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CREATIVITY 'MISRULES': FIRST YEAR ENGINEERING STUDENTS' PRODUCTION AND PERCEPTION OF CREATIVITY IN DESIGN IDEAS

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ABSTRACT

We report four cases from a larger study, focusing on participants' self-identified "most creative" concept in relation to their other concepts. As part of an ideation session, first-year engineering students were asked to create concepts for one of two engineering design problems in an 85-minute period, and were exposed to one of two different forms of fixation. Participants worked as individuals, first using traditional brainstorming techniques and generating as many ideas as possible. Design Heuristics cards were then introduced, and students were asked to generate as many additional concepts as possible. After the activity, participants ranked all of the concepts they generated from most to least creative. Representative cases include a detailed analysis of the concept that each participant rated as "most creative," idea generation method used, and relative location and relationship of the concept to other concepts generated by that participant. Across four cases, we identified a number of characteristic "misrules" or misconceptions, revealing that first-year students judge creativity in their concepts in ways that could inhibit their ability to produce truly novel concepts. We present Design Heuristics as a tool to encourage the exploration of creative concept pathways, empowering students to create more novel concepts by rejecting misrules about creativity.

Keywords: idea generation; creativity; Design Heuristics; engineering education

INTRODUCTION

First-year engineering students often fixate on ideas during the idea generation process, but it is unclear how they decide which of their concepts are most creative to pursue, and where their perceived "most creative" ideas occur in this process. These beliefs about creativity impact the ways in which students are able to conceive of and develop creative and novel solutions to the big engineering challenges of our age [1,2].

First year experiences for engineering students have been dramatically expanded in the past decade to include situated design activities, support for developing technical skill alongside mathematics and physics instruction, and team-based or collaborative design projects [3]. Engineering students have cited project-based learning as important to their understanding of the engineering discipline, and a lack of contextual experiences has been linked to lower retention [4], underscoring the importance of student engagement in authentic engineering activities. To this end, many scholars have suggested pedagogical tools and strategies to engage students in these early experiences [5,6], including curricular structures [7] and specific strategies to increase creative potential [8,9]. It is less clear, however, which specific barriers beginning students face in learning *how* to be creative, especially in relation to existing beliefs they hold regarding the nature of creativity [6,10].

BACKGROUND

Advancing Creative Ability in Engineering Education

Creativity is currently viewed as essential to the success of engineering as a discipline, and is particularly important for future engineers who are being asked to solve engineering challenges. Scholars have proposed that creativity is developed through a wide variety of approaches, including the introduction of specific design methods [e.g., 11,12], the creation of curricular goals that reinforce creative skill development [7], and the support of faculty in adapting pedagogical strategies to encourage creativity [13,6]. The most frequent framing for the discussion of creativity and creative development in engineering education is the barrier known as *fixation*—the inability to create concepts that diverge from known examples [14,15]. As with the methods for encouraging the development of creativity, many of these methods have been used more directly to discourage fixation [16], such as through the generation of more, and more varied, concepts with Design Heuristics [17], analogical thinking [18,19], or the decomposition of existing products [12].

But within all of these approaches, particularly in addressing fixation as one diagnostic outcome of a student lacking creative ability, we don't have a clear understanding of what students believe, perhaps inaccurately, about creativity and how those beliefs might influence behavior. Adequate knowledge of these processes is critical to helping students become *more* creative.

Design Heuristics

Design Heuristics is an empirically validated method for idea generation. It includes a set of 77 design strategies that help users increase the quantity and creativity of concepts generated. The Design Heuristics were distilled from strategies evident in award-winning products [20], controlled studies with practicing engineers and students [17,21,22] and the design activity of professional designers [23]. This method has been successfully used in engineering education contexts to support the idea generation process, encouraging students to develop richer sets of ideas, resulting in more novel and elaborate outcomes [24,25,11]. Each Design Heuristic is presented on a card containing the heuristic, such as "utilize opposite surface" (Figure 1), along with a description, a simplified visual depiction, and on the back, two example products where the heuristic is evident in the design.

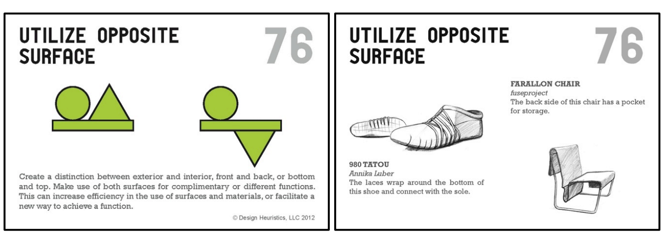

FIGURE 1. SAMPLE DESIGN HEURISTICS CARD (FRONT AND BACK).

Confronting Beliefs about Creativity

While substantial research has been done on the nature of creativity, such as its characteristics [8], there is little documentation of how students gain beliefs about creativity, or what existing beliefs might already be held. In particular, it appears that student beliefs about creativity—even if misguided—provide substantial influence on how they evaluate creativity in their own work, or the corpus of designs present in a given discipline.

These issues of misconception or misdirected generalization have been addressed in the broader educational community, often through the lens of mathematics [e.g., 26,27] or educational philosophy [28]. Scholars in this area have highlighted how students come into the curriculum with "bugs" [26] or "misrules" [27] that they then apply in their work. These intrinsic beliefs are deeply held, and are difficult to change without direct instruction [27,29]. In particular, the misrules that students use, or *perform*, in learning activities are difficult to address apart from a systemic correction of the misrules through worked examples, similar to the student- or artifact-centered desk critique common in most design disciplines [29]. We view misconceptions about creativity through much the same lens, assuming that students' tacit biases about creativity shape their labeling of designs as "creative," and may serve as a barrier to their creation and recognition of truly novel and useful concepts [30,31].

RESEARCH QUESTIONS

Our goal in this study was to explore student-identified "most creative" concepts by examining the temporal emergence of beliefs about creativity, production of design concepts, and idea generation methods. Within this framing, our analysis assesses the following research questions:

1. Where do first-year engineering students identify their "most creative" idea in an idea generation activity, when compared with all generated concepts?
2. What characterizes the relationship between a participant's espoused belief about creativity and their ordering of creative concepts?
3. Does Design Heuristics as a pedagogical tool have an impact on the student's perception of a concept's creativity?

METHOD

Participants and Setting

204 incoming first-year engineering students participated in a two-day design-build-test experience in the month prior to their matriculation at a large university in the U.S. midwest. Of these participants, 156 fully participated in an 85-minute idea generation session, and are considered the research population for the remainder of this paper. Out of 156 students, we chose four cases, which will be detailed later on, to further investigate how student rankings of creativity reveal beliefs about creativity in relation to the concepts participants generated. Two criteria were used to determine the participants included in this analysis, including: students must have generated concepts in both idea generation phases (i.e., Brainstorming and Design Heuristics), and the generated concepts could not substantively diverge from the problem provided.

FIGURE 2. IDENTIFICATION OF "MOST CREATIVE" CONCEPT VARIABLE AND REPRESENTATIVE CASES.

Data Collection

Participants were exposed to two idea generation techniques: brainstorming and Design Heuristics during an 85-minute session. Students were asked to individually generate concepts for one of two engineering problems: a bike rack and a spill-proof coffee cup [14]. These two problems were chosen based on their previous use in the research literature to investigate creative idea generation in an engineering context. Students were also exposed to two different forms of idea fixation: a provided existing design solution to the problem given, and their own first ideas they generated prior to formal ideation. Each of the four experimental conditions, comprised of the two problem types and two forms of fixation, were carried out in separate sessions with a random subset of participants. In all subsets, students first used traditional brainstorming techniques in the first half of the session, generating as many ideas as possible. In the second half, the Design Heuristics method was introduced, and students were asked to use a randomly selected subset of the Design Heuristics cards to generate as many *additional* concepts as possible for the same problem. At the conclusion of the activity, students were asked to complete a short survey and rank all of the concepts they had generated through both methods from most to least creative, along with identifying generated concepts that were similar to the fixation source (either participant-created or provided). Participants then completed a survey about their beliefs on creativity.

Analysis

Our initial analysis focused primarily on (1) the temporal location of the concept that each participant rated as most creative, (2) the method the participant used, and (3) the qualities of the most creative concept in relation to other concepts by that participant.

We then calculated the relative location of the identified "most creative" concept for each participant within the 85-minute idea generation activity (Figure 2). If the most creative concept was identified within the brainstorming (BS) phase, the variable ranged from -1 to 0; similarly, if the most creative concept was identified in the Design Heuristics (DH) phase, the variable ranged from 0 to +1. To further situate the location of the most creative concept without having tracked the actual time of creation, the variable range was divided by the total number of concepts each participant generated in that phase, and the midpoint of the most creative concept was calculated numerically. Without any data on the exact creation time for each concept, calculating an average allowed us to compare relative positions for further analysis. For instance, if a participant generated three concepts in the brainstorming phase and the middle concept was chosen as the most creative, the corresponding most creative concept variable would be calculated as -0.5.

Using this calculated variable, we then divided each method phase once more, to separate all participants that identified their most creative concept in the first or second half of each method, relative to the total number of concepts generated in that phase by each participant. This process yielded four subsets: I-BS (n=21), II-BS (n=54), III-DH (n=50), and IV-DH (n=31). Descriptive statistical analysis was performed on each subset (Table 1).

Finally, we selected a corresponding representative case from each subset, with the resulting four cases including diversity of gender, total number of concepts generated, and location of the participant-identified most creative concept. Each of these cases will be presented in a later section, including further analysis of the progression of ideas in relation to the source of fixation, the nature of the relationship of the most creative concept to the fixation source, and stated beliefs regarding creativity from the exit survey in relation to the concepts generated.

RESULTS

The 156 participants included in our analysis comprised 102 male and 54 female students, 17 to 18 years of age. In total, these participants generated 1134 concepts (M=7.27; SD=2.69; min=2; max=15) across both idea generation methods. Participants in the four subsets were equally distributed across problem and fixation types.

Using these descriptive statistics (Table 1), we can explore several characteristics of participants who identified their "most creative concept" from various portions of the overall ideation exercise. Table 1 includes the number of participants in each subset, the mean location for the "most creative" and "least creative" concepts, and the mean number of concepts generated within each idea generation method. Participants in II generated more total concepts (M=8.01) than participants in IV (M=7.61), with participants in the other two phases generating fewer concepts (I: M=6.95; III: M=6.40).

TABLE 1. PARTICIPANT AND CONCEPT CHARACTERISTICS BY SUBSET.

Subset (Method)	Participants (% male)	Most Creative Concept (Least)	M (BS)	M (DH)
I (BS)	21 (38.1%)	-0.76 (0.05)	4.19	2.76
II (BS)	54 (70.4%)	-0.30 (-0.27)	4.91	3.10
III (DH)	50 (60.0%)	0.37 (-0.32)	3.72	2.68
IV (DH)	31 (80.6%)	0.77 (-0.31)	4.55	3.06
TOTAL	156 (65.4%)	0.06 (-0.25)	4.36	2.91

This suggests that students who identify their "most creative" concept later in a phase may feel more comfortable using the method introduced in the second half of the session. Participants were well distributed across all four subsets, following a normal distribution, with the central tendency very close to the zero midpoint of the calculated "most creative" variable (M=0.06). As expected, the participants identifying their "most creative" concept in IV created a significant number of concepts using Design Heuristics (M=3.06); interestingly, however, participants in II created more concepts using Design Heuristics, even while selecting their most creative concept from the brainstorming phase. Participants in subset III created the least concepts using Design Heuristics—albeit the highest proportion of Design Heuristics concepts to brainstorming concepts—choosing their "most creative" concept from the limited number of Design Heuristics concepts.

We also note the disproportionately high number of female participants located in I as compared to the other subsets. While additional work is needed to identify the role of gender in early idea generation activities such as this, this distribution is suggestive of unique challenges females may face in overcoming idea fixation or creative fatigue.

FOUR CASES

Drawing on a mixed methods approach, we use a multiple case study format to describe the differences in approach used by participants in each subset, with descriptive statistics being used to identify the boundaries of each subset. We chose one case from each subset that we identified. Each representative case includes a rich description of the participant's concepts, the relationship of these concepts to the ideation method used, any instances of fixation, and analysis of the characteristics of the participant's "most creative" and "least creative" concept in relation to the other generated concepts.

The four cases we will focus on are described in Figure 3, with the location of the "most creative" and "least creative" concept as identified by the student. Each concept the participant generated is identified by a colored block, whose width is relative to the total number of concepts generated in that phase (e.g., Student I generated 4 concepts in the brainstorming phase, while Student II generated 8 concepts in the same phase).

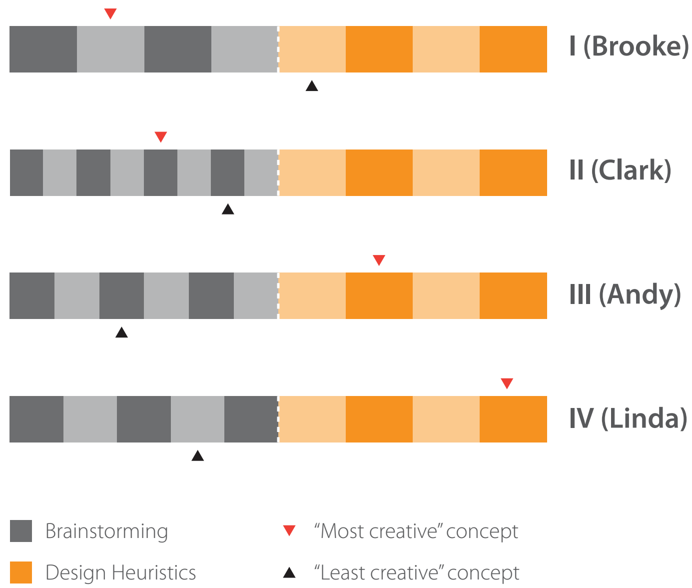

FIGURE 3. CONCEPTS GENERATED BY CASE, WITH MOST AND LEAST CREATIVE CONCEPTS MARKED.

I: Brooke

Brooke is an 18-year-old female who generated concepts for the bike rack problem. In total, she generated eight concepts—four in each phase—after receiving an example bike rack solution as a form of priming fixation. Brooke labeled her most creative concept (Figure 4, left) as a moveable bike rack:

> *A section of the roof of the car can be brought down so it is in the back seat or the floor when the seats are down. The bikes can be attached to the roof on clamps that are located on the roof already. Once attached, controls lift the roof back into place, with the bikes already secured.*

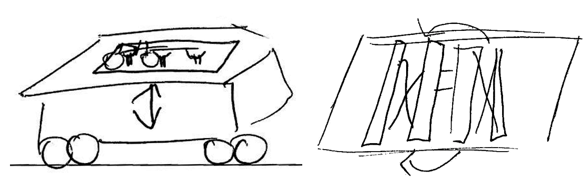

FIGURE 4. BROOKE'S MOST CREATIVE (LEFT) AND LEAST CREATIVE (RIGHT) CONCEPTS.

This bike rack represents an impractical idea—in that it modifies the car itself—but is seen by Brooke as a more creative option than her lowest ranked concept (Figure 4, right), a modification of the mounting portion of the rack: "The bike rack can be folded in half when it is not being used. The supports are folded down into 'x's'. These supports are then used in multiple ways & different positions." Within the overall ranking of concepts (from most creative to least creative), only one of the top five creative concepts out of the 8 concepts proposed was generated using the Design Heuristics method; solutions included the moveable roof (n=1), adjustable attachments for wheel mounting (n=2), a rack embedded into the top of the roof (n=1), and a multipurpose portion of the rack that could be used as a stepping stool (n=1). Only this final concept was created using Design Heuristics, with heuristic #10 ("allow user to reconfigure"). All three of the lowest ranked concepts were generated using Design Heuristics, with two of the three also indicated as being similar to the example fixation concept. Solutions included an indent in the car roof (n=1), a portion of the rack that can attach and pull a bike up from ground level (n=1), and the foldable rack (n=1).

Brooke described her approach to assessing creativity in her concepts as follows: "The concepts that I consider more creative are the ones that seem less practical/ realistic. They are harder to design, but much easier to use." This belief about creativity is borne out in her highest ranked concepts. While the progressive improvements suggested in some lower ranked concepts might represent more creative pathways (e.g., using a portion of the rack as a step stool), the least realistic concept—requiring the most modification to the vehicle itself—was judged as "most creative." Brooke's conception of progressive enhancement seems to reinforce her beliefs about what constitutes a creative concept—where similar concepts are those where "I used the same type of design in a new way." In her summary regarding learning about idea generation in the activity, she again linked unrealistic ideas with creativity: "I learned that unrealistic ideas can be used to generate a very realistic/creative product."

The concepts Brooke created when using the Design Heuristics cards represented more incremental changes from the example fixation this group was provided; three of the four concepts generated with this method were marked as similar to the example concept—and presumably, based on the creativity ranking Brooke provided—less creative than the more divergent ideas generated in the brainstorming phase. The specific application of Design Heuristics was often unclear in Brooke's concepts. While her use of #10 ("allow user to reconfigure") was clearly evident in her repurposing of the rack as a stepping stool, other uses, such as #73 ("multiple components for one function") for the lowest ranked foldable rack, provided less insight into how Brooke conceptualized the use of heuristics in relation to her concept.

II: Clark P105

Clark is an 18-year-old male who generated concepts for the spill proof coffee cup problem. In total, he generated 12 concepts—eight in the brainstorming phase, and an additional four in the Design Heuristics phase—after generating an initial solution (Figure 5) that was used as a form of priming fixation. This initial solution includes a relatively standard lid with a moveable tab that can be locked in place to avoid spillage when the cup is not in use.

Clark labeled his most creative concept (Figure 6, left) as a cup with a hinged outer lid generated in the brainstorming phase, which can be rotated up and snapped into place when not in use. He noted concerns about the production of several of the concepts he generated, explaining that this product would "probably [be] more expensive than the ones in current production."

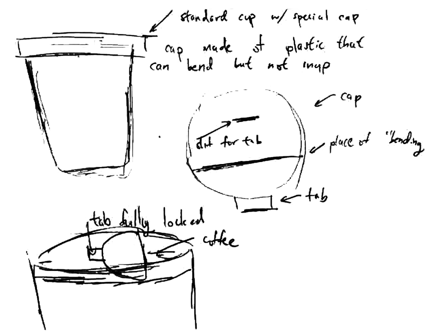

FIGURE 5. CLARK'S INITIAL SELF-FIXATION CONCEPT.

In contrast to this relatively simple design, focusing only on the mechanics of the lid, Clark identified another concept from the brainstorming phase as the least creative (Figure 6, right):

FIGURE 6. CLARK'S MOST CREATIVE (LEFT) AND LEAST CREATIVE (RIGHT) CONCEPTS.

> *...cup has many layers of coffee. When filled pushing down on the tab will rotate a flat fan on the bottom of the cup which will slowly push the coffee up.*

Within the overall ranking of concepts, two of the top five creative concepts were generated using the Design Heuristics method; similarly, two of the bottom five creative concepts were generated using this method. Solutions included the creation of a hollowed out space for an internal handle (n=2), a hinge to allow the lid to be opened and closed (n=2), a button controlling a component that allows liquid to flow (n=3), compartments or a fan to allow mixing and addition of cream and sugar (n=2), a small hole requiring the user to suck the liquid out (n=1), gravity flow of liquid through the bottom of the cup, and a fan that forces coffee to the top of the cup when activated (n=1). The mixing and hollowed out handle concepts were all generated using Design Heuristics, while the rest were created using the brainstorming method. Clark identified one of the button-controlled concepts, the small hole with sucking required concept, and one of the hinged lid concepts as being related to the self-generated fixation concept he generated at the beginning of the activity, but interestingly did not note the similarity of the other button-controlled concepts that also made use of a moveable "tab."

Clark described his approach to determining the creativity of his concepts as simply "if ive seen it before," adding that another method of determining creativity was "if I thought I was witty when drawing." This stated belief about creativity leads us to assume that, while more novel approaches to addressing a spill-proof cup (e.g., fan to force contents upward, gravity flow through bottom of cup with vacuum seal at top), the hinged lid seemed more novel to him. Or it is equally possible that his belief about creativity was different than his actual method of assessing creativity, as evidenced by his concept ranking. In summarizing the things he learned about idea generation, Clark does reveal that he doesn't like coffee, which could have affected the concepts he generated; he also shares his approach to generating new ideas, stating that he "collect[s] past ideas and use[s] them as a basis [to generate new concepts." When asked to identify concepts that were similar to his initial concept, Clark identified three early concepts from the brainstorming phase that he felt evidenced fixation, particularly in modifications to the drinkable portion of the lid. His later concepts, several from the Design Heuristics phase, focused more broadly on the form and function of the entire product, even though many of these concepts indicated only the use of a "standard lid," presumably identifying a tabbed or hinged lid, as in the initial self-fixation concept.

III: Andy

Andy is an 18-year-old male who generated concepts for the spill proof coffee cup problem. In total, he generated ten concepts—six in the brainstorming phase, and an additional four in the Design Heuristics phase—after generating an initial solution (Figure 7) that was used as a form of priming fixation. This initial solution includes a two-part locking mechanism, with a "circular button [that] the user must push…to release part #4." Andy also defines additional portions of the design as numbered callouts—a differentiating factor of his concepts—which identify a tapered body for easy handling (#1) and textured grip for "temperature control purposes" (#2).

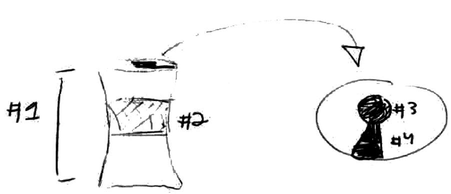

FIGURE 7. ANDY'S INITIAL SELF-FIXATION CONCEPT.

Andy's most creative concept (Figure 8, left), created in the middle of the Design Heuristics phase, was a kidney-shaped vessel with a stem to hold it on the bottom (#1), a "stopping 'cork' made of recycled material" to keep the liquid from spilling (#2), a spout to drink from when the cork is removed (#3), and the vessel itself, which "could be a gourd" (#4).

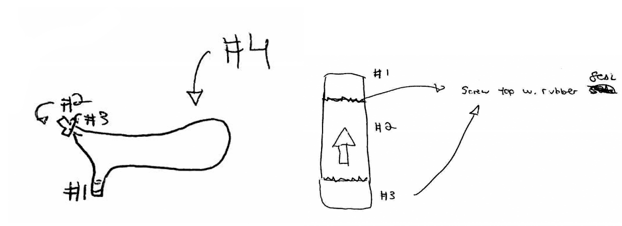

FIGURE 8. ANDY'S MOST CREATIVE (LEFT) AND LEAST CREATIVE (RIGHT) CONCEPTS.

His lowest ranked concept was missing from the scanned data, but the next lowest concept available (Figure 8, right), also created during the middle of the brainstorming phase, describes a thermos-like form with a screw-top to access the liquid inside. A separate screw-off segment on the base was envisioned as a storage area, such as cream and sugar.

Within Andy's overall ranking of concepts, all four concepts generated using Design Heuristics were ranked in the top five creative concepts, along with a single concept generated using the brainstorming method. Solutions included the creation of multiple compartments for storage or additional drink options, using a flip-top for closure (n=3), a removable cork (n=1), stackable coffee "boxes" in a milk carton form (n=1), a flip-top lid (n=2), a button to release liquid at the base of the cup (n=1), and a screw-top lid (n=1). The cork, milk carton, one flip-top concept, and one compartmentalized flip-top concept were generated using Design Heuristics; in the cases where a category of concept had already existed in the brainstorming phase, these later concepts modified the category in interesting ways, such as a cup with a flip-top lid being contained within a fabric cover to control temperature, using heuristic #27: "distinguish functions visually."

Andy offered a relatively sophisticated definition of creativity, as used in identifying his most and least creative concepts:

> *I seem to think the more* <u>*novel*</u> *something is, the more creative the object is. Why? Because I firmly believe it takes creative think [sic] to invent something novel. I also think that unconvential [sic] things, things that are revised, and things not used for their primary function are creative.* (underlining in original)

This statement aligns with Andy's selection of most creative concept—where the unusual gourd-shaped form with a cork for closure was selected—demonstrating a preference for a *holistically* novel concept. This is borne out in Andy's assessment of how he selected concepts that were similar to his initial self-fixation concept, where he selected concepts that "look like a conventional cup, [have] no handle, and [have] temperature controlling in mind." So while there were numerous attempts to address the mouthpiece closure of the device, as present in the self-fixation concept, these attempts (e.g., button at top to release liquid at the bottom; screw-top; plastic gasket) were generally ranked lower. Also interestingly, given Andy's description of novel or creative concepts as being revised and "not used for their primary function," is the gravity-fed concept, which was ranked third from the bottom; this concept represents an interesting adaptation of an idea Andy says came from hamster water bottles, but yet is not ranked highly. When describing what he learned about idea generation, Andy further extols the value of novelty, explaining: "There are many ways to approach a problem. The key is to be imaginative before being critical." Imagination or novelty on the holistic level appears to be a primary characteristic of creativity in the concept ranking Andy generated, while novelty on the function or component level was deemphasized.

IV: Linda

Linda is an 18-year-old female who generated concepts for the bike rack problem. In total, she generated nine concepts—five in the brainstorming phase, and four in the Design Heuristics phase—after receiving an example bike rack solution as a form of priming fixation. The concept Linda identified as her most creative (Figure 9, left) was a rack that moved the bike from ground level to the top of the car:

> *The bike is fastened to a rack that is just above ground level (attached with locks like any normal bike). The ground-level rack collapses to a rack sticking off the back of the car, and then the rack collapses in so the bike is above the car.*

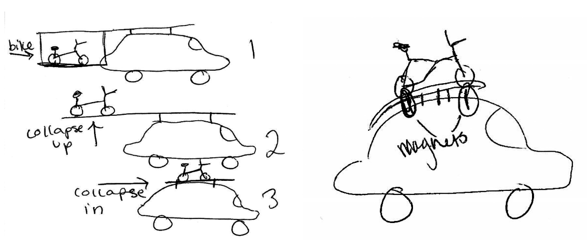

FIGURE 9. LINDA'S MOST CREATIVE (LEFT) AND LEAST CREATIVE (RIGHT) CONCEPTS.

This concept was created at the end of the Design Heuristics phase, using heuristic #65 ("telescope") to define horizontal and vertical "collapsing" of the moveable rack in order to facilitate movement of the bike on the car. Linda's lowest ranked concept (Figure 9, right) was a more traditional rack concept, using magnets to attach the rack to the vehicle and bicycle to the rack. Three of her top four concepts were generated using Design Heuristics, including the top-ranked moveable rack (1), a rectangular prism used to hold the bike into place (1; using #66—"texturize"), and fastening the bike on its side rather than standing up (1; using #75—"use recycled or recyclable materials"),). Her bottom three ranked concepts, all of which were generated during the brainstorming phase, included ways to move the bike into place automatically (2) and the use of magnets to attach the rack (1). The center two concepts included another iteration of the moveable rack generated using brainstorming, and a collapsible roof area to contain the bike, generated using Design Heuristics #65 ("telescope").

Linda enunciated the broadest definition of creativity of these four cases, asserting:

> *My most creative concepts came from the heuristics cards. They allowed me to think outside of the box and come up with new ideas. I also think that not analyzing while brainstorming helped me significantly. It allowed me to get my ideas down before comparing it to others.*

She noted that she had seen bike racks attached to the top and back of cars before, and this may explain two of her moving rack concepts from the brainstorming phase where the rack originates at the back of the vehicle, both of which she marked as being similar to the priming example. Linda directly cites the Design Heuristics cards as an aid in more divergent ideation, noting that the brainstorming concepts "are very similar because I did not have the heuristic cards (so I did not think as much out of the box)."

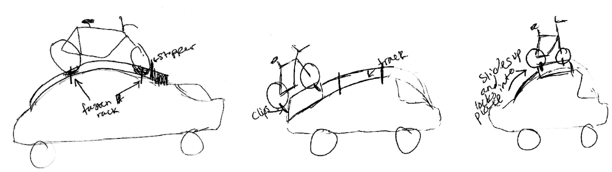

FIGURE 10. RACK MOVEMENT SIMILAR TO EARLY BRAINSTORMING CONCEPTS.

Linda appears to make use of Design Heuristics in refining earlier concepts that were generated in the brainstorming phase—making the specific function that she had initially documented clearer or better designed. For instance, the telescoping motion Linda describes in her last and highest ranked concept, where the rack collapses in a vertical, then horizontal direction, was present in her very first concept of the brainstorming phase (which was ranked eighth). The highest ranked concept includes a specific way for the rack to change positions, while in the lower ranked, only a general movement along a track is described. Interestingly, Linda notes the similarity of two other concepts—both from the brainstorming phase (Figure 10)—that include some movement of the rack from the side or back of the car to the top; but even though this general concept of movement is shared with the top-rated concept, no similarity is noted in that concept. As such, Linda appears to demonstrate some preference for concepts generated later, even where the core idea was articulated earlier, albeit with less specificity.

DISCUSSION

Across these four cases, we have identified the beliefs of individual participants regarding the nature of creativity, and how these beliefs are performed in the context of idea generation and creativity ranking. Participants who identified their "most creative" concept later in the idea generation activity (III, IV) appeared to have more nuanced beliefs about creativity, which were often more closely aligned with the ranking of their concepts. However, we noted a number of areas where beliefs were not in alignment with the ranking of concepts across all four subsets, revealing a range of "misrules"—or established misconceptions—about creativity that participants appear to be relying on when internally assessing their concepts. We will first describe each of these emergent misrules in more detail, and then discuss how Design Heuristics, alongside other established design methods, may be used to encourage the construction of more accurate knowledge about creativity through interrogation of idea pathways.

Misrules about Creativity

First-year engineering students in this study had a range of beliefs about creativity, especially related to their self-assessment of creative concepts, which manifested in their ranking of concepts. We noted a range of such emergent beliefs that function as misrules: deeply embedded assumptions about the nature of creativity that have been formalized as generalizations through consistent action on the part of students. We will examine four such misrules, starting with the most explicit, and moving to the most nuanced.

1. Creative Concepts Must Never Have Been Thought Of Before. This misrule is best demonstrated by Clark, who assessed creativity based on whether "ive [sic] seen it before." This belief about creativity often leads to a weak chain of iteration between concepts, with a particular struggle in generating an initial concept that is judged sufficiently "creative" vis-à-vis existing concepts on which to begin generating alternatives [32]. In practice, as demonstrated by Brooke, this misrule can lead to outlier concepts that disregard identified constraints (e.g., moveable roof to attach and lift bike), which are difficult to assess or iterate from.

2. Creative Concepts Must Be As Little Like Shipping Products as Possible. Starting with this misrule, participants judge existing solutions—no matter how novel—as uncreative, although often tacitly so. Instead of being able to identify components or approaches of existing products that may be modified to create an equally creative concept, participants attempt to create concepts that are extremely different from existing products on the market (e.g., Andy's gourd-shaped vessel with a cork).

3. Creative Concepts Are Generally Impractical. Embedded within this misrule is the latent assumption that existing concepts are practical concepts—in other words, they are technologically or economically possible. So therefore, concepts which are not currently possible, due to available materials and manufacturing processes, or other factors, must inherently be creative.

4. Creative Concepts Must Be Completely Creative. This misrule is perhaps the most nuanced, but can have a dramatic effect on the quality of divergence that students are able to create in their concepts. Similar to the first two misrules, this one starts with the tacit assumption that the product must not have been thought of before, or be totally different than existing products. Within this perspective, embodied by all four cases to some degree, the holistic product is being assessed—and its match to other holistic products. This leaves out the opportunity for progressive enhancement through the creative addition of a component or product function, and results in potentially creative solutions that bridge off of existing products being seen as not very creative, at least in comparison to "completely new" concepts.

For example, even in the case of Linda—an otherwise exemplary case—we see a pathway of concepts that is not entirely realized; while creative ideas emerged very early in the idea generation process, she did not recognize this idea as creative (as evidenced by her ranking) until the technical issues surrounding specific functional concerns were addressed, often one or two iterations after the core idea was created.

Design Heuristics as an Instructional Tool for Combatting Misrules

While many of these misrules are deeply embedded in students' approach to generating and assessing ideas, Design Heuristics has been successfully used to promote the generation of divergent concepts in engineering contexts, producing a greater quantity of concepts which are of higher quality than other concepts produced through brainstorming alone. Because the focus of Design Heuristics is the application of heuristics to generate early design solutions, which function as modifiers to existing design concepts, it is an ideal tool to communicate the nature of idea pathways, and the relationship of these pathways to the misrules discussed above. We will briefly discuss how Design Heuristics may be used—not only as an idea generation tool, but also as a guided instructional tool to directly combat misrules about creativity.

The instructional use of Design Heuristics can be carried out through both self-reflection and guided reflection, which encourages the development of metacognitive ability to understand how to modify concepts; and, by including heuristics as an alternate source of inspiration and constraint, resulting in more creative concepts. When these misrules are deeply embedded, self-reflection must be preceded by guided reflection, which can be productively carried out by a peer that is a more knowledgeable other [33], or an instructor that is sensitive to the thresholds students must cross to combat their own internal misrules about creativity [34]. Several areas of focus are included below, along with relevant instructional approaches to combat creativity misrules.

Creative Concepts Can Be Based On Existing Ideas. To demonstrate that iterating from existing concepts can generate creative concepts, Design Heuristics can be used to progressively transform an existing concept into a revolutionary one by applying a different heuristic in each stage to alter some component or portion of the concept [35]. By comparing the starting and ending concepts, the student can then articulate the idea pathways that were followed, demonstrating that even a series of small changes can result in the complete transformation of a concept [36].

Creative Concepts Can Improve on Shipping Products. Through progressive enhancement or component redesign, Design Heuristics can be used to identify and reimagine components of an existing, successful product, resulting in a related product that is creative in its own right. Decomposition techniques such as functional decomposition or morphological analysis can be used to identify a range of components within a larger design. Through the selection of a specific component, such as an existing "pain point," a scoped idea generation activity can be framed, allowing the student to reimagine that component in isolation, encouraging the development of alternatives to an existing approaches.

Creative Concepts Can Be Practical. An approach to address this misrule might be to identify what is truly innovative about the concept. Qualities of materiality and functionality can both be countered through targeted ideation, either through adaptation of extant morphological analysis approaches, or through adoption of a subset of Design Heuristics cards. The sci-fi or futuristic concept can also be beneficial, but must be redirected into implications for concepts that are actually possible to create; for instance, what social or experiential qualities of a given "fantasy" device might be desirable, and how those qualities might map (in preliminary form) to products that *can* be designed [37,38].

Ordinary Concepts Can Have Creative Components. Similar to the improvement of existing products, seemingly ordinary products can contain highly creative components. Decomposition techniques may be used to identify such components in existing products, which can then be applied in new and unexpected contexts. Design Heuristics can also be a useful tool in combining ideas or components from multiple products, including strategies for synthesizing functions or recognizing and altering the use qualities of a product based on external or contextually-dependent characteristics. Students appear to confuse "novel" as the sole criterion for creative, while "useful" or "having value" is another [39] As a result, they may reject concepts with familiar components even though highly novel components are included.

CONCLUSION

In this study, we have addressed the attitudes and beliefs first-year engineering students bring to an ideation session. These pre-existing beliefs about creativity affect their understanding and evaluation of creativity, including which concepts are chosen for further development or exploration. While existing research has focused primarily on the development of creative potential—in the broad sense, using divergent and convergent approaches—there has been less guidance on how to identify barriers in students' perception of creativity, especially in supporting students with a broader conception of creativity.

By locating students that identified their "most creative" concept in multiple subsections of an idea generation activity, we have demonstrated the differing beliefs about creativity that can lead to concepts at various stages of ideation being identified as most creative. These beliefs, often based on misrules about creativity, may be combatted through targeted use of reflective idea generation tools such as Design Heuristics, which foreground constraints, alternatives, or ways of thinking about existing concepts. We identify several pedagogical approaches for instructors and students that encourage a broader set of beliefs about the nature of creativity, and how it is revealed through iterative idea generation.

While engineering education has rightly focused on expanding opportunities for divergent idea generation, this programmatic focus must be coupled with knowledge of pedagogical barriers and accompanying techniques to encourage the development of student ability in relation to creativity. This study is limited to first-year engineering students, but additional research is needed to understand how beliefs about creativity change throughout the undergraduate engineering experience, and how pedagogical approaches might be used to promote this change.

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