Investigating impacts on the ideation flexibility of engineers

Dr. Seda Yilmaz, Iowa State University

is an Assistant Professor of Industrial Design who teaches design studios and lecture courses on developing creativity and research skills. For her research, she investigates design approaches and ideation, ethnography in design, foundations of innovation, creative processes, and cross-disciplinary design team dynamics. She is the author of more than 20 peer-reviewed journals and conference proceedings. She also serves on review, advisory, and scientific boards of various journals and conferences. Her current research focuses on identifying impacts of different factors on ideation of designers and engineers (funded by NSF), developing instructional materials for 77 cards (funded by NSF), and designing innovation workshops for students without design or engineering background and teaching them design thinking methodologies (funded by Procter and Gamble). She received her PhD degree in Design Science in 2010 from University of Michigan. She is also a faculty in Human Computer Interaction Graduate Program and a research faculty in Center for e-Design.

Dr. Kathryn Jablokow, Pennsylvania State University

Dr. Kathryn Jablokow is an Associate Professor of Mechanical Engineering and Engineering Design at Penn State University. A graduate of Ohio State University (Ph.D., Electrical Engineering), Dr. Jablokow's teaching and research interests include problem solving, invention, and creativity in science and engineering, as well as robotics and computational dynamics. In addition to her membership in ASEE, she is a Senior Member of IEEE and a Fellow of ASME. Dr. Jablokow is the architect of a unique 4-course module focused on creativity and problem solving leadership and is currently developing a new methodology for cognition-based design. She is one of three instructors for Penn State's Massive Open Online Course (MOOC) on Creativity, Innovation, and Change, and she is the founding director of the Problem Solving Research Group, whose 50+ collaborating members include faculty and students from several universities, as well as industrial representatives, military leaders, and corporate consultants.

Dr. Shanna R. Daly, University of Michigan

Shanna Daly is an Assistant Research Scientist and Adjunct Assistant Professor in the College of Engineering at the University of Michigan. She has a B.E. in Chemical Engineering from the University of Dayton and a Ph.D. in Engineering Education from Purdue University. Her research focuses on idea generation, design strategies, design ethnography, creativity instruction, and engineering practitioners who return to graduate school. She teaches design and entrepreneurship courses at the undergraduate and graduate levels. Her work is often cross-disciplinary, collaborating with colleagues from engineering, education, psychology, and industrial design.

Eli M. Silk, University of Michigan
Meisha Nicole Rosenberg, Iowa State University

Meisha Rosenberg is a 2nd year PhD student in Mechanical Engineering and Human-Computer Interaction at Iowa State University. She received her BS in Mechanical Engineering from Iowa State University in 2011. Her research interests include the use of Immersive Computing Technologies in collaborative design work among engineers and design students. She is current working with Dr. Seda Yilmaz to investigate the role that cognitive style plays in a designer's ideation process and how tools can be used effectively to modify the ideation process for a variety of circumstances.

Investigating Impacts on the Ideation Flexibility of Engineers

Introduction

Ideation is a critical skill for all engineers as they explore problem spaces and develop both short-term and long-term solutions. Engineers can benefit from developing proficiency in a diversity of ideation approaches in order to successfully perform in a variety of problem situations. However, the current engineering education paradigm lacks opportunities for engineering students to understand their own natural approaches to idea generation and to learn how to approach idea generation in other ways.

The focus of our work is ideation flexibility, what we define as the ability to ideate in both incremental and radical ways – or, more precisely, to be able to ideate along a continuum of approaches depending on the needs of the problem. Based on existing research, we expect three key factors to influence ideation flexibility: 1) *problem framing* (the way a problem and its constraints are "set"); 2) the use of *ideation tools*; and 3) *ideation teaming* (interactions with others during ideation). Our research investigates the impacts of these key factors on engineering ideation flexibility and correlates them with students' cognitive styles. Our aim is to create guidelines and methods that will help engineers increase that flexibility by learning how to deliberately engage in ideation using different approaches. The project uses experimental studies with pre-engineering and engineering students, at various stages in their educational programs, testing each factor's impact on their approaches to solving design problems.

In this paper, we focus on the development of a sustainable foundation for our investigations of the factors impacting ideation flexibility. We present our basis and vision for this foundation, and illustrate some of our preliminary findings through case studies.

What is ideation flexibility and why is it important in engineering?

Concept generation, or ideation, occurs most notably in the early stages of design, when designers propose solutions that they will later explore and refine (or reject). Design research indicates that successful ideation involves both divergent and convergent thinking, meaning there are times in the process when designers generate multiple ideas for consideration, as well as times when designers narrow down the collection of ideas and elaborate on the details of one (or a few) of them[1-3]. The role of ideation in design is to produce promising design concepts to pursue; many and diverse ideas increase the potential for successful design outcomes by increasing the number of possibilities available during concept evaluation and selection[4, 5]. This, in turn, increases the potential for creating a design solution that best meets a problem's given constraints.

Design solutions represent potential paths to changing an engineering system or structure. Abernathy and Utterback[6] identified two patterns of change – radical and incremental – that represent extreme positions on a continuous scale. *Radical change* corresponds to the development of new products when technical and market uncertainties exist, while *incremental change* corresponds to the improvement of existing products for which infrastructure and processes are already established – with a range of possibilities in between. The outcomes involved in any design task can be mapped along this scale, with no greater or lesser value attached to any particular position overall. This aligns with the work of other scholars[7, 8] who have shown that radical change and incremental change are equally valuable and can each be necessary (alone or in combination) in specific situations. Thus, engineers must be prepared to ideate in "both" ways – or, more accurately, to ideate along a continuum of thinking that will enable them to generate ideas from radical to incremental (and every point in between) as needed.

Based on Kirton's[8] cognitive diversity research and several exploratory studies with engineers[9, 11], we expect to be able to characterize engineers' *preferred ideation approaches*. Using Kirton's *cognitive style* construct and terminology, engineers that are "more adaptive" can be characterized as preferring more incremental change, whereas engineers that are "more innovative" can be characterized as preferring more radical change[8]. As shown in Figure 1, we hypothesize that ideation behaviors can be shifted from one's natural preferences through the way a problem is framed[12], the ideation tools that one uses to support ideation[13] (specifically the 77 Cards Ideation Tool[14]), and those with whom one interacts during ideation[15, 16].

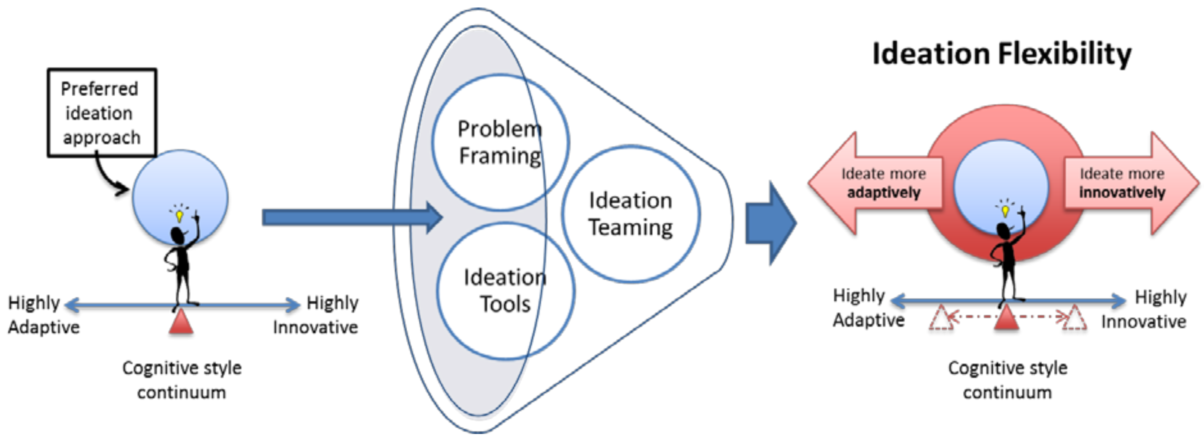

Figure 1: Preferred ideation approach and three factors impacting ideation flexibility

In the following sections, we define and discuss these factors in detail, along with previous work related to their potential impacts on ideation.

1. Cognitive Style

Cognitive style is defined as the strategic, stable, preferred way in which people respond to and seek to bring about change, including problem solving[17]. Among the theoretical frameworks proposed for understanding cognitive style diversity[8, 18-20], Kirton's Adaption-Innovation (A–I) theory stands out in terms of its robustness and its elegance in explaining the complexity of cognitive style. In addition, the problem solving context in which A–I theory was originally developed makes its application in engineering straightforward and appealing. Perhaps as a result of these qualities, the use of A–I theory in engineering education research has grown in recent years, particularly through scholars investigating the impact of cognitive style within engineering problem solving and creative behavior[9, 11, 21, 22]. Following this chain of development, we are using A–I theory as our lens on cognitive style in this project.

Previous general studies suggest that more adaptive individuals tend to generate more detailed ideas that remain closely connected to the original constraints of a problem (digging deeper), while the more innovative tend to generate ideas that stretch the boundaries of the solution space in tangential ways[8, 22, 23]. As a consequence, we expect more adaptive students to be less comfortable and to struggle/cope more with problems they perceive as loosely structured, while more innovative students are apt to be less comfortable and struggle/cope more with problems they perceive to be tightly constrained. As real-world problems are likely to have both loose and tight constraints, it is important for engineering students to understand their reactions to different problem structures and to be able to "shift" between different ideation strategies in order to perform effectively.

2. Problem Framing

The term "framing effect" refers to differences in how individuals respond to diverse descriptions or "framings" of the same problem with respect to variations in their expectations, types of goal setting, and task instructions[12, 24]. For example, Förster et al.[25] showed that when individuals expected a novel event, it enhanced their abstract processing, whereas expectations of a familiar event enhanced their concrete processing. Although Förster et al. did not make explicit links to cognitive style, we are investigating whether expectations of novelty versus familiarity can be used to induce engineers to shift their thinking more adaptively or more innovatively.

Scholars have also compared the impact of simple prompting (e.g., quantity goals) with other types of task instructions, including more elaborate instructions on *how* to think in a particular way. For example, O'Hara and Sternberg[26] reported higher performance for specific, goal-related instructions ("be practical" or "be analytical") over no special instructions, and Litchfield[27, 28] found that difficult goals in combination with more elaborate instruction yielded the best results (most ideas). A few studies have established tentative links between goals/task instructions and cognitive style. O'Hara and Sternberg[26] explored differences in task performance between individuals with "legislative" versus "judicial" thinking styles (based on Sternberg's early model of thinking styles[29]). Although this work was preliminary, it supports our assertion that both cognitive style and problem framing (and the interaction between them) require further investigation.

3. Ideation Tools

Over time, individuals tend to develop or gravitate toward "favorite" approaches for generating ideas based on cognitive comfort and familiarity[8]. Idea generation tools can be used to facilitate new ideation approaches, helping engineers to think beyond their "normal" perspectives and results[13, 30, 31]. A wide variety of ideation tools exist, including brainwriting[32], analogical thinking[33], morphological analysis[34], Synectics[35], lateral thinking[36], SCAMPER[37], and TRIZ[38] (among many others), all of which vary in focus, specificity, and usability.

One ideation tool that has been tested to determine its efficacy in an engineering ideation setting is 77 Cards[13, 39-41]. The 77 Cards ideation tool consists of cognitive prompts that encourage the exploration of different ideas[42-45]. These prompts are intended to help engineers and designers move through a larger "space" of potential solutions, guiding them to generate diverse (and potentially non-obvious) ideas. They can also be used to help engineers become "unstuck" when they have worked on a task for a long time and are struggling to generate more ideas. The 77 Cards are a result of combined outcomes from previous studies, including protocol studies of engineers and industrial designers at varying expertise levels, as well as award-winning product analyses[42, 43, 46-48]. The strategies extracted from these combined studies[13] are depicted on hand-held cards (see example in Figure 2); each card includes a description of the strategy, an abstract image depicting the application of the strategy, and two product examples that show how the strategy is evident in existing consumer products.

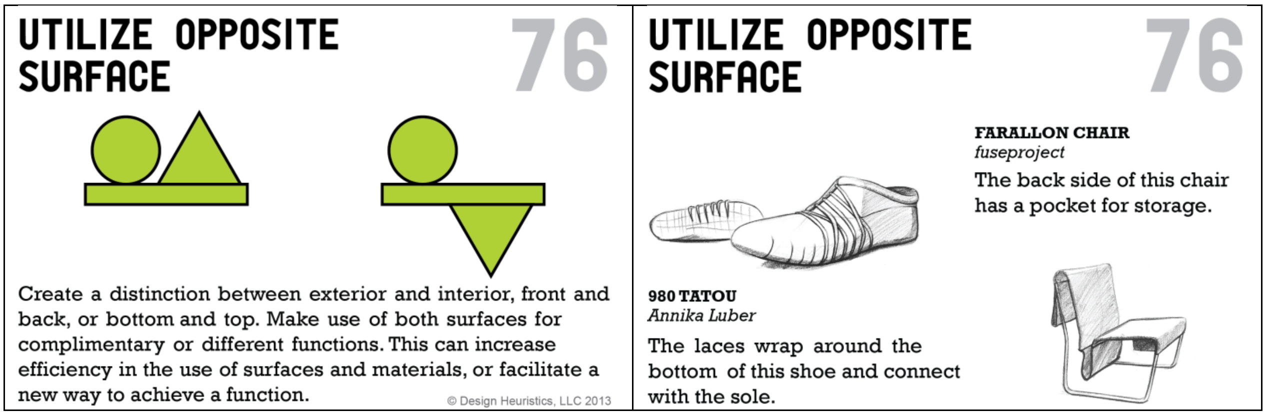

Figure 2: Example of the 77 Cards ideation tool (front and back of Card #76)[13]

In previous validation work, we investigated the outcomes of undergraduate engineering students' idea generation while using the 77 Cards ideation tool[13, 41]. The results showed that the concepts created without 77 Cards were less developed, replications of previous ideas, or minor changes to existing products, while concepts created with 77 Cards resulted in more complex, less obvious designs. While the impact of 77 Cards on ideation has been explored in previous work, we have not investigated their interaction with cognitive style. For example, do certain prompts from 77 Cards inherently represent more adaptive or more innovative ideation? How will 77 Cards support students' coping behaviors, and thus, ideation flexibility? We are exploring these and other related research questions in the current work.

4. Ideation Teaming

Many engineering problem-solving activities involve teamwork, especially as the complexity of the problem increases. The team approach requires exploiting the knowledge and expertise of all parties involved, while avoiding conflict resulting from their differences. The smallest team is a pair or *dyad*[8]. Research has shown both positive[15, 49] and negative impacts[16, 50] on ideation outcomes from working in teams. Positive impacts include a process gain effect[51], with groups outperforming individuals, and data showing that as a team develops more concepts, the quality of the concepts improves[52]. Shared ideas can also foster new idea tracks, more complete layouts, and diverse synthesis[52, 53]. On the other hand, teams have also been shown to be *less* successful than individuals in ideation. Some research has shown that working individually can be more efficient than collaborating[16], which may result in "group process loss"[54]. A study with engineers showed that brainstorming produced fewer ideas than the combined efforts of an equal number of individuals working alone[55]; this effect is consistent among the majority of the studies focused on Osborn's brainstorming[56]. While teaming effects on ideation have been explored in some contexts (with mixed results), further investigation is needed. For example, how do interactions with someone of a different cognitive style impact the degree of novelty in ideation – or the choice of a final concept? Do large cognitive gaps between ideation partners enhance or limit ideation flexibility? We are seeking answers to these and other related questions in our work.

Project Methods Overview

Our work is guided by the following research questions:

- What is the relationship between *cognitive style* and preferred ideation behavior/outcomes?
- What impact does *problem framing* have on ideation flexibility?
- What impact do *ideation tools* have on ideation flexibility?
- What impact does *ideation teaming* have on ideation flexibility?

We have begun by investigating how students' preferred ideation behaviors and outcomes relate to their cognitive styles. This mapping of ideation behaviors and outcomes to the cognitive style spectrum will be used throughout the remainder of the project as a foundation for understanding the impact of problem framing, ideation tools, and ideation teaming on ideation flexibility. That is, do these factors shift an individual's ideation behavior and outcomes toward more adaptive and/or more innovative performance relative to the original spectrum?

Within the first year of the project, we collected data from approximately 500 students with diverse backgrounds and education levels across three institutions. In this paper, we report on the structure of our studies thus far, and use a small sample of student data to illustrate some preliminary findings. Figure 3 depicts an example flow for one of our experimental studies, in which the impact of each factor on ideation is investigated separately – i.e., cognitive style, problem framing, teaming, and design heuristics, respectively. In other studies, we varied the sequence of interventions and explored the impact of only one factor in addition to natural ideation preferences. As discussed in more detail below, each intervention is followed by a reflection survey, in which participants self-assess their ideation outcomes and behavior.

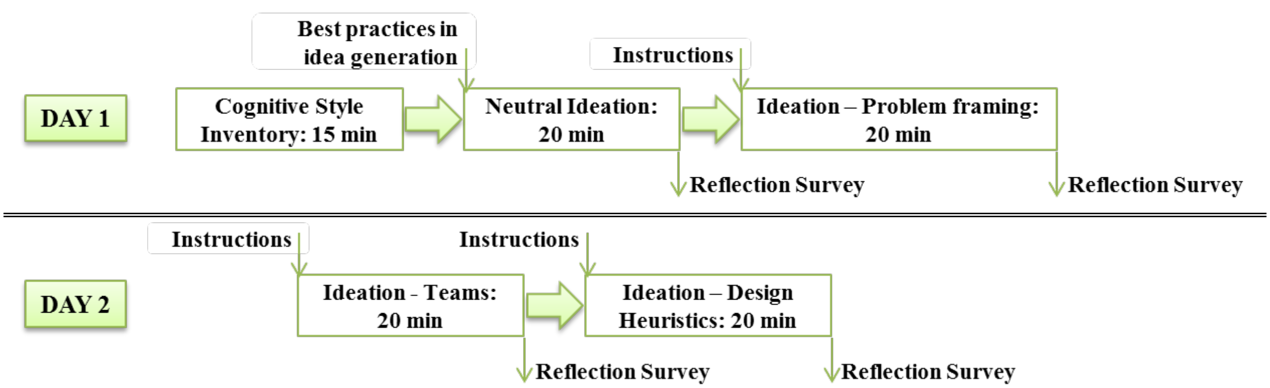

Figure 3: Example flow from one of our studies

- <u>*Cognitive Style Inventory:*</u> KAI inventories (www.kaicenter.com) were administered to determine the cognitive style of each student at the beginning of the study.

- *Neutral Ideation:* Students were given one of four design problems, in a randomized order. Using Adaption-Innovation (A-I) theory as a guide, these problems were neutrally framed so as not to encourage one type of ideation behavior (more adaptive or more innovative) over another[57, 58]. This activity was used as a benchmark to understand how each factor impacts students' outcomes.
- *Ideation with Problem Framing:* Again using A-I theory as a guide, two versions of each design problem were developed, one aimed to encourage more adaptive ideation behavior, and the other to encourage more innovative ideation behaviors[57]. Students were randomly assigned to one of the two problem frames, with half of each experimental group assigned to each framing.
- *Ideation in Teams:* Students were put into two-person teams (dyads). Each team was given another design problem[58] that neither student was exposed to previously. They were asked to design together, but record (sketch and document the details) separately.
- *Ideation with Design Heuristics:* Students were given the same set of ten (of 77) Design Heuristics cards and asked to apply the cards while solving a given design problem.
- *Reflection Surveys:* At the end of each intervention, students were asked to complete a short survey focused on their perceptions of that intervention. Typical questions included: "How did the structure of the problem statement affect your idea generation?" or "Which of the ideation cards appealed to you most/least?" The aim of these surveys was to establish the presence (or lack) of coping behavior (i.e., behavior away from preference) in students as they performed ideation tasks under the impact of different factors.

An Initial Study and Preliminary Findings

Our goal in reporting these preliminary findings is to illustrate how engineering students with different cognitive styles approach ideation without the introduction of any proposed interventions. It is our aim to map students' ideation behaviors to the cognitive style spectrum, so that educators can make general estimates of their students' cognitive styles without the need for formal assessment (although such assessment will be necessary for a detailed evaluation). Our research questions for this experiment included: How do students naturally ideate? How do students' cognitive styles impact the way they address design problems? How diverse are their ideas from each other? Can students' ideation behaviors be mapped to segments of the cognitive style spectrum?

Participants

Our sample for this experimental group included 32 senior and graduate mechanical engineering students at a large, public, mid-western university. They were enrolled in an upper level engineering course. To illustrate our results, we chose two students (both males) who are more adaptive and another two students (both males) who are more innovative on the KAI cognitive style spectrum to represent (to the extent possible) the extremes of that continuum. With these case studies, we examined some suggestive differences between distinctly more adaptive and distinctly more innovative thinkers that will inform our future studies.

Method

The study took place during class time. Initially, students were given the KAI inventory in order to determine their Adaption-Innovation cognitive styles. Then, students were introduced to best practices in ideation and were given a design problem. The problem involved designing a low-skill snow transporter and specified design criteria and constraints. Our goal for this problem was to make it neutrally framed, meaning it did not prompt the participants to generate any particular kind of design solutions (e.g., incremental or radical), but instead allowed them to generate the types of solutions that they preferred. Below is the design problem statement provided to the students:

> *Today, skis and snowboards are widely used as personal transportation tools on snow. But to be able to use them, a lot of skill and experience are required that a user cannot normally learn within one day. Moreover, skis and snowboards cannot run uphill easily. It would be better if there were other options of personal tools for transportation on snow, which still allowed the user to control direction and braking, but did not require much time to learn how to use.*
>
> *Design a way for individuals without lots of skill and experience skiing or snowboarding to transport themselves on snow.*
>
> *Develop solutions for this problem. Be sure to write each solution on a different piece of paper, and use drawings to sketch your ideas. It's important that you do your best and continue working for the full time of the activity.*

Students were given a set of ten concept sheets, each of which included a blank box for their sketches and an additional box in which they could describe each idea in terms of how it worked and the details of its features and mechanisms. We also made additional concept sheets available for those participants who needed more. Students were given twenty minutes to generate solutions individually.

Results

The results reported here include the four students' KAI scores and the concepts they generated for the problem provided. Our goal is to consider how cognitive style may have impacted the students' ways of approaching the design problem.

The average (mean) KAI score for the general population (across cultures) is 95 (± 0.5) with a standard deviation of approximately 17 points. Even though the theoretical range is broader (32 to 160), the observed range is 45 points to 145 points[8]. Two thirds of all people fall between the scores of 78 and 112, and the vast majority (95%) fall between 61 and 129. Simplifying for the purpose of this discussion, we might say that anyone with a KAI score less than 95 is more adaptive, while anyone with a KAI score greater than 95 is more innovative, although these terms are best used relatively across the entire spectrum (i.e., every person is more adaptive than some and more innovative than others). In this study, Participant 1 (KAI=72) and Participant 2 (KAI=88) were more adaptive, while Participant 3 (KAI=119) and Participant 4 (KAI=120) were more innovative. This gave us a substantial range of KAI scores from which to explore differences between the more adaptive and more innovative thinkers.

In general, people who are more adaptive tend to master details, build on assumptions, and take more prudent risks, even in generating ideas. On the other hand, the more innovative tend to generate concepts with less focus on detail, challenge the assumptions, and take more daring risks. Another difference is that more adaptive people feel less comfortable with ambiguity and prefer more structure, while the more innovative prefer less structure and are more comfortable with ambiguity. Below, we describe the four participants' concepts as generated in the session.

Participant 1 (KAI score= 72). Participant 1 was the most adaptive student in this experimental group. He generated five concepts (see Figure 4), which were similar to existing solutions. His first concept was a sled pulled by trained animals. His second concept was also a sled, but this time, it was maneuvered by the person sitting in it. His third concept shifted from a sled to a machine that can grip the snow with back treads, where the direction is controlled by the front handle bars. His fourth concept illustrated a device that is attached to existing shoes with an increased surface to distribute the weight while walking, and his last concept proposed riding a trained horse for transportation on snow. His exploration of the solution space focused on refining familiar solutions. Although his ideas were diverse (i.e., two sleds, one motorized vehicle, one shoe attachment, and one animal as the means to transport on snow), he did not alter their features dramatically. However, this also allowed him to propose ideas that would have immediate efficiency, as they relied on existing, practical solutions.

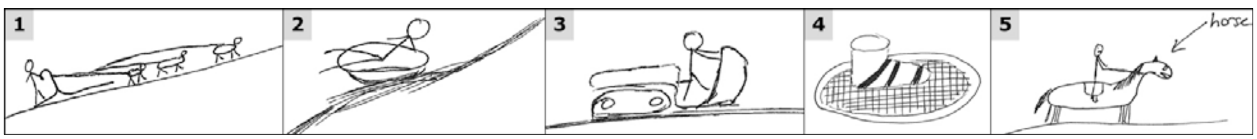

Figure 4. Participant 1's (KAI score = 72) concept sketches

Participant 2 (KAI Score= 88). Participant 2 was the second most adaptive student in our experimental group, with a 16-point style difference (in the more innovative direction) with Participant 1. Prior research has identified the "just-noticeable-difference" (JND) for KAI as 10 points (Kirton 2011), meaning that differences of 10 points or more between two individuals' cognitive styles will be noticeable over time (by the individuals themselves and those around them). Participant 2 generated four concepts, which also appeared to be modifications of existing solutions; however, he was more elaborate and detailed in his sketches than Participant 1 (see Figure 5). His first concept was a sitting sled powered by bike pedal with chains attached to a paddle wheel on the back. The steering wheel is attached to the skis and placed in the front for direction. His second concept was a set of single skis with small engines in each with added paddle wheels. His third concept was also a sled-ski integration; however, instead of sitting (first concept) or standing (second concept), he proposed a solution where the user would lie down on the device and steer to move on the snow. His last concept was another sled, this time controlled by steering handles in snow. One difference in this concept compared to his prior solutions was a folding feature that converts this sled into a backpack.

In this case, the student repeatedly changed the position of the user and adapted existing products that accommodate these positions (sitting, lying down, or standing). He did in-depth explorations (as opposed to breadth) by taking features from one solution to the next, combining and further improving them. His last concept was rather different than the others, since he brought a new feature into the solution: folding for compactness and ease in carrying. This final concept revealed a shift in his approach, which may have come from looking back on his initial concepts, where he integrated an engine to either a sled or ski. In his final concept, he left the engine as the power source to move on snow, but incorporated human power with steering handles. The introduction of the human as the energy source might have prompted him to consider how the human would carry the transporter.

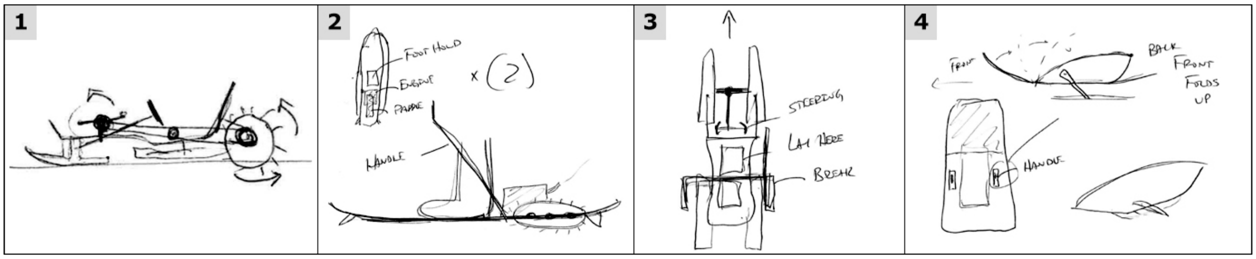

Figure 5. Participant 2’s (KAI score = 88) concept sketches

Participant 3 (KAI Score= 119). Participant 3 was one of the two more innovative participants in this experimental group. With a 47-point KAI difference with Participant 1, and a 31-point difference with Participant 2, Participant 3 is considered highly innovative; he generated six concepts (see Figure 6). His initial three concepts were similar to those of Participant 1, with strap-on snowshoes, riding a horse, and a snow mobile. However, his last three concepts seemed to be very different than what one might expect. His fourth concept was a snow tamper, where the user flattens the snow ahead of him, while making the snow compact and easy to walk on. His fifth concept merged a dart and fishing, and introduced these two into the snow context. He proposed that the user would ride on a snow tube attached to a dart with a fishing pole, so he can choose a spot as a target and pull himself along using the fishing pole. In his final concept, he used two plywood boards that one could step on, pick up the next one, throw it a distance ahead, and step on it again.

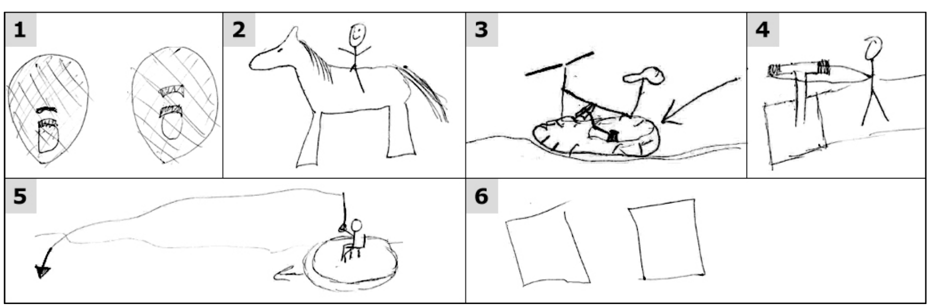

Figure 6. Participant 3’s (KAI score= 119) concept sketches

In addition to the jump from familiar solutions to more unusual ideas in the middle of the session, the progression of Participant 3’s concepts was also interesting. He started with rather simple ideas and moved toward more complex ones, but then ended his ideation session with the simplest solution he created: two plywood boards. Potentially, Participant 3 realized he was re-creating existing solutions and consciously changed his pattern. Additionally, Participant 3’s transition from simple to complex to simple solutions suggests larger jumps in his exploration of the solution space.

Participant 4 (KAI Score= 120). Participant 4, with a KAI score of 120, was the most innovative student in this experiential group, although with only a 1-point difference from Participant 3, we would expect him to approach ideation similarly. Participant 4 generated ten concepts (see Figure 7), which was the greatest number for all four participants (another common trait for more innovative people, given equal intellectual capacity). His initial concepts were adaptations of existing solutions in the snow context. In his first concept, he proposed a large hamster wheel to walk in that keeps you from breaking into deep snow. His second concept took the large fluffy circle and inserted a bike's wheels that can stay on the snow, while it functions like a regular bike. His third concept took the same big fluffy wheels and used them on a recumbent bike: a 4-wheel pedal-powered vehicle. His fourth concept was a transition from a rollerblade into a snowblade without the wheels, and his fifth concept was a snow scooter with flat boards instead of wheels. Participant 4 made a jump with his sixth concept, where he integrated a heating coil inside a boot's sole to melt snow while walking, which results in a personal sidewalk wherever the user goes. His next concept was a giant animal-like creature that is driven by the user, where the user is located at its head. His eighth concept was a snow platform that functions like a reverse treadmill; the user stands on the platform and a tank-like tread underneath moves the vehicle along the snow. Participant 4 carried this "standing on a platform" idea into his next concept, where he introduced a pair of snow stilts. His last concept was a modification of his ninth concept; here, he proposed a 'snow-go-stick', similar to a pogo stick, where the user bounces along to catapult him through the snow.

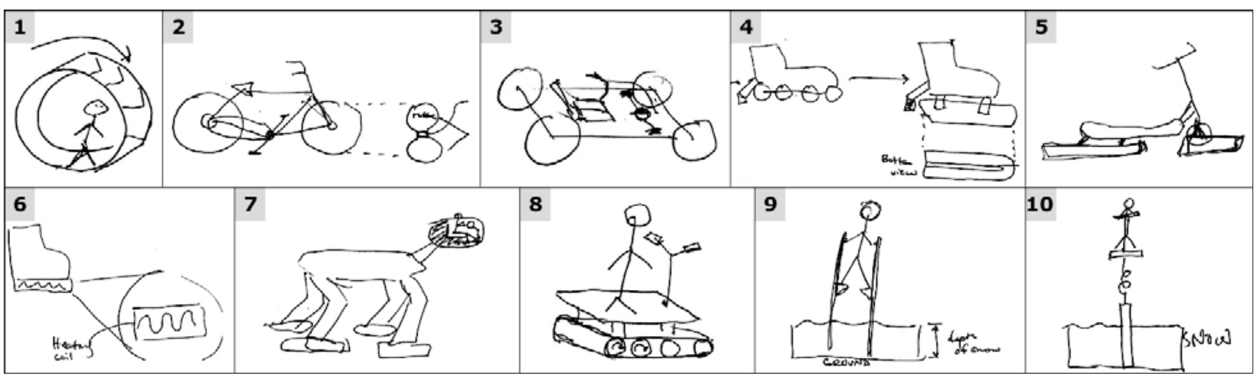

Figure 7. Participant 4's (KAI score: 120) concept sketches

Discussion

These four cases of two distinctly more adaptive and two distinctly more innovative students suggest some potential areas to explore with our larger population. One difference between the two sets of participants was their focus on adapting existing ideas shown to be effective (more adaptive students) versus producing a variety of ideas that are more dissimilar to what currently exists (more innovative students). Participant 1 (most adaptive) generated five concepts, which were all based closely on existing, common products that are already used on the snow, such as a sled, a snowshoe, and a snow mobile. Participant 2 (second most adaptive) generated four concepts, which, other than his final concept, were commonly used products on snow. While Participant 3 (second most innovative student) considered more familiar, common solutions initially, he moved toward exploring ideas that seemed more different than existing products. For example, he proposed to flatten the snow with a machine to make it easier to walk on. He achieved this with two concepts: one was a snow tamper, a machine that would flatten the snow as you push it, and the other was two plywood boards. Similarly, while a few of Participant 4's ideas could be compared to existing products, many of them seemed outside of the traditional scope of expected snow transport equipment.

Another difference was that the ideas generated by the more adaptive students (Participants 1 and 2) seemed more practical, more efficient for immediate implementation, and easier to predict that they would work as planned than the more innovative students (Participants 3 and 4. The majority of ideas proposed by Participants 3 and 4 seemed like they would need more extensive pilot testing and experiments to prove they would function, and would take longer to bring to the implementation stage.

A third difference was noticed between Participant 2 (a more adaptive student) and Participants 3 and 4 (the more innovative students), specifically the breadth and depth of their explorations of the solution space. Participant 2 seemed guided by exploring the depth in the ways the human would position him/herself on the device and his ideas focused on exploring the depth in this characteristic. On the other hand, Participants 3 and 4 had moments where they used an element of a previous concept to jump to the number (e.g., Participant 4's snow tamper to compact the snow and plywood boards that would also compact the snow), however, their collection of concepts seemed more varied in their features and ways in which the user would interact.

Considering the outcomes of these four participants prompts several questions with regards to guidance and education in design. For example, what made the two more innovative participants move more broadly throughout the solution space? How can we introduce this 'jumping' in the solution space notion to students who are on the more adaptive side of the style spectrum? Also, how do we guide students to develop more immediately implementable solutions when the time is right or solutions that will take more time to test and develop when appropriate in the design context? Finally, one of the more adaptive students seemed to dig deeper into a particular component of the design, a feature that the more innovative students' concepts lacked. How can we introduce this 'digging into detail' feature to students who are on the more innovative side of the style spectrum?

Conclusions

We will continue to explore differences revealed from this preliminary data analysis in our larger population. These cases indicated a potential difference in that students who are more innovative on the KAI spectrum would generate solutions that venture away from familiar solutions compared to students who are more adaptive on the KAI spectrum. However, more adaptive students seemed to focus on more practical, less risky solutions with a promise of immediate efficiency. Additionally, one of the more adaptive students elaborated more on the ways the user would interact with the product by proposing solutions that varied in position on the device. We will explore if this difference is evident in other adaptive students in the larger sample. Our ongoing research will investigate how these differences can inform ways to support ideation flexibility, as well as how multiple factors, problem framing, using the 77 cards as an ideation technique, and working in teams, help students behave more adaptively or more innovatively during the ideation phase.

Acknowledgements

This research was supported by the National Science Foundation, Research in Engineering Education (REE) Grants #1264715, #1265018, and #1264551.

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