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Comparing Ideation Techniques for Beginning Designers

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Concept generation techniques can help to support designers in generating multiple ideas during design tasks. However, differences in the ways these techniques guide idea generation are not well understood. This study investigated the qualities of concepts generated by beginning engineering designers using one of three different idea generation techniques. Working individually on an open-ended engineering design problem, 102 first year engineering students learned and applied one of three different ideation techniques—design heuristics, morphological analysis, or individual brainstorming (using brainstorming rules to generate ideas working alone)—to a given design problem. Using the consensual assessment technique, all concepts were rated for creativity, elaboration, and practicality, and all participants' concept sets were rated for quantity and diversity. The simplest technique, individual brainstorming, led to the most concepts within the short (25 minute) ideation session. All three techniques produced creative concepts averaging near the scale midpoint. The elaboration of the concepts was significantly higher with design heuristics and morphological analysis techniques, and the practicality was significantly higher using design heuristics. Controlling for number of concepts generated, there were no significant differences in diversity of solution sets across groups. These results demonstrate that the use of design heuristics does not limit the creativity of ideation outcomes, and helps students to develop more elaborate and practical ideas. Design heuristics show advantages in the initial idea generation phase for beginning engineering students. These findings point to specific strengths in different ideation techniques, and the value of exposing beginning designers to multiple techniques for idea generation.
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Introduction

Success in design is grounded in the concepts generated, developed, and executed throughout a design process. There are several recommended best practices in concept generation, including generating a lot of concepts, generating a variety of concepts, and withholding judgment on the value of concepts [1–7]. For initial idea generation, the goal is to explore, in both depth and breadth, the "design solution space," which is the theoretical space containing all possible solutions for a given design problem [8–10]. In the design solution space, some solutions are readily identified, even by novice designers, because they are already known, or involve simple combinations of familiar features or elements [11–18]. Additionally, designers may inadvertently carry over features from existing solutions to new concepts [19,20]; while this approach has some advantages, it can also limit the types of solutions designers consider. Ideally, designers learn ways to generate nonobvious solutions that reflect less well-known, and more creative, parts of the design solution space.

Because creative idea generation is both so valuable and so difficult, a variety of approaches to support designers have been proposed. For example, the SCAMPER technique (Substitute, Combine, Adapt, Modify, Put to other users, Eliminate, and Reverse) suggests general strategies for transforming existing solutions [5,21,22]; analogical thinking applies past design solutions in order to generate concepts for new design problems [23–27]; and TRIZ principles help a designer address contradictions existing in new concepts [28–33].

One of the most prominent idea generation approaches is brainstorming. While it is used colloquially to refer to the sudden appearance of an idea, its definition as a technique includes a set of rules to guide group ideation sessions [5]. Another popular technique in engineering idea generation is morphological analysis [1,2,6,34–36], where needed subfunctions are first defined; then, multiple "means" to achieve these subfunctions are generated, and then combined to produce whole concepts [37,38]. A recently developed technique called design heuristics stimulates idea generation through cognitive prompts [8,39–41]. Each design heuristic prompt is derived from the empirical evidence about its utility in past product designs. Across these ideation techniques, empirical evidence of utility, ease of application, and goals for idea generation processes vary [42].

As techniques vary, designers and educators may be uncertain as to which techniques may be helpful in idea generation. Both brainstorming and morphological analysis have been documented as successful methods, and are commonly used in engineering education [1,2,6,34–36]. More recently, design heuristics has been documented as a valuable technique for idea generation in engineering design contexts [8,39–41]. Studies have shown improvements in solution space explorations [43,44] and both instructors and students reported increased confidence in teaching and generating ideas using design heuristics [45,46]. However, few studies have compared design heuristics to the existing, prominent approaches to idea generation in engineering design education. Thus, the goal of our study was to compare the outcomes of these techniques within a controlled experimental setting. A second goal was to extend our understanding of the impact of these techniques on ideation outcomes for designers just beginning their formal training in engineering. The results will contribute to the larger literature on the comparative qualities of idea generation techniques for the early phases of design.

Background

Design is focused on the creation, development, and implementation of ideas to meet needs [47,48]. Idea generation, as a phase

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in a design process, is a stage where designers consider multiple alternatives. Idea generation in design, however, is not restricted to a single phase. It occurs throughout a design process as ideas are transformed and developed [49,50]. Prior work has shown that the designers of all levels of expertise can struggle to explore design solution spaces during initial idea generation (e.g., see Refs. [12], [14], [17], [19], and [20]). In response, various techniques have been developed to assist designers in achieving both quantity and diversity of ideas, as well as ideas that are creative and will eventually lead to something that works.

Ideation techniques have been used in both design education and practice settings to aid in solution space exploration during idea generation and development, including initial exploration of ideas, building on and expanding ideas, and refining final ideas (e.g., see Refs. [6], [23], [26], [30], [34–36], [51–53]). For example, design heuristics, individual brainstorming, and morphological analysis can be used throughout a design process to generate and transform ideas. These techniques are usually introduced in design texts and guidebooks where the idea generation phase of design is described (e.g., [6], [34–36], [53]), thus, helping students to incorporate these techniques in the earliest stages of idea generation.

Prior studies demonstrated that idea generation techniques enhance generation processes and outcomes [22,54,55]. For example, White et al. [54] assessed a suite of idea generation techniques with eight engineering student teams, and found that more ideas were generated and the creativity of the concepts generated was better when using a suite of nine techniques versus with only one. Another study compared 30 students using techniques, including a short checklist [56] and Osborn's 73 idea-spurring questions [5], as prompts to trigger creativity [55]. Using these techniques resulted in a greater number of ideas and more ideas of better quality. These studies establish the success of idea generation techniques in improving the number and quality of generated concepts.

However, less is known about how the various ideation techniques compare to one another, such as whether there is an optimal technique, or what advantages are offered by differing techniques. One study compared outcomes by 83 mechanical engineering seniors using combinations of existing methods including mind-maps and bio-inspired design, brainstorming and TRIZ, morphological analysis and design heuristics, and collaborative sketching and design by analogy [51]. They found the use of morphological analysis and design heuristics in combination resulted in better quantity, novelty, quality, and variety of ideas than did other combinations of idea generation techniques. Another study compared the C-sketch method with two other group ideation techniques (the 6-3-5 method and the gallery method) [57]. The C-sketch method was shown to produce better quality ideas than the 6-3-5 method, and more novel and varied ideas than both the gallery method and the 6-3-5 method. A different measure was used in a study of brainstorming, hierarchical, and perspective-changing techniques. This study asked participants to identify whether their best ideas in the session resulted from using a technique [58]. The brainstorming group perceived their best ideas as resulting from the technique, and was most likely to attribute their single, most creative idea to the technique. The hierarchical method group also perceived their best ideas as resulting from the technique. Only participants using the "changing perspectives" technique did not perceive their most creative ideas as resulting from the technique.

Across studies, relative strengths of some approaches have been identified; however, other studies suggest that the techniques have qualities in common. For example, in a study comparing five different idea generation techniques, the variety and novelty of the ideas generated were similar across the techniques [59]. The study also found that most groups explored only a small fraction of the total solution space even when supported by an ideation technique, suggesting a need for more effective techniques. In line with this need, the goal of our experiment was to compare outcomes generated using a fairly new technique, design heuristics, to the widely used techniques of individual brainstorming and morphological analysis. By examining concept generation with three idea generation techniques often used in engineering design settings, we hoped to identify the strengths of ideation techniques for beginning designers.

In particular, we were interested in beginning engineering designers. Prior research has shown that the design heuristics are helpful for professional designers, advanced engineering students, and first year engineering students [43,44,60,61]. However, a focus on beginning designers places constraints on the difficulty of using a technique, and on the amount of time needed to master it. For example, TRIZ [33,62] is a promising technique, but proper instruction requires a significant period of training [63]. Other methods such as analogical reasoning require some knowledge of engineering in order to apply design principles from an existing solution to a new problem. Analogical methods also involve the selection and provision of example designs. An additional important constraint was the utility of the technique for the initial stages of idea generation, when there is no information developed except the problem statement.

The choice of techniques for the study—comparing design heuristics to morphological analysis and individual brainstorming—was guided by how they are discussed in the research literature and in textbooks, as well as how and when they are commonly introduced in engineering curricula. All three of these techniques are described as supporting the exploration of initial ideas (though they are also useful for idea development). For example, TRIZ is described as more appropriate for use once initial ideas have been developed and explicated, and resulting tradeoffs identified [62]. The two techniques selected were based on the popularity in use in engineering design education that met these constraints. Design heuristics was included as a newer method with demonstrated advantages in studies with engineering students. These three identified techniques chosen for our study (individual brainstorming, design heuristics, and morphological analysis) are also practical with only a short teaching time and short ideation session within an experimental study.

Brainstorming. Brainstorming is one of the most well known techniques for creative problem solving due to its simple and easy to learn nature [64,65]. In its original conception, brainstorming was defined as a group activity with a set of rules to guide the group ideation process: (1) postpone all judgment of ideas, (2) encourage wild ideas, (3) aim for quantity over quality, (4) build on ideas, and (5) every person and every idea has equal value [5]. Additionally, best practices for brainstorming include a preparation phase [66] where individuals independently ideate prior to the group session. This preparation phase has been linked to more successful ideation outcomes [5,67,68]. In professional settings, a brainstorming facilitator familiar with the approach provides leadership [69] to help a group follow the original rules of brainstorming [70–74]. However, over time, the term "brainstorming" has been used in many circumstances to describe any open-ended, free-thinking session where one allows ideas to flow naturally, either as a group or working individually [70,75]; or, colloquially, to refer to sudden appearances of ideas in conscious thought. Most often, a more general use of "brainstorming" describes a natural, intuitive effort to generate ideas [74,76] either in groups or individually.

Numerous positive impacts of brainstorming techniques have been documented. For example, individuals in brainstorming sessions have been shown to generate new ideas based on ideas from other group members, guided by the "build off of other ideas" best practice [59,77,78]. Additionally, some research has shown that brainstorming leads to broader exploration of the design solution space [59], an increase in the number of ideas generated by a group (compared to an equal number of people generating ideas individually [79], called a process gain effect [80]), and an increase in the quality of ideas [59]. Organizations also credit brainstorming for supporting their companies' successful ideas (e.g., see Refs. [67] and [72]).

Research has also documented that the groups significantly overestimate their productivity [81] and produce fewer ideas than the same number of individuals generating ideas independently over the same time period [80–88]. Research has shown that working individually can be more efficient than collaborating [83,84], which may result in "group process loss" [89]. Dominating personalities are overly influential, and quieter members are not heard. A study with engineers showed that the brainstorming produced fewer ideas than the combined efforts of an equal number of individuals working alone [90]; this process loss effect is consistent among the majority of the studies using Osborn's original Brainstorming technique [84]. While outcomes are mixed, Brainstorming is the most widely used ideation technique in professional organizations [52,72,86,91], and it is also common in design education across disciplines, including engineering, industrial design, and architecture [92,93]. Because of its popularity, brainstorming was selected as one of the ideation methods in this study. Because individuals work alone in the study, we adopted the more open definition for brainstorming by individuals, but maintained the same rules of the technique in training students to use it (following Taylor, Berry and Block's [87] recommendations). We call this technique "individual brainstorming," defined as using Osborn's [5] Brainstorming rules to generate ideas while working individually.

Morphological Analysis. Morphological analysis defines a process for generating solutions to problems by first breaking down a problem into its parts (or *subcomponents* or *subfunctions*), generating ideas for each part, and then exploring combinations of the resulting ideas to develop a solution or concept as a "whole" [37,38]. Morphological analysis is implemented by developing a morphological chart by listing the identified subfunctions that must be achieved and creating solutions for each subfunction (also called "means") [2,34,94–96]. Generating a list of subfunctions is facilitated through *functional decomposition* [54]. Usually, subfunctions are listed in a column on the left side of the table, and ideas for implementing the subfunctions are listed in a row to the right. Table 1 shows a basic morphological matrix for a product designed to "wake someone up."

There are few studies supporting the use of morphological analysis, yet many engineering design textbooks include morphological analysis as a recommended idea generation technique [2,6,34,35,96]. One study with 54 mechanical engineering students found those who generated a higher proportion of means (compared to functions) produced better concepts than those producing charts with more functions than means [97].

One challenge with morphological analysis is determining what means are available to combine in the resulting whole solution ideas [98,99]. Approaches include systematic combinations of all means, random combinations of means, and intelligent combinations of means [100]. As tradeoffs exist for each of these approaches, there is a gap in the literature with regard to a clear approach to teach beginning designers. Research on professional use of the morphological analysis suggests that the technique can be challenging to apply if one has not reached a high level of comfort with the procedures [52,101]. However, morphological analysis has been identified as particularly valuable for complex problems where it is difficult to think about all of the parts of the whole at one time [102].

Design Heuristics. Design heuristics are "prompts" that encourage exploration of design solution spaces [8,40,43]. They are theoretically grounded in the psychological construct of a cognitive heuristic, which is a rule of thumb for decision-making [103] developed through experience [88] and is often used without awareness [104]. Design heuristics capture patterns for design derived from empirical observations of designers' concepts. Over several studies, a set of 77 "rules of thumb" for product design idea generation has been identified [8,39,105–108]. For practical purposes, each design heuristic is represented on an index card, with the front showing the heuristic name, description, and graphical depiction of its use, and the back presenting two existing product examples demonstrating the heuristic [41]. A sample card is shown in Fig. 1, and the full list of design heuristics is shown in Fig. 2 [109,110].

Multiple heuristics can be employed within a single design, and each heuristic can be applied repeatedly to initiate ideas, transform existing ideas, and generate ideas for subcomponents of complex designers [44,60,61,111]. An online course [112] and resources on the design heuristics website [41] provide practical recommendations, demonstrations of activities with the technique, and downloadable slides for instructional use.

While the design heuristics technique is a recent development, there are a number of studies on its efficacy [40,43–45, 51,60,61,111,113]. In one study with 48 engineering students, concepts developed with design heuristics were compared to concepts developed without them [43]. Concepts created with the heuristics were rated significantly higher in creativity, while concepts generated without the heuristics were typically simpler approaches to the design problem. Concepts generated with the design heuristics often used combinations of approaches to solve the problem, and added functions and components to enhance designs. In another study of novice engineering students using the Design Heuristics cards in ideation, the technique was found to enhance the elaboration of ideas, as well as facilitate more attention to particular components of concepts [111]. Design heuristics have also been shown to support the development of practical and functional ideas across diverse design problem contexts [60,61]. In a classroom study with 105 mechanical engineering students, product design concepts were traced from initial ideation through to final design solution. The results showed that 80% of the final team solutions were initiated from a single, early session of design heuristics use [61]. Design heuristics were also shown to have a positive impact on the ideation processes for a group of engineering design practitioners working for years on a particular product line, who then attributed their novel, creative ideas during a workshop to the use of design heuristics [44].

While research has shown positive outcomes from using the design heuristics, a question remains about how other idea generation techniques compare. The 77 design heuristics are more specific than some other idea generation techniques, and they offer an intermediate level of description on how to use each heuristic [114]. However, because design heuristics are more specific, there are consequently more of them. In addition, design heuristics do not offer guidelines on when to apply a given heuristic; in fact, each heuristic is shown to be applicable in the same type of product (as differing designs for seating devices). It is likely that some

Table 1 An example of a morphological chart to design a way to wake someone up

Possible sources of power	Wound spring	Falling weight	Pendulum	Electric battery	Solar cells
Ways of indicating the time	Hands	Electronic display	Audio output	Projection display	Visual changes
Types of alarm systems	Buzzer	Bell	Various sounds	Vibrations	Flashing light

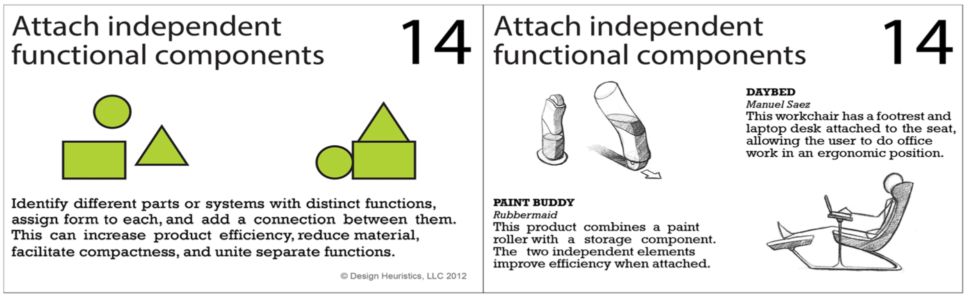

Fig. 1 Heuristic card example: attach independent functional components

heuristics are more useful in some problems, but further research is needed to identify cues about when the given heuristics are most relevant for application in a problem. Another open question is the technique's impact on initial idea generation compared to idea development later in the design process [60,61]. Increasingly, studies are showing the advantages of idea generation techniques, and which are most effective in given circumstances; however, few comparative studies including design heuristics exist [29,54,115–117].

This study sought to examine the qualities of ideas generated with the newer technique, design heuristics. For comparison, the most widely studied technique, brainstorming, and the most common technique from engineering design contexts, morphological analysis, were included. Additionally, by comparing these three techniques in a controlled experimental setting, subtle differences in the quality of the resulting concepts may be identified. In particular, this study investigated the relative advantages of idea generation techniques in the context of instruction for beginning designers.

Method

Research Goals. The goals of this research were to compare the qualities of students' designs generated using individual brainstorming, design heuristics, or morphological analysis as techniques for generating initial ideas for a design problem. Because our interest was in beginning designers, we recruited first year engineering students just prior to their first day of university instruction for the study. The following research questions guided our study:

- How do concepts generated with individual brainstorming, design heuristics, and morphological analysis compare in creativity, elaboration, and practicality?
- How do concept sets generated with individual brainstorming, design heuristics, and morphological analysis compare in quantity and diversity?

Based on our prior studies, we expected to replicate evidence (as discussed above) that more creative ideas result from the use of design heuristics; however, it was unknown how the three techniques might compare in facilitating creativity. We expected the structured guidance of both design heuristics and morphological analysis would foster student's ability to develop more elaborate and practical designs.

With regard to the set of ideas generated by participants, we expected fewer ideas to be generated with design heuristics and morphological analysis, as the time it takes to apply a more structured technique would likely result in fewer ideas in the short (25 min) idea generation period in this experiment. However, we expected the diversity of ideas to be greater using both design heuristics and morphological analysis because they support thinking while going beyond the natural tendencies of freethinking in brainstorming.

Participants. Participants were 102 entering first year engineering students at a Midwestern University. Students participated

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

Fig. 2 Heuristic card list

at the beginning of a design workshop just before starting their formal engineering curricula. Students volunteered to attend the workshop based on an interest in learning more about design. Participants were randomly assigned to one of three groups: an individual brainstorming section of 32 (27 male and 5 female); a design heuristics section of 35 (22 male and 13 female); and a morphological analysis section of 35 (20 male and 15 female).

Procedure. Three graduate students with prior teaching experience were trained to conduct the ideation sessions. PowerPoint presentations and scripts developed by the research team were used by the presenters in their separate, concurrent, 50-min sessions. The script focused on defining idea generation in design and describing the procedure for how to use a specific technique.

The introduction to idea generation and one technique was taught to each group during the first 15 mins of their sessions. Then, the students practiced their techniques in pairs for 5 minutes using a sample problem (for design heuristics, students were provided a subset of 15 cards). Next, instructors answered questions and asked students to share ideas with the whole group (5 minutes). Finally, students were asked to work individually on a new design problem, and to generate as many concepts as they could for a 25-mins period. They did not consult with other students during this individual idea generation period. Blank concept sheets were given to students to document their ideas, which prompted students to both sketch their ideas and describe them in words. The instructions for the concept generation task asked students to use their technique "to generate as many varied and creative ideas as possible."

The design problem chosen for the study was the same across the three techniques. It was intended to represent a mechanical engineering design scenario that was accessible for first year engineering students. The problem was developed in multiple rounds by first reviewing design problems documented in design research experiments, engineering curricula, and national reports. This collection of design problems was filtered based on multiple qualities, including that the problem would be recognized as an engineering design task, situated in a context in which students had some background or experience, accessible to beginning designers, solvable without in-depth content knowledge, amenable to product design solutions, and novel enough to avoid many popular existing solutions students may have known. Two researchers rated the design problems based on these criteria, and the top three were used in a pilot test. During the pilot test, students learned each of the three ideation techniques, and applied it to one of the three pilot design problems, and then rated its ease in use to generate ideas. The problem rated most equally in ease of use across the three techniques was selected for the study.

The final design problem (provided in a paper handout) used in the experiment was: Many full-grown adults are constrained to a sitting position or have limited vertical reach, including paraplegics (people with paralyzed legs), the elderly, stroke victims, people recovering from leg or back injuries, people who have muscle or nerve disabling disorders, or little people. Limited vertical height can make many day-to-day tasks (such as reaching an overhead cabinet or changing a light bulb) a significant challenge. Your task is to design devices that would help people to overcome these height-constraining disabilities.

After data collection ended, all students were instructed on the remaining two idea generation techniques for educational purposes.

Data Analysis. Concept sheets collected in the study were de-identified, and textual descriptions were transcribed. The size of the drawings was adjusted for all concepts so that they were approximately the same. Examples of the concept sheets are shown in Fig. 3 (a randomly assigned concept number is in the upper left). In total, across the three experimental conditions, 102 students generated 439 concepts in the 25 min session, ranging from 1 to 11 from each student, with an average of 4.3 (SD = 1.95).

The analysis assessed all of the concepts generated for creativity, elaboration, and practicality, and measured each individual's concept set for quantity and diversity of ideas. These characteristics are commonly used to assess ideation success in open-ended tasks [118–121]. The consensual assessment technique was utilized for all measures besides concept set quantity [118]. This technique is the most widely used metric for assessing qualities of creative work samples based on knowledgeable raters' intuitions about what creativity means within a field. In this technique, two coders independently perform subjective ratings of every concept [122]. This has the advantage of capturing aspects of creative work that are subjectively recognized by judges, but are difficult to define or code objectively. The CAT has been widely used because subjective judgments of creativity have been shown to result in high levels of consensus across judges [123]. The two raters for this study were more expert in the mechanical engineering product design domain than the participants, having completed at least 3 years of mechanical engineering product design coursework. They also each had multiple design experiences in which they developed conceptual ideas and physical functional prototypes. This level of rater expertise is comparable to other research leveraging the consensual assessment technique [124,125].

The raters were "blind" in that they did not know any specifics of the study; for example, they, did not know that the concepts were created with the three different idea generation techniques, which concepts were generated by which subjects, the condition a given subject was in, or the study hypotheses. The 439 concepts were presented on paper in a different randomized order for each rater.

Consistent with the Consensual Assessment Technique, we asked the raters to score each concept using a scale from 1 to 7 (where 7 is the "most" of a category—most creative, most practical, or most elaborate–and 1 is the "least") based on their understanding of the field and looking at concepts relative to one another [118]. The raters completed multiple rounds of scoring while considering only one variable at a time. Each rating task (creativity, practicality, and elaboration) occurred in separate installments, with the concepts placed in a random order at the beginning of each round. The raters were instructed to begin by gaining exposure to the full range of concepts in a first round of rating, placing concepts into piles labeled 1 through 7. After completing this first round, raters had a clearer understanding of the scale. Then, in the next round, they took each pile (representing a rating of #1 though #7) from the first pass and sorted through all of the concepts again, moving concepts into different piles as needed until there were no changes. When the rater felt that all concepts had been placed in the appropriate piles to reflect their rating, that round of sorting was considered complete. The two

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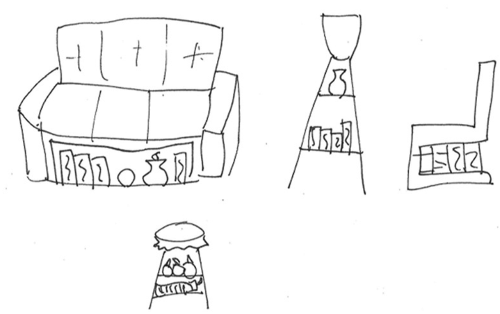

Furniture which doubles as storage. Couches, chairs, and lamps for the family living room, stools & tables for the kitchen, beds for the bedroom, etc.

Fig. 3 Students' work shown on transcribed and adjusted concept sheets

raters each scored 439 concepts for creativity, elaboration, and practicality.

A final rating round assessed each individual's concept set for the number of concepts generated (fluency, a simple count of concepts) and their diversity. Diversity scores were completed in a similar manner using the modified CAT approach. Booklets of each participant's concepts were created, and the raters considered the diversity of the entire set of concepts from a single student on a seven-point scale. The piles in this rating task represented the diversity of a subject's set of concepts on a scaled from 1 (not diverse) to 7 (most diverse). Because subjects generated different numbers of concepts, the set size of the concepts considered varied with each individual student. Raters scored 102 concept sets for diversity.

This coding effort was conducted on separate days for each round over a period of 2 weeks. Examples of high and low scores for the creativity, elaboration, and practicality metrics are included in Fig. 4. To estimate the consensus between raters on each dependent measure, a popular modification of the percent of adjacent agreement was computed. With seven levels in each scale, ratings for each concept were considered to have reached consensus if they did not differ by more than one point above or below the other judge [126]. For the creativity ratings, the percent of adjacent agreement (within one score point) between raters was 74%; for elaboration, 90%; for practicality, 83%; and for diversity, 75%. Cronbach's alpha coefficient was also determined for each measure to estimate the consistency between raters: for the creativity ratings, $\alpha = 0.70$; for elaboration, $\alpha = 0.83$; for practicality, $\alpha = 0.79$; for diversity, $\alpha = 0.78$. All values greater than 0.70 are typically considered acceptable for consistency estimates of inter-rater reliability [123,127].

Averages of the two raters' scores for each assessment characteristic were used for statistical analyses. Concept-level analyses were computed using a linear mixed model to account for clustering of concepts by the same subject (i.e., a random effect intercept nested by subject); subject-level analyses were computed using the traditional general linear model (i.e., analysis of variance). Post hoc tests comparing cell means used the Tukey method for correcting for multiple tests. As appropriate, we also conducted an analysis of covariance (ANCOVA) to address an alternative explanation as outlined in the subsequent text. We used the conventional two-tailed, type I error rate of alpha = 0.05.

Results

Example solutions generated by participants using each of the three ideation techniques are represented in Fig. 5. The types of concepts generated with each technique varied in the approach to supporting vertical reach, as well as in the specificity of the concept. For example, with individual brainstorming, the examples demonstrate a range of ideas, from a stand that can be cranked up and down, to moving shelves, to a kitchen that can be rearranged by connecting it to a computer. Examples generated with design heuristics included a vacuum tube that picks up items, a mechanical track to bring items down to the user and back up to the shelf, and sliding shelves that are rearranged by remote control for access. Examples of morphological analysis-inspired concepts included a chair with wheels and a lifting mechanism, an

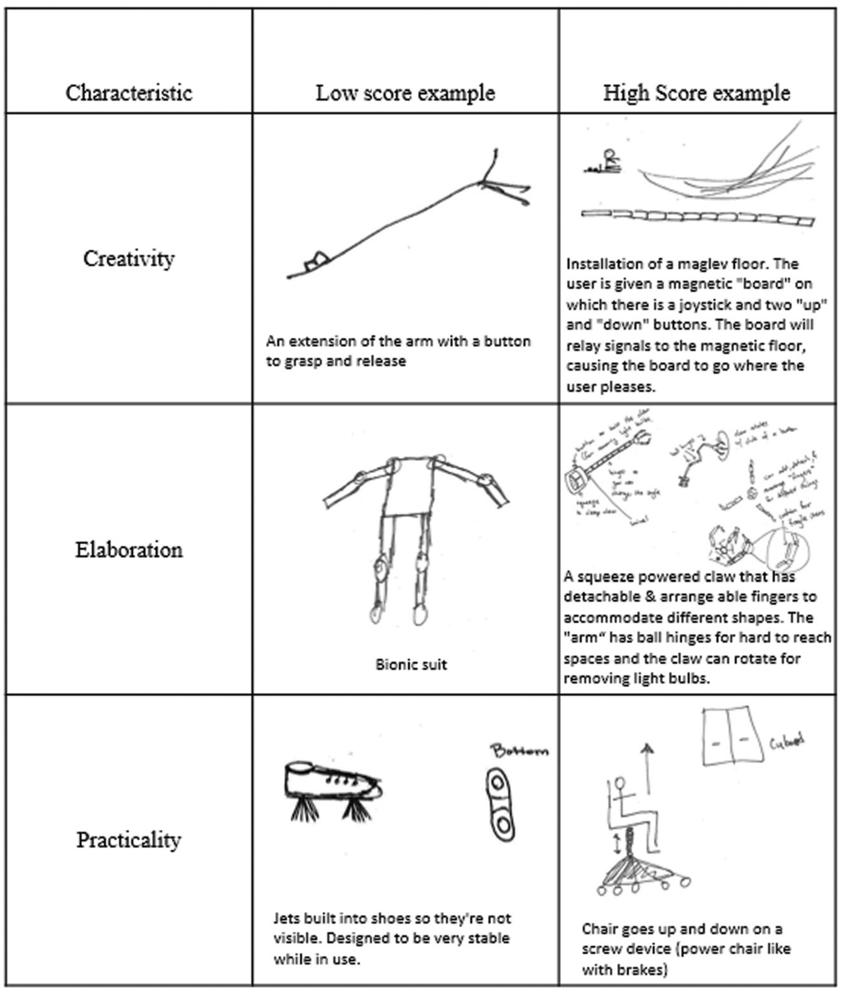

Fig. 4 Examples of low and high scoring concepts

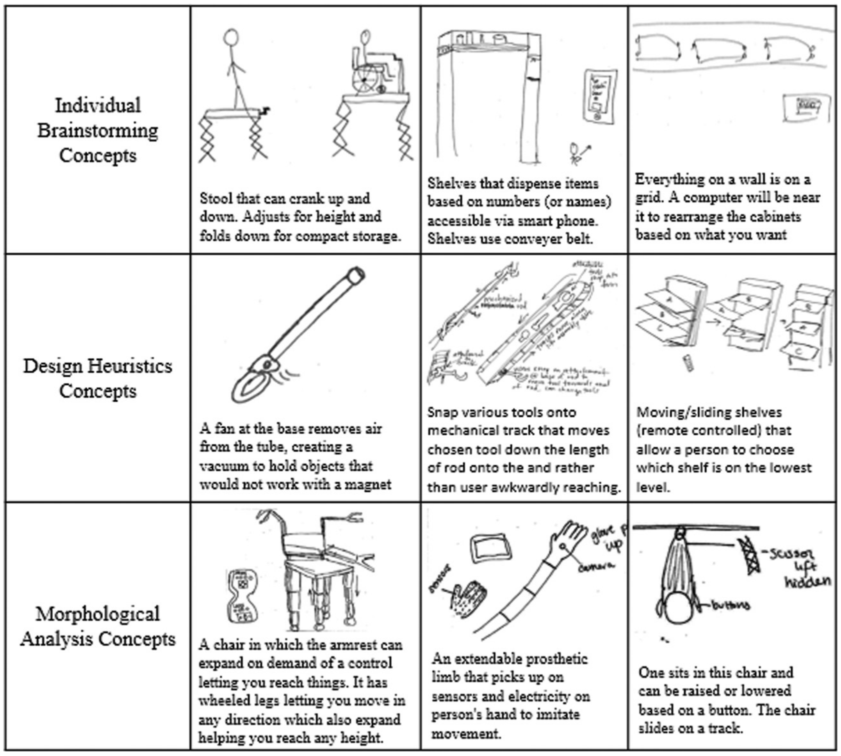

Fig. 5 Example solutions using each ideation technique

extendable prosthetic limb, and a hanging chair that lifts, lowers, and slides. The results of our analyses across all concepts in each of the three groups are reported in the next two sections: (1) analysis of concepts and (2) analysis of concepts sets.

Analysis of Concepts: Creativity, Elaboration, and Practicality. The averages for each experimental group on the ratings for creativity, elaboration, and practicality are shown in Fig. 6. For the creativity ratings, no significant differences emerged among the three concept generation techniques. However, for both practicality and elaboration ratings, there were observable differences among the technique groups. Practicality was significantly higher in the design heuristics group compared to both individual brainstorming ($p = 0.001$) and morphological analysis ($p = 0.02$). There was no significant difference between individual brainstorming and morphological analysis for the practicality measure ($p = 0.14$). For elaboration ratings, both design heuristics and morphological analysis groups scored significantly higher than individual brainstorming ($p = 0.05$ and $p = 0.02$, respectively). There was no significant difference between design heuristics and morphological analysis for concept elaboration (level of detail; $p = 0.91$).

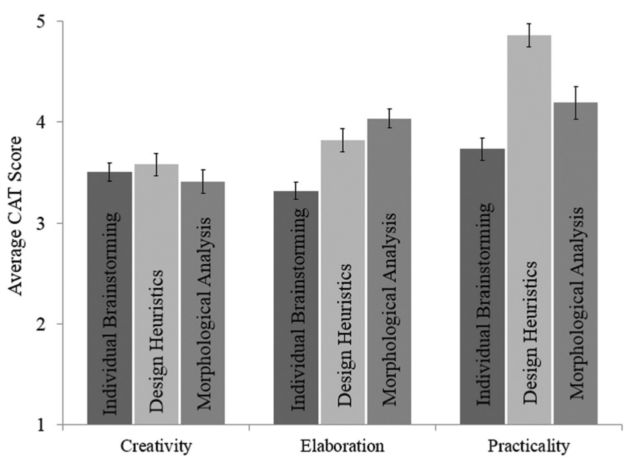

Fig. 6 Average CAT scores for concepts generated with each ideation technique

Analysis of Concept Sets (Subject-Level): Quantity and Diversity. The average number of concepts generated (idea fluency) and the diversity ratings for the concept sets are shown for each group in Fig. 7. More ideas were generated in the individual brainstorming group compared to both the design heuristics ($p < 0.001$) and morphological analysis ($p < 0.001$) groups in the 25-min work session. Design heuristics resulted in a similar number of ideas generated as morphological analysis ($p = 0.09$).

For the diversity ratings of concept sets, individual brainstorming was not different than design heuristics ($p = 0.09$), but both brainstorming ($p < 0.0001$) and design heuristics ($p = 0.02$) differed from morphological analysis. However, the assessment of diversity for each participant was confounded with the size of the concept set, in the sense that concept sets with more concepts have a greater potential to show greater diversity.

To examine whether there were group differences in diversity after controlling for number of concepts, we conducted an ANCOVA. Across technique groups, there were no significant differences in diversity ratings of solution sets (all p's > 0.10). The number of concepts generated and diversity ratings were very highly correlated across the entire sample ($r = 0.57$) (see Fig. 8), with similar correlation values within each of the three experimental conditions. Thus, the diversity differences observed may be partially accounted for by the differing number of concepts generated by each subject.

Discussion

The results from the analysis of concepts using the three idea generation techniques showed differences in the observed

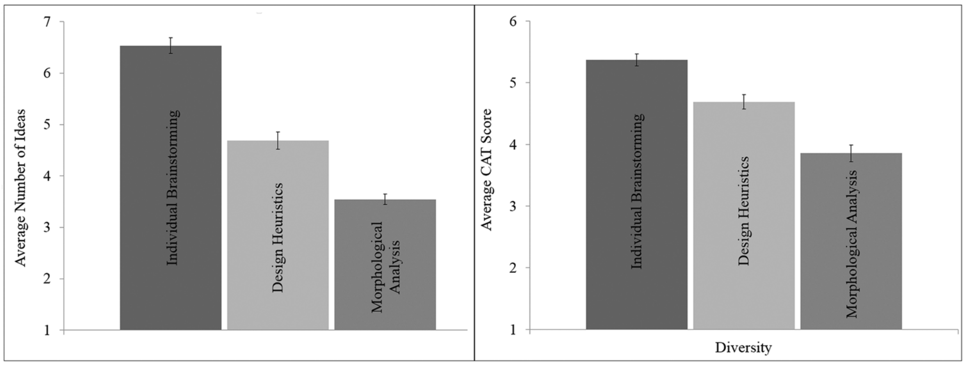

Fig. 7 Average number of concepts generated and CAT scores for diversity of concept

qualities as assessed by independent raters. Key results from our analysis included:

- Practicality ratings for concepts were highest in the design heuristics group compared to the others.
- Elaboration ratings for concepts generated in the design heuristics and morphological analysis groups were higher in than in individual brainstorming.
- More concepts were generated in the short (25 min) ideation period with individual brainstorming.
- There were no significant differences in rated creativity of concepts based on the ideation technique used, nor were there differences detected in diversity ratings when controlling for differences in quantity.
- The newer design heuristics technique performed at levels equal to or better than the widely used idea generation techniques of individual brainstorming and morphological analysis.

The results revealed differences in some of the concept qualities (elaboration and practicality) by ideation technique. Design heuristics and morphological analysis are more specific, and more technical, concept generation techniques than individual brainstorming. These two techniques may facilitate a more structured or detailed idea generation process, shaping the concepts being generated toward those useful in engineering. As a result, these qualities of practicality and elaboration are enhanced in design heuristics and morphological analysis compared to individual brainstorming.

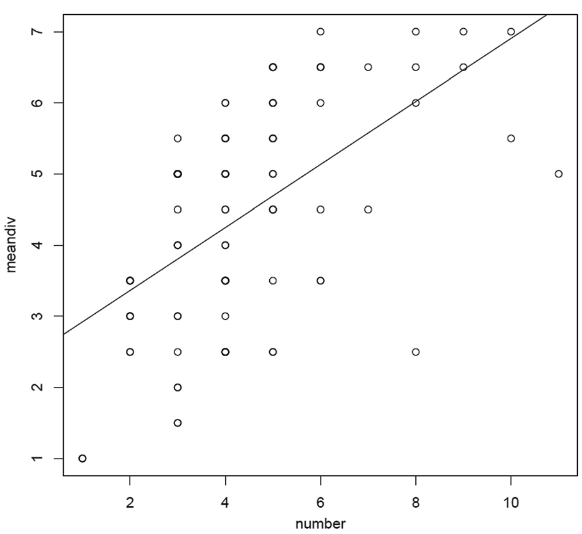

Fig. 8 Correlation analysis of number of ideas and diversity score

However, creativity ratings showed no method was superior; rather, the three techniques produced similar ratings. In addition, the ratings of the diversity of the concept sets produced were similar across techniques. These findings are consistent with those of Linsey et al. [59], who compared group ideation techniques including brainsketching, gallery, 6-3-5, and C-sketch. Their results (using different metrics) showed no differences in concept diversity and novelty based on ideation techniques. These parallel findings suggest that alternative idea generation methods may work to promote creativity to the same degree, but in differing ways. It is important for further studies to identify how idea generation methods affect the creativity of concepts in order to understand these findings.

Though we observed differences in the number of concepts generated across the three conditions (and hence more diverse set of concepts), there were no differences in observer-rated creativity among ideation techniques. One explanation could be that current metrics are not suitable for detecting differences in the creativity of concepts. This study and Linsey et al.'s [59] used different metrics, but both studies were not able to detect differences in creativity of designs. In our own prior work [43], as well as work of others (e.g., see Refs. [121], [128], [129]), creativity metrics have identified differences, but those contexts had notable differences, including a more limited solution space [130], fewer concepts [43], and more extreme conditions (such as with and without an ideation technique) [22,43,54,55]. If there are no differences in creativity across the three techniques, at least in this short task time frame, simply producing more concepts does not necessarily guarantee more creativity. Instead, there may be a greater number of concepts required before differences in creativity can be detected. This notion of a quantity threshold provides an additional lens to understand when and if generating more ideas leads to more creative ones [131,132–134].

In contrast with the present findings, Sangelkar et al.'s study [51] found that more ideas, more diverse ideas, and more novel ideas were created with a combination of design heuristics and morphological analysis compared to other techniques (including brainstorming). Key differences in the studies included that students in their study had a longer ideation session (50 mins of class time and a between class periods to incubate) to generate ideas and that students had been working on the design problem prior to the ideation session. Both prior exposure to the design context and the amount of time available to generate ideas are important factors in the impact of idea generation techniques on creativity. Because the ideation session in the present study was short (25 mins) and students had not had any prior exposure to the design problem, it is possible that the task may not have continued long enough for the creative advantages of any technique to become evident, or for deep exploration of the design space. Longer ideation sessions, with more concepts generated by each participant, may be necessary in order to observe differences in creative performance based on generation method. For example, it is possible that the less-structured technique of brainstorming may result in eventual impasses in generating solution ideas compared to the more structured morphological analysis and design heuristics. However, no changes in creative concepts would be observable in a short ideation task, where time runs out before ideas.

Prior research provides ample evidence that the designers often come to idea generation sessions with ideas to which they are already attached [12–14,16,17,19,20,135]. It may be that idea generation techniques may be better differentiated on creative impact on outcomes once students have exhausted the ideas they already have. Design heuristic and morphological analysis techniques may be more helpful after concept generation by brainstorming or other intuitive methods is exhausted. Students in all groups may have been most likely to use their ideas that came to mind naturally during initial ideation. One prior study has shown the value of an initial period of free-flowing ideation prior to the use of a specific technique; that is, allowing students to "get out" their first and obvious ideas, which then allows more productive use of alternative methods [136]. In the present study with its short work time, students' initial ideas may have interrupted attempts to use the idea generation techniques as directed.

A comparison of fluency scores found that more concepts were generated by the individual brainstorming group within the 25-min ideation session. Individual brainstorming may be faster to learn and apply than design heuristics and morphological analysis, and so may facilitate more concepts generated in a short time window. Students were more likely to have had prior exposure to, and familiarity with, the brainstorming approach. For both morphological analysis and design heuristics, students had to practice, for the first time, a new, more formal technique during their concept generation.

However, the results for elaboration and practicality suggest advantages to the other methods as well. Achieving higher fluency through Brainstorming may trade-off with the more elaborate designs created using morphological analysis, and with the more elaborate and more practical designs generated using design heuristics. Depending on needs for the design session, each of the three techniques provides advantages in solution qualities. And because the techniques differ in the design qualities they facilitate, it may be important for students to gain experience with all three techniques in order to generate creative designs. Based on the similarity in the creativity results across methods both here and in Linsey et al. [59], a argument can be made for training students on multiple idea generation techniques so that the relative advantages of each can be evoked.

Limitations. In studies comparing ideation techniques, it appears important to ensure that initial ideas are exhausted, and that sufficient time is provided to allow potential advantages of differing techniques to become evident. Because the present findings showed relative advantages among the three techniques, it is important for future studies to look for comparative strengths and weaknesses for differing techniques. Importantly, more time allowed for idea generation, perhaps with multiple work sessions, should be considered in future studies. In addition, it is important to include a variety of design problems when testing idea generation techniques. In the present study, a single design problem was employed, as is common in ideation studies. However, properties of design problems may result in differences in the utility of different techniques. Future research could compare the techniques across many design contexts.

An additional limitation of the present study was the size of the concept set that raters scored (over 400 concepts, a much larger set than in much of the existing literature on the CAT [43,131,137]). It may be that there is a limit to the ability to differentiate design qualities with that many concepts, resulting in less reliable judgments by coders. The reliability measures indicated consistency, but not high levels of agreement. Performing so many ratings may be especially difficult with variables like creativity and diversity of concepts that have more flexible interpretations.

In addition, the prior training of participants will likely affect their use of new techniques. A prior study of design heuristic use with nondesign students resulted in higher levels of creativity compared to controls [40]. In the present study, engineering students participated just before beginning their formal training, and so likely experienced similar levels of lack of knowledge in completing the design task. However, more advanced students (and even first year engineering students) have been shown to benefit from design heuristics instruction and produce more creative concepts [43,60,61]. For beginning engineers, brainstorming offers advantages of very brief training and rapid idea generation; however, the improvement in design elaboration and practicality observed with the other techniques may be increasingly important as domain expertise develops.

Finally, the ideation processes sampled in this study represent only a fraction of the idea generation process in real-world engineering settings. Longitudinal studies of idea generation and development guided by the use of idea generation techniques would contribute to a larger understanding of the impact of idea generation techniques on design outcomes.

Implications. These results have implications for engineering education practices for beginning designers. Design heuristics provides an approach to ideation that does not limit the creativity of ideation outcomes, and helps students to develop more elaborate and practical ideas. The design heuristics technique showed advantages in the initial idea generation phase for beginning engineering students, thus can be a useful addition to engineering pedagogy on concept generation in design processes.

Synthesis across the collection of studies comparing ideation method effectiveness reveals that different techniques have different strengths across different contexts and design problems, and likely across different students. Thus, design educators could support their students by exposing them to a variety of techniques, rather than relying on one. Our experiment suggests that if the goal is to generate as many ideas as possible in a short fixed time interval, individual brainstorming is the best of the three techniques. However, if the goal is to generate a practical set of concepts, our results suggest design heuristics is the best of the three. Elaboration was best fostered using design heuristics or morphological analysis rather than individual brainstorming. Design educators can benefit students and their ideas by exposing them to a variety of techniques that have demonstrated strengths.

Conclusions

Natural brainstorming is the simplest method to support initial idea generation by individual engineering students, and it also produced the most concepts. However, a short training session on either morphological analysis or design heuristics was sufficient to support students in creating novel designs, and morphological analysis and design heuristics resulted in more elaborated concepts than natural brainstorming, and design heuristics produced the most practical concepts. In this short ideation task, the three methods showed no differences in rated creativity of concepts. For a given design setting, differential weighting of criteria such as elaboration, practicality, and fluency may lead to different preferences for the use of idea generation techniques, or an advantage for learning and applying each technique.

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