
Elevate or lower
Expand or collapse
Expose interior
Extend surface
Extrude
Flatten
Fold
Hollow out
Impose hierarchy on functions
Incorporate environment
Incorporate user input
Layer
Make component multifunctional
Make components attachable or detachable
Make product reusable or recyclable
Merge functions with same energy source
Merge surfaces
Mirror or Array
Nest
Offer optional components
Provide sensory feedback
Reconfigure
Recycle to manufacturer
Reduce material
Reorient
Repeat
Repurpose packaging
Reverse direction or change angle
Roll
Rotate
Scale up or down
Separate parts
Slide components
Stack
Substitute
Synthesize functions
Telescope
Texturize
Twist
Unify
Use alternative energy source
Use common base to hold components
Use continuous material
Use human-generated power
Use multiple components for one function
Use packaging as functional component
Use recycled or recyclable materials
Utilize inner space
Utilize opposite surface

Figure 3. Descriptive Titles for the 77 Heuristic Cards

Next, the students individually generated ideas for the given design task. The design problem was read aloud to students as they read along on a worksheet, and then they had 25 minutes to generate solution concepts. The design problem was stated as follows:

> Sunlight can be a practical source of alternative energy for everyday jobs, such as cooking. Simple reflection and absorption of sunlight can generate adequate heat for this purpose. Your challenge is to develop products that utilize sunlight for heating and cooking food. The products should be portable and made of inexpensive materials. It should be able to be used by individual families, and should be practical for adults to set up in a sunny spot.

> Note: Specific materials for a targeted temperature can be postponed to a later stage. Do not worry about the specific quantity of heat that can be generated. Please focus on conceptual designs.
>
> Please consider both the ways of capturing the light, and the structural variety of the concepts.

Also included in the student packets was an information sheet that briefly summarized ways solar energy could be converted to thermal energy (see Appendix). This was included to avoid problems with a potential lack of technical knowledge about solar and thermal energy. The written directions instructed students to generate as many concepts as they could, and to draw one concept per page and label aspects of their ideas.

After concept generation, on a separate preformatted post-it© note, students wrote a short description of each idea, and reported on the origin of the concept by answering the question, "Where did the idea come from?" They were instructed to write on the post-it the numbers of the Heuristic Cards that helped facilitate the generation of that concept. After labeling each of their generated concepts with a post-it note, they completed demographic information, rated their success and creativity on the task, and answered three specific questions about the experience: "1) What do you think was your most creative idea? Why? How did you arrive at that idea?; 2) Which heuristics were most useful to you in this task? Why?; 3) Which heuristics were difficult to apply in this task? Why?"

After twenty minutes, we collected the materials and discussed the experience with the students. We did not collect data during this open-ended discussion. The goal of the discussion was pedagogical; we wanted to support students in framing the lessons from the experience and applying it to their course work.

Data Analysis

Student concepts were scanned and their written descriptions and answers to the handout questions were transcribed. Two coders, one with a background in engineering and art & design, and the other with a background in engineering and engineering education, analyzed the data according to two coding schemes: 1) evidence of heuristic use and 2) type of solution in the design solution space. Of the 161 concepts analyzed, coders agreed on both coding schemes 90% of the time. The other 10% of the time, coders discussed the codes to reach consensus.

The coding process involved examining the data for each participant separately. The set of 12 cards given to the student was reviewed and compared to each concept the student generated. The additional written data (concept description, concept origin, and responses to three worksheet questions) were included in this analysis. The sketches and descriptions were reviewed to determine whether each heuristic was evident in the design concept. For example, if a student had the card *Fold*, and they included folding solar panels in their design, the heuristic was considered "present." In addition, each student had self-identified the heuristic strategy they felt had influenced their design (if any). Other heuristics not in their set of 12 may have been present in their concepts, but since we were only interested in the impact of the given cards on their ideas, only those heuristics in their specific instructional card set were coded.

Another group of codes captured categories of possible solutions that could be generated given the problem statement. Our goal was to develop a simple coding scheme that showed the "typical" and "common" ideas, as well as the "atypical" and "original" ideas. Based on the range of proposed solutions in previous studies[10,11], the following categories were used to code the design concepts:

1) Solar panel attachment: A solar panel attached to a common cooking device, e.g., a grill, an oven, a microwave
2) Simple box: A box-like item, sometimes painted black, sometimes insulated, e.g., a cardboard box, a pot, a standard grill
3) Simple box with reflector: A box-like item that also had a means to reflect light to the food, e.g., the examples in category 2 with aluminum foil angled flaps or some other reflector attached or unattached
4) Simple reflector: Some kind of reflective material, sometimes parabolic, to direct light on to the food, e.g., a parabola with food on a stand at the focal point
5) Simple lens: A lens to direct the sunlight to a focal point, e.g., a large magnifying glass or lens
6) Other: A combination of any of the above five categories, a more detailed version of the above that included additional features, a new mechanism, or an idea that did not fit into the above categories

The coding scheme captured the simple concepts (e.g., "just a lens") proposed by these novice engineers. When the concept included additional details beyond those explicit to categories 1-5, it was considered "other." This category included a wide range of concepts, including concepts like the combination of a lens with a reflector, a box with side panel reflectors and a foldable handle, adjustable controls, and a compartment for cooking utensils. The categories in the coding scheme represent typical designs observed (categories 1-5), as well as more complex, original designs (category 6). Each concept was placed in only one category.

Results

The 48 student participants generated a total of 161 concepts, ranging between 1 and 8 concepts per participant. The average number generated was 3.4 concepts.

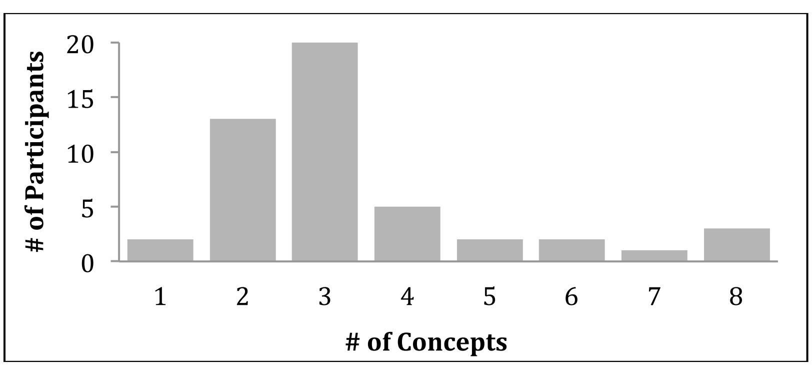
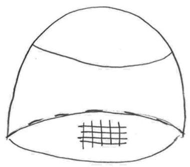


Figure 4. Summary of Number of Concepts Generated by Participants

In 46% of the concepts, none of the instructional heuristics were apparent. However, during the 25-minute session, 35% of students generated only three or fewer concepts. Had they attempted to use the heuristics, they may have been able to create more concepts, a goal of this heuristic instruction. It is possible that a longer testing session would have resulted in greater use of the heuristics provided once their own initial concepts had been exhausted. In 10 of these 75 concepts without apparent heuristic use, students claimed to have used a heuristic. One example is the heuristic “Use an alternative energy source”, which was noted by a student with a comment that he had "used energy from the sun." Because the task instructed the students to use the sun’s energy, this was not counted as an alternative source (e.g., wind energy) suggested by the heuristic.

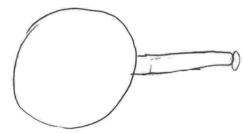
Figure 5 shows 10 concepts in which students claimed that they did not use any of the 12 Heuristic Cards they were given, and no use was apparent. We agree, as we did not see evidence of use of the strategies on their set of 12 cards. The participant number and concept number is in the upper right left corner of the concept drawings.

P24 C3



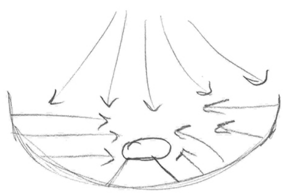
Hemispherical magnifying glass covers cooking rack, bottom half of glass covered in black absorbent material

P8 C1



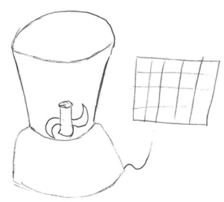
Solar panel wrapped around handle of pan to electrically heat the pan

P28 C1



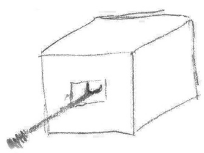
Parabolic reflector concentrates sunlight to top of cooking surface

P5 C4



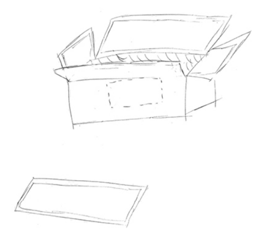
Solar panel used to power food processor

P39 C1



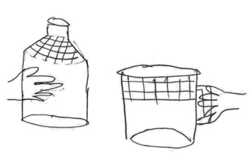
Box made of thick, absorbent material that cooks like an oven when food is placed inside

P49 C4



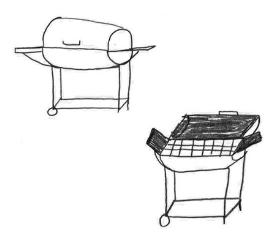
Box with mirrors stored inside lid when not in use and black foam insulation, removable window and glass sheet to cover top during use

P30 C1



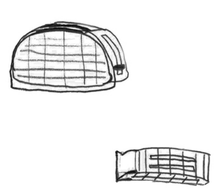
Thermos powered by solar panels to power heating and cooling mechanisms that control temperature of drink

P25 C1



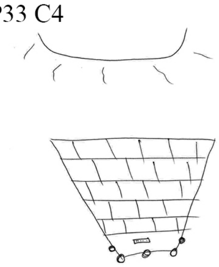
Standard grill with solar panels on inside of lid to collect sunlight energy when the grill is open

P36 C2



Toaster covered in solar panels used to power internal heating elements

P33 C4



Solar-panel wall on wheels placed in front of window, used to power anything in house

Figure 5. Concept Examples from Category “No Heuristic Use”

Five of these concepts use common, pre-existing cooking items with attached solar panels (e.g., a grill, a blender, a toaster). The other 5 concepts appear to be simplified forms built around direct use of a basic principle of light, such as reflecting light with a mirror or dish. These concepts tend to be familiar, basic forms (e.g. the cardboard box with saran wrap). The concepts that were categorized as “other” within this group of “No Heuristic Use” were often simple adaptations to existing cooking items, or slightly more complex uses of solar panels.

The remaining 53% of the concepts showed evidence of the use of the instructional heuristics in their designs. Students claimed 43 of these concepts came from using their set of Heuristic Cards. In the other 43 concepts, use of the instructional heuristics was apparent even though not identified by the students. We report the number of concepts, the categorization of the concept in the design space, and whether heuristic use was identified in each for each solution type in Figure 6.

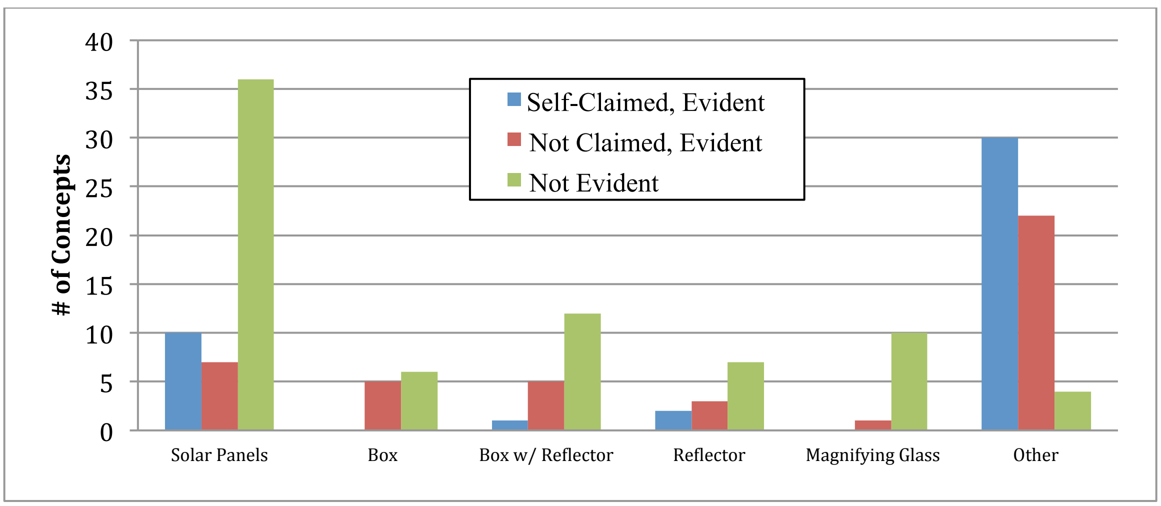


Figure 6. Relationship between Heuristic Strategy Use and Design Solution Space

Figure 6 shows that concepts without any evident use of heuristics often fell in the "solar panel" category. Of all designs in which heuristics were not evident, 48% of the concepts were solar panels, another 47% were other “typical” simple designs, and only 5% were designs we coded “other”, representing more complex concepts that could not be categorized as typical designs.

In contrast, concepts developed by students who claimed that heuristics were the prompt for their designs were most prevalent in the “other" category. Of these self-identified heuristic-based designs, 70% were "other," 23% were solar panels, and the other 7% were other typical designs. For concepts in which heuristics were evident but not self-identified, a similar pattern of more than half of the concepts coded as "other" designs emerged. Concepts that showed heuristic use, whether self-identified or not, often went beyond the simple, typical categories and were categorized into the more complex, combination concepts in the "other" category.

Figure 7 shows 10 concepts in which students did not specifically claim to use a heuristic from their provided set, but were coded as showing evidence of heuristic use. The table includes the participant’s drawing of their concept, a summary of the student's written description of their concept, and, the specific heuristics coded for the concept.

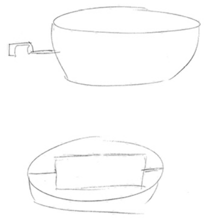
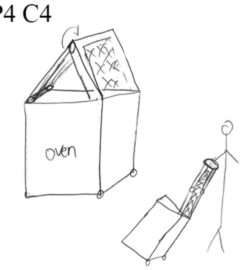
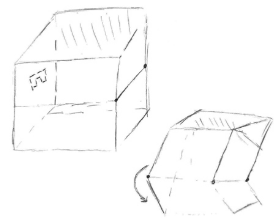
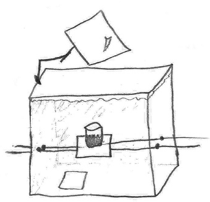
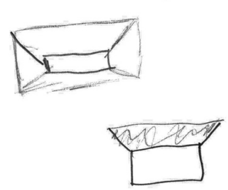
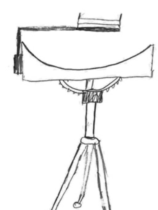
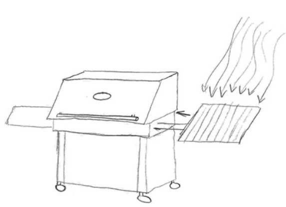
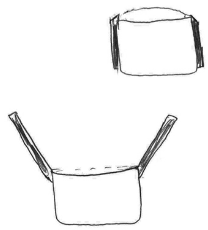
P49 C7  Black box with food suspended inside a larger pot, smaller box turned to stir food and distribute heat Rotate	P4 C4  Oven with wheels powered by solar panels that extend into a handle for transport Expand or collapse, Reconfigure
P11 C1  Solar cells attached to outside of “flower petals” to charge when closed, when cooking, open petals reflect and focus light to central cooking surface Change flexibility, Change geometry, Utilize opposite surface, Cover or wrap	P5 C1  Solar oven hinged to fold for easy storage and portability Fold
P38 C2  Large black-bottomed cardboard box with foil sides and covered with saran wrap, includes clip-on, adjustable magnifying glass to focus light Make components attachable or detachable	P40 C4  Black box with glass sheet cover and adjustable mirrors that reflect light into center Fold
P33 C2  Two parabolic dishes use solar panels to power stove Repeat	P12 C1  Parabolic mirror on adjustable tripod stand that directs sunlight to flat cooking surface Elevate
P1 C1  Sides of a standard grill replaced with solar panels Substitute	P14 C3  Pot with reflective edges that extend to collect sunlight Extend surface

Figure 7. Concept Examples from Category “Heuristic Strategies Evident”

In these concepts where heuristics are evident, even the more typical concepts show signs of more developed or complex ideas. For example, the P4C4 concept, coded as "solar panel attachment," is an oven with solar panels that also serve as an extendable handle for portability. Instead of simply attaching, the participant, whether consciously or subconsciously, applied the heuristics *Expand or collapse* and *Reconfigure* to create a more unique concept. However, he himself did not identify the use of these heuristics in his concepts, despite having these in his set of 12 Heuristic Cards. It is possible that the application of heuristics, once understood, can occur without conscious awareness. In a prior study of an expert designer, extensive use of heuristics without conscious reflection was also observed[11]. Because the overall set of heuristics was developed from examples of their use in a variety of designs[10,11,12,13], they are by nature easy to grasp and applicable across problems. As a result, designers may not be aware of their use even while benefitting from them.

For some concepts, participants wrote a description of the source of their ideas that reflected their personal notions of creativity falling outside of the purview of the experiment. For example, Participant 11 (C1) did not claim any use of heuristics in the generation of the “Sun Bud” concept above. Instead, the student claimed that the idea came "from God." This type of response suggests the student was not aware, or was unwilling to acknowledge, when heuristics may have influenced the concept. For this concept, the student had the cards *Change flexibility*, *Utilize opposite surface*, *Change geometry*, and *Cover or wrap*, and these are readily apparent in his design concept. For example, a solar panel was placed on one side of the flower petals, and a reflective surface on the opposite side indicating use of the card *Utilize opposite surface*. Thus, another factor in the reporting of heuristic use may be the individual's conceptions of the sources of creative thinking.

Finally, Figure 8 represents 10 concepts in which students claimed use of one or more of the evident heuristics to guide the development of their design concepts. Beneath the concept description is a list of the self-claimed heuristics, marked with an asterisk. Beneath that list is a list of additional heuristics in their set of 12 that were evident in the concept but not claimed.

* Self-Claimed Heuristics

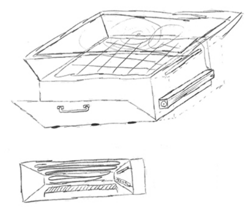
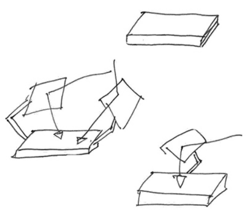
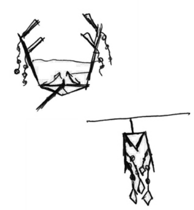
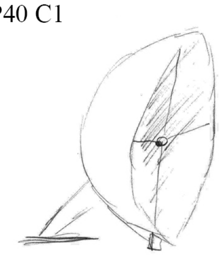
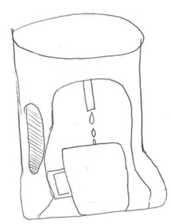
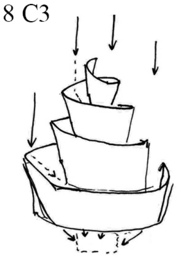
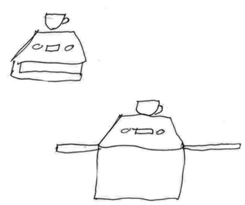
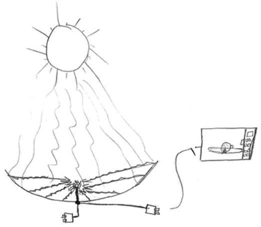
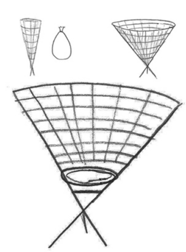
P13 C1  Cylindrical oven with foldout legs, insulation and glass dome lid to intensify and trap heat; comes with multiple screens to adjust amount of sunlight *Offer optional components Apply existing mechanism in new way, Layer	P37 C1  Reflectors at edge of box concentrate light onto attached solar panels that power heating element and fans that circulate air through heating and food compartments *Change contact surface, *Compartmentalize
P23 C2  Reflective panels with swivel arms slide out from flat black cooking surface, allowing adjustment to angle of sunlight *Adjust function through movement Animate, Repeat, Use common base to hold components	P15 C4  Mirrors to concentrate light on water in bucket; when inverted, mirrors hang freely and act as wind chimes *Convert for second function, *Separate parts, *Unify, *Incorporate environment. *Add motion, *Make component multifunctional
P40 C1  Large parabolic reflector concentrates sunlight to small bowl for cooking *Convert 2D to 3D	P31 C2  Solar-panel-powered coffee pot with built-in storage for tea bags, coffee grounds, and stirring straws *Hollow out
P18 C3  Spiral-shaped reflective surface points directly at sunlight and focuses it toward food placed below *Twist Convert 2D to 3D	P35 C2  Hot pot powered by solar panels that fold out from beneath *Fold
P29 C1  Parabolic reflector concentrates sunlight to solar-panel-powered battery charger with multiple plugs for different users to power personal electric cooking devices *Build user community	P2 C1  Reflective cone with tripod stand, magnifying glass and food rack inside, parts detach and reflector rolls to fit in sack *Allow user to assemble, *Expand or collapse, *Reduce material Nest, Separate parts, Use multiple components for one function

Figure 8. Concept Examples from category “Self-Claimed Heuristic Use”

When the participants were aware of heuristic use, their concepts were also more complex and unique, with 70% of these concepts categorized as "other". Many of these concepts (P13C1, P2C1, P15C4) are not similar to the other concepts in the set of 161, nor do they represent typical existing solar devices. Additional examples include participant 15 (C4), who generated the idea of a solar water heater that also serves as a "wind chime" when not in use, and participant 2 (C1), who designed a twistable reflector that expands into a tripod stand.

Another source of originality in the concepts was a strong consideration of context (who will use it, how it will fit into the community, secondary functions, etc.). Concepts P29C1 and P13C1 seemed to have looked beyond ways to collect light toward marketable products. For example, Participant 29 (C1) designed a large parabolic reflector that focused light to a small solar panel. The participant added multiple electrical outlets to the this reflector, using the heuristic *Build user community*. Different users could access the same solar power source without carrying around the large dish.

Some solutions using heuristics appeared more "elegant," meaning they accomplished the complicated or challenging in a simple way. Participant 18 (C3) developed a spiral-shaped reflector that focused light to a central location, a common theme in light "harvesting." But while most solutions focused on costly, resource-intensive parabolic reflectors, the proposed spiral reflector was comprised of a single, twisted piece of reflective material. This participant noted they developed this concept with the assistance of the heuristics *Twist* and *Convert 2D to 3D*.

Some concepts with self-identified heuristic use incorporated more complex systems, or detailed design elements. For example, Participant 13 (C1) designed a system to heat and transport air passing through a series of compartments. He included details, such as rubber handles, that showed an awareness of user interaction. This participant claimed to use the heuristic strategies *Compartmentalize*, and *Change contact surface*.

Students identified heuristic use in 27% of their concepts. These concepts were also much more likely to go beyond the typical solutions (coded in categories 1 through 5) commonly generated for this design problem. They showed an increased level of originality and uniqueness. These more unusual concepts added to the diversity of the solution set generated by that participant, and so consequently added alternatives as a result of the ideation process. With more, and more diverse alternatives generated, the selection and development of promising concepts could proceed through the design process.

Discussion

This empirical study explored the outcomes of instructing novice students in the application of Design Heuristics. Our results indicate that Design Heuristics were an effective way to support students in the exploration of the design solution space, and the concepts resulting from the application of heuristics were more original. Students who did not use any heuristic strategies seemed to generate simple concepts by replication of known ideas, or minor changes to existing products (e.g. a solar-panel-powered grill, oven, or hot pot; a cardboard box with aluminum foil; a magnifying glass on a stand). These concepts often involved simple replacement of a functional component (e.g., an existing electric or gas-powered device) with a solar panel. These concepts often involved simple replacement of a functional component (an existing electric or gas-powered device) with a solar panel. These trends in idea generation are consistent with previous findings on novice concept generation[14,15,16,17,23]. On the other hand, students who did use Design Heuristics showed more development of basic or existing concepts, and more application of novel elements and concepts. The Design Heuristic Cards seemed to provide students with specific direction for how to generate new ideas.

The observed concepts also differed in focus. Some emphasized function alone, and others elaborated on function in the context of what the product would look like, who would use them, and other features that might be important to users. When concepts showed no evidence of heuristic use, they tended to be less developed, and focused on harnessing energy from light. On the other hand, many concepts generated with heuristics included features that went beyond basic light principles, and included features relevant to a more complete product that would be desirable, easy to use, and aesthetically pleasing. The Design Heuristic Cards seemed to help students consider other aspects of the product beyond the basics, which resulted in the generation of more diverse concepts. As a result, using Design Heuristics facilitated their exploration of the design space of potential solutions.

This study also contributed to our understanding of how Design Heuristics are understood by novices. Students applied the same heuristics in a variety of ways. For example, the heuristic, *Fold*, was interpreted on many levels, from folding added solar panels down for storage to folding reflectors and an outer case separately for packaging in a small bag. Both are applications of the heuristic; however, the second concept seemed to develop the concept further. In future studies, the relationship application complexity and idea originality could be examined.

Design Heuristics vary in their ease of application, and in their relevance within any particular design problem. In this study of novice students, we saw evidence that some Heuristic Cards were more challenging for students to apply than others. Additionally, some students interpreted a specific Heuristic Card as useful, and some did not, for the same design problem. For example, Participant 18 (C3) used the *Twist* card to generate an idea for a spiral reflector (shown in Figure 7). Another student responded to the question, “What heuristics were difficult to apply in this task?” by saying, “Twist. What would I even twist? I mean, come on.” Many differences in how readily students grasped and made use of the Design Heuristics were apparent. However, a larger scale study is required to identify which heuristics are particularly difficult, and how this varies across design tasks.

In initial concept generation, students are traditionally encouraged not to evaluate ideas because it limits them from exploring multiple diverse concepts[25]. Ideas also transform along the way from initial concept generation to a detailed concept, to a prototype, and so on. In this study, no major differences in the practicality of concepts were readily apparent in this design problem. On the whole, the ideas suggested by novice students who used the heuristic strategies were not less practical than the ideas suggested by students who did not use them. In fact, many were more developed, and provided promise for continued development of the heuristic-based concept.

A limitation of the present study is the absence of a control group who were not instructed to use Design Heuristics. However, because many students chose not to do so, we were able to compare concepts with and without their use. The reasons why students chose not to follow the instructions are unclear; potentially, they found it difficult to do so, too onerous, or that their own approaches were adequate to handle the problem in the time provided. Altering the method to allow an initial period of free ideation, followed by instruction on Design Heuristics, may be more beneficial to students because they would see how the heuristics could take them further in diverse idea generation than their own current processes.

Some previous studies have found that simple exposure to relevant strategies for divergent thinking has been effective (e.g., 1, 40). However, in this study, we found that a short introduction was effective for only some of the students. Other students did not apply the heuristics to the design task, either because they did not see the need, or did not understand how to apply them. Because other ideation tools have not been tested in empirical studies, the present results provide important evidence that ideation can be improved through instruction. Future work will continue to explore best practices for instruction to foster more diverse ideation, and on the role of Design Heuristics in innovation.

Conclusions

The application of Design Heuristics by novice engineering designers proved to be an effective way for them to explore more original ideas in the design solution space. Incorporating this instructional tool into engineering education can support novice engineers as they develop skills in ideation, and foster the creation of innovative ideas. Design Heuristics can help to broaden the scope of solutions considered, thereby improving the set of concepts available for further development in the design process.

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References

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

[2] Cross, N. (2001). Design cognition: Results from protocol and other empirical studies of design activity. In C. M. Eastman, W. M. McCracken & W. C. Newstetter (Eds.), Design knowing and learning: Cognition in design education (pp. 79-104). Elsevier, Amsterdam.

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

[4] Rowe, P. (1987). *Design thinking*. Cambridge, MA: MIT Press.

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

[6] Treffinger, D., Young, G., Shelby, E. and Shepardson, C. (2002) *Assessing Creativity: A Guide for Educators*. Storrs: The National Research Center on the Gifted and Talented.

[7] Dym, C., Agogino, A., Eris, O., Frey, D., & Leifer, L. (2005). Engineering Design Thinking, Teaching, and Learning. *Journal of Engineering Education*, 103-120.

[8] Cropley, A. (2001). Creativity in education and learning. Virginia: Stylus Publishing.

[9] Smith, G. (1998). Idea-generation techniques. *Second Quarter, 32*, 107-133.

[10] Yilmaz, S., & Seifert, C. M. (2011). Creativity through design heuristics: A case study of expert product design.

Design Studies (in press).
[11] Yilmaz, S., & Seifert, C. M. (2010). Cognitive heuristics in design ideation. In the Proceedings of 11th International Design Conference, DESIGN 2010, Dubrovnik, Croatia.
[12] Daly, S. R., Yilmaz, S., Seifert, C. M., & Gonzalez, R. (2010). *Cognitive heuristic use in engineering design ideation.* Paper presented at the American Society for Engineering Education Annual Conference (ASEE), Lousville, Kentucky.
[13] Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2010a). *A comparison of cognitive heuristics use between engineers and industrial designers.* Paper presented at the 4th International Conference on Design Computing and Cognition (DCC'10), Stuttgart, Germany.
[14] Smith, S., Ward, T., & Schumacher, J. (1993). Constraining effects of examples in a creative generation task. *Memory and Cognition, 21*, 837-845.
[15] Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies, 12*(1), 3-11.
[16] Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies, 17*, 363-383.
[17] Christensen, B., & Schunn, C. (2009). Setting a limit to randomness [or: 'Putting blinkers on a blind man']: Providing cognitive support for creative processes with environmental cues. In K. Wood & A. Markman (Eds.), *Tools for Innovation*: Oxford University Press.
[18] Linsey, J. S., Laux, J., Clauss, E. F., Wood, K. L., & Markman, A. B. (2007). Effects of analogous product representation on design-by-analogy. *Proc. International Conference on Engineering Design, ICED, Paris, France*.
[19] Perkins, D. (1997). Creativity's Camel: The Role of Analogy in Invention. In T. Ward, S. Smith & J. Vaid (Eds.), *Creative Thought* (pp. 523-528). Washington, DC: American Psychological Association.
[20] de Bono, E. (1967). New think: The use of lateral thinking in generation of new idea. New York: Basic Books.
[21] de Bono, E. (1975). Think links. Blandford, Dorset, UK: Direct Education Services.
[22] Finke, R. A.; Ward, T. B.; Smith, S. M., *Creative cognition: Theory, research, and applications*. The MIT Press: Cambridge, MA, 1992.
[23] Cross, N., Expertise in design: an overview. Design Studies 2004, 25, 427-441.
[24] Newell, A. & Simon, H. (1972). *Human problem solving*. Englewood, NJ: Prentice-Hall.
[25] Osborn, A. (1957). *Applied imagination: Principles and procedures of creative problem-solving*. NY: Scribner.
[26] Geschka H., Schaude, G.R. and Schlicksupp, H. Modern techniques for solving problems. *International Studies of Management and Organization*, 1976, 6, 45-63.
[27] Perkins, D. (1997). Creativity's Camel: The Role of Analogy in Invention. In T. Ward, S. Smith & J. Vaid (Eds.), *Creative Thought* (pp. 523-528). Washington, DC: American Psychological Association.
[28] Zwicky, F. (1969). *Discovery, invention, research through the morphological approach*. New York, NY: Macmillan.
[29] Allen, M. (1962). *Morphological Creativity*. New Jersey: Prentice-Hall.
[30] Gordon, W. J. J. (1961). *Synectics*. New York: Harper & Row.
[31] Eberle, B. (1995). *Scamper*. Waco, Texas: Prufrock.
[32] Altshuller, G. (1985). *Creativity as an Exact Science*. New York: Gordon and Breach.
[33] IDEO (2002). Available at http://www.ideo.com/work/method-cards/.
[34] Von Oech, I. (2010). Available at http://www.creativethink.com/.
[35] Horowitz, R. (1999). *Creative problem solving in engineering design.* Tel-Aviv University.
[36] Nisbett, R. and Ross, L. (1980). *Human inference: Strategies, and shortcomings of social judgment*. Englewood Cliffs, NJ: Prentice-Hall.
[37] Klein, G. (1998). *Sources of Power: How People Make Decisions*. Cambridge, MA: The MIT Press.
[38] Pearl, J. (1983). *Heuristics: Intelligent Search Strategies for Computer Problem Solving*. New York, Addison-Wesley.
[39] Clapham, M. M. (1997). Ideational Skills Training: A Key Element in Creativity Training Programs. *Creativity Research Journal, 10*(1), 33 - 44.
[40] Warren, T. F., & Davis, G. A. (1969). Techniques for creative thinking: An empirical comparison of three methods. *Psychological Reports, 25*(1), 207-214.

Appendix

The Basic Principles of Transferring Solar Energy into Thermal Energy:

- Concentrating sunlight: Using usually a mirror or some type of reflective metal to concentrate light and heat from the sun into a small area makes the energy more concentrated and therefore stronger.
- Converting light to heat: Any black colored material will improve the effectiveness of turning light into heat, as black absorbs light.
- Trapping heat: Once the light is absorbed and converted to heat, trapping the heat inside makes it possible to reach similar temperatures on cold and windy days as on hot days.