Design Fixation From Initial Examples: Provided Versus Self-Generated Ideas

Keelin Leahy
University of Limerick,
Limerick V94 T9PX, Ireland
e-mail: keelin.leahy@ul.ie

Shanna R. Daly
Assistant Professor
Department of Mechanical Engineering,
University of Michigan,
2350 Hayward Avenue,
Ann Arbor, MI 48109
e-mail: srdaly@umich.edu

Seda McKilligan
Professor of Industrial Design
Iowa State University,
715 Bissell Rd,
Ames, IA 50011
e-mail: seda@iastate.edu

Colleen M. Seifert
Arthur F. Thurnau Professor
Department of Psychology,
University of Michigan,
530 Church Street,
Ann Arbor, MI 48109-1043
e-mail: seifert@umich.edu

*Jansson and Smith (1991, "Design Fixation," Des. Stud., **12**(1), pp. 3–11) demonstrated that design fixation occurs when an example solution is provided along with a design problem. After seeing an example concept—even with its flaws pointed out—new designs often share its features. In Jansson and Smith's studies, a control group saw no example and showed less fixation to the example provided only in the other group. However, another source of fixation from an initial example may arise in the control group from the designer's own first-generated concept. We conducted a large-scale experiment with beginning engineers to investigate whether design fixation occurs even without seeing a provided example. Half of the participants saw an example solution and half were given no example; instead, they generated their own initial design. Next, all students were individually brainstormed ideas for 30 min. We analyzed both groups' concepts for fixation on the first solution they saw—either the example provided or their own initial concept. The results showed that the students provided with an example concept experienced* less *fixation on the initial example than those in the control group, whose concepts were evaluated for similarity to their own initial concept. To consider whether fixation on initial examples (provided or self-generated) might be mitigated, we asked these students to complete a second (30 min) idea generation phase using Design Heuristics for idea inspiration. The results showed that both groups experienced less fixation during the second-generation phase. These findings suggest that fixation on first solutions occurs in individual idea generation arising from both provided examples and self-generated concepts. However, more divergent idea generation can be facilitated through the use of design tools, such as Design Heuristics, to mitigate the consequences of design fixation.* [DOI: 10.1115/1.4046446]

Keywords: conceptual design, design education, design methodology, creativity and concept generation, cognitive-based design, generative design

Introduction

In an ideal world, an initial idea generation session results in plausible design concepts that are varied in nature, providing a diverse set of possible solutions. If a designer generates more concepts with varied features, the development of novel and innovative solutions seems likely to ensue [1,2]. However, engineering designers have been shown to struggle with generating multiple alternative designs and instead tend to focus on a few specific options early in a design process [3–6]. As a result, developing a successful solution may be challenging for designers [7,8].

In particular, *design fixation* arises when designers become focused on an initial example early in a design process [9], leading to limitations in a variety of alternative designs considered. Recent research has identified multiple factors within the design process that can prompt overreliance on pre-existing designs, example solutions, current designs, and prior knowledge [10,11]. While fixation naturally arises in many cognitive tasks as a result of associative memory processes [12–14], creativity in design requires identifying ways to move past fixation to identify divergent ideas. A wide variety of methods have been examined as ways to mitigate overreliance on existing designs and current knowledge [10,15,16].

For beginning designers, learning to generate design concepts is potentially less impacted by fixation than more advanced designers because by definition, they have less prior knowledge in memory to interfere with new ideas. On the other hand, with a limited repertoire of design ideas, beginning engineering students may be at higher risk of fixation on a solution they see presented as an example, and so may be in greater need of methods to reduce its impact [17]. While prior studies have examined student engineers and novice designers, beginning engineers present an opportunity to examine the value of presented designs and their interference in generating divergent alternatives.

In the present study, we conducted a large-scale experiment with beginning engineers to re-examine design fixation within the classic Jansson and Smith [9] paradigm. While their studies of novice and expert engineers showed that providing an initial example solution resulted in more frequent fixation, their comparison was a control group where no example was presented. But what if these engineers in the control group also fixated on an initial example? Their own self-generated examples may serve as an alternative source for fixation. Studies have shown that designers prefer their own initial designs, giving them higher rankings than solutions created by others [3,18]. Thus, we hypothesized that in an idea generation session (as in the Janssen and Smith [9] paradigm), providing no example (in the control group) may result in initial example fixation arising from the designer's self-generated initial concept.

If so, methods to mitigate the effects of design fixation are even more important; thus, we included an additional idea generation phase where an ideation tool, design heuristics, was provided to determine whether fixation observed in the first phase could be reduced. Other studies have shown that fixation can be reduced through the use of idea generation supports, such as analogy after a delay [15,16]. In our experiment, students worked alone to generate designs in an initial individual brainstorming phase either with or without a provided example as in Ref. [9]; then, all students went directly on to complete a second idea generation phase where they used a prompt-based generation tool, design heuristics

Contributed by the Design Theory and Methodology Committee of ASME for publication in the Journal of Mechanical Design. Manuscript received August 28, 2019; final manuscript received February 7, 2020; published online February 22, 2020. Assoc. Editor: Scarlett Miller.

[19,20] to spur the creation of new designs. We hypothesized that the design heuristics ideation tool could mitigate the effects of fixation on initial examples.

Background

Jansson and Smith [9] defined design fixation as "…blind, sometimes counterproductive adherence to a limited set of ideas in the design process." Studies have shown that designers can fixate on pre-existing solutions related to the problem at hand [11] and on more general prior knowledge [10]. Consequently, the term *design fixation* has been generalized to refer to any situation where designers limit their proposed concepts by including features from any form of pre-existing knowledge [9]. The cognitive factors influencing fixation have also been explored, resulting in a taxonomy defining fixations as unintentional or intentional, and conscious strategies or unconscious influences on the designer [10]. Reviews of this burgeoning research area have explored how variations in cognitive processes lead to fixation, and called for further research to identify how fixation on examples limits the generation of alternatives [10,11,21,22]. Other studies have examined fixation in more varied design settings, including additive manufacturing [23], information system design [24], and "in the wild" [25].

Expertise and Fixation. Fixation has also been documented in professional design practice [6,26–28]; for example, Condoor and Lavoie [8] found no differences in fixation occurrences between expert and novice designers, and Kim and Ryu [29] found experts were even more prone to fixation than novices [29]. In case studies of professional architectural design, Rowe [30] observed that initial design ideas appeared to dominate, suggesting a preference for repairing an existing concept (even if further effort is required) rather than starting again with a new one. Protocol studies of experienced mechanical engineering designers also found they typically pursue only a single design concept [3]. Ball et al. [4] documented fixation with senior student engineers in a longitudinal study and observed "…fixation on initial concepts and the attempt to make them satisfy the problem requirements whatever the eventual cognitive cost." However, fixation may not necessarily be negative; for example, the narrowing of search seen in fixation may lead to higher quality and more novel proposed concepts by encouraging a narrower and deeper search [31]. Cross' [32] review of studies of expert designers suggested a more focused search approach is characteristic of expert practice. For example, a study of expert software designers found they focused on one solution very early and did not explore any alternative solutions in depth [33]. With greater expertise, a designer may be successful even when they focus on a single solution approach.

Like experts, novice engineering designers also appear to have an attachment to early solution ideas and hang onto concepts even when they realize they may be extremely problematic or include major flaws [3,4,30]. For beginning engineers (entering professional school) and novices (those in their first 2 years of study), fixation may be an even larger threat than for experts because their inexperience in generating designs may increase the perceived value of known solutions. Engineering students have limited idea generation strategies to support exploring alternative solution concepts [5,34]. Engineering students may also prefer their own early ideas, and Rowe [30] documented that their concepts were often minor variations on the same initial idea. Engineering students may be unaware of strategies to support the exploration of other solutions different from their initial ideas [5,34]. Fixation may also take the form of false assumptions, perceived (invalid) limitations, feeling overwhelmed, gathering incomplete or partial information, and applying ad hoc solution methods [35], all more likely for beginning students.

Thus, techniques to help overcome fixation in idea generation may be especially important for beginning designers developing their divergent idea generation skills. In addition, developing the skills to generate diverse solutions requires an ability to identify fixation as it occurs during one's own idea generation process. With awareness of fixation, the designer can decide how to direct idea generation efforts. However, if the designer does not recognize that fixation is occurring, they are both unable to consciously focus on a chosen direction and unable to generate a diverse set of potential concepts. Developing expertise about fixation may be critical in reaching a decision to "…scrap their initial design and start afresh with a new design concept" [36] and improve solution quality.

Fixation on Provided Examples. For beginning engineers in particular, examples appear to play an important role in design problem presentation. In instructional settings, examples play a variety of pedagogical roles, such as making design criteria more complete or concrete, illustrating qualities needed in potential solutions, and even simply confirming that a solution is in fact possible [37]. Examples may carry weight because they are introduced by the instructor along with the problem description. When seeing a provided example, research students may simply copy examples in order to avoid unnecessary work [10]; thus, some design fixation may occur because students recognize the example as an existing solution they can adopt and adapt.

While examples have been shown to *cause* fixation in experiments with designers, researchers have also proposed that examples can *mitigate* fixation. Vasconcelos and Crilly [11] suggest that example solutions may "inspire" new solutions, giving rise to "… new ideas that… would otherwise be very unlikely to emerge" (p. 1). They reviewed 25 studies exploring factors such as modality of the example, number of examples provided, diversity, and novelty of examples; however, findings have been inconsistent across studies. Familiar examples produced more fixation [38,39], though Perttula and Silipä [40] found it also led to better design outcomes. Logically, the number of examples provided with a problem should impact fixation, but Perttula and Sipilä [40] and Dahl and Moreau [41] found no effect. Sio et al. [21] suggested that providing several examples could even further inhibit creativity and concluded that providing a single example is better than multiple ones.

While examples can be valuable to student engineers, in addition to deciding which examples to provide, there is the question of *when* to provide them. Sio et al. [21] concluded that presenting examples at the beginning of solution attempts produces a larger positive impact. Perttula and Liikkanen [42] found that presenting examples in the middle of a design process resulted in the exploration of more categories. Vasconcelos and Crilly [11] suggested providing examples when designers are experiencing exhaustion in their solution attempts. Other studies suggested examples are more effective after designers reach an impasse (are "stuck") in concept generation [43], while Siangliulue et al. [44] added that designers must also be aware that they are stuck. In addition to these questions about whether and how to present examples to developing engineers, the larger questions of how design fixation arises from cognitive processes remains undetermined [21,22].

In their seminal study of fixation on provided examples, Jansson and Smith [9] introduced a method for identifying design fixation. First, they showed engineers an initial example solution alongside the presented design problem. The example provided was an "unsatisfactory" concept, with concomitant flaws pointed out in a text description. Nonetheless, the engineers in the study (both expert and novice) made use of the flawed designs as models for their own concepts. Across four studies, presenting a single, flawed example did not affect fluency (the number of new designs created) compared with a control group not provided with an example. Fixation was measured by counting the similarity of the example's key features within the new designs created by each engineer. Jansson and Smith [9] found a higher rate of fixation on the provided example features and concluded that provided examples were a major contributor to design fixation.

Later studies replicated fixation arising from provided examples, demonstrating their continued influence in subsequent concepts [27,45]. Sio et al. [21] performed a meta-analysis of over 40 studies using Janssen and Smith's (1998) paradigm, and concluded that providing examples leads designers to spend more time exploring and developing more concepts; but, these concepts are more often similar to the provided examples. As Crilly and Cardoso [22] pointed out, such studies are now sufficient in number that several literature reviews have summarized fixation [10,11,21] as the consistent impact of a single provided example.

Fixation on Initial Ideas. Even when no example is provided, a designer always has an initial example available: their own, first-generated concept. Cross [5] identified this self-generation source of fixation in settings where designers perseverated on their first-generated concept even when difficulties and shortcomings were identified. Other studies identified a tendency for designers to prefer their own initial concepts [18] and to hang on to concepts even when they realized they were extremely problematic or had major flaws [3,4,30]. Designers have also shown a "sunk cost" effect [46], where there is an early commitment to an initial concept, especially when investments such as prototype costs are involved [47]. Other studies have identified existing designs and initial concepts created by the designer as sources of fixation [10]. However, no study has compared these two alternative sources of design fixation within a single study.

In both situations, fixation on an initial example could be mitigated by setting quantity goals and engaging in broad exploration of a solution space [48–53]. Setting explicit quantity goals while brainstorming ideas have been shown to result in producing more ideas [54]. If designers cling to initial examples because generation is challenging, using generation tools as support may reduce fixation. Previous studies have explored design-by-analogy tools to support idea generation and shown that fixation effects from presented examples can be reduced [15,16]; however, these studies included a 2-day delay between an initial generation phase and a second phase with the support tool. Is it possible to mitigate design fixation within a design session? And, which idea generation tools might be effective?

In a report from an international workshop on design fixation research, Crilly and Cardoso [22] pointed out that induced "fixation is a good context for studying the effectiveness of creativity tools." A wide range of over 170 different concept generation techniques have been identified (Smith, 1998), including analogical thinking [55], morphological analysis [56], Synectics [57], questioning [58], lateral thinking [59], conceptual combination [60], Scamper [61], transformation principles [62], and TRIZ [63]. However, few of these strategies have been empirically validated for their effectiveness in improving the diversity of designs generated [64].

One idea generation tool, design heuristics (summarized in Ref. [20]) was derived from empirical studies of product designs: (1) protocol studies of industrial and engineering designers [65], a comprehensive analysis of over 400 products [20], and a qualitative analysis of over 200 concept sketches by an expert designer [66]. The resulting 77 design heuristics capture patterns of cognitive strategies that guide designers in introducing variations into concepts [20]. These cognitive "rules of thumb" were shown to prompt designers to consider ways to add variation into their concept set; however, each prompt was also shown to be applicable across different design problems and concepts, and even used repeatedly to produce different concepts [65]. *Design heuristics* have been shown to be effective for beginning, novice, and advanced engineering students [64,67–69] as well as expert designers [70,71]. However, research has not yet examined whether "induced fixation" [22] on initial examples—both provided and self-generated—could be mitigated in the same session through the use of the design heuristics generation tool to spur changes in the diversity of concepts considered.

Method

Our goal in this research was to re-examine and extend the methodology from Jansson and Smith [9] documenting fixation on initial examples. As in their study, we wanted to compare fixation arising from an example provided with the design problem to fixation arising when no example is provided. In this control condition, we hypothesized that fixation may still occur based on one's own initial design as a source. The fixation from provided examples and initially generated examples can then be directly compared. This study design is based on Jansson and Smith [9] as the dominant paradigm for design fixation studies, as reported in a review by Vasconcelos and Crilly [11]. Second, in order to examine ways to overcome fixation effects, we extended this paradigm by adding a second (immediately following) idea generation phase supported by a design ideation tool. This added phase can determine whether observed fixation can be mitigated by using the design heuristics tool for inspiring idea generation.

Research Goals. Our study used the same materials and procedures as in Jansson and Smith [9] in order to make a specific comparison of the two alternative fixation sources in initial examples. The first research question was: How does fixation on provided examples compare to fixation on self-generated designs? Our hypothesis, based on previous findings [9] and the well-documented fixation effects in the design literature [5,11,26], was as follows.

Hypothesis 1: Providing Examples Leads to More Fixation. These prior studies report those who see a provided example show fixation in their generated solutions compared with a control group where no example is provided (as in Ref. [9]). However, these studies do not examine whether fixation could be occurring in the control group as well; if so, fixation may arise from the initial example generated, as reported by Youmans and Arciszewski [10].

Because fixation on provided examples is so pervasive, we also sought to examine ways to mitigate its effects. Our second research question was: Can designers showing evidence of fixation (from either source—a provided example or their own initial example) break away from it in the same session through the use of a design ideation tool? While several idea generation tools have been shown to reduce fixation [23], design heuristics were selected for this study as an example of a design ideation tool supporting idea generation [64]. Design heuristics are empirically tested and shown to be helpful in idea generation [64,69,70,72]. Our second hypothesis was as follows.

Hypothesis 2: Using the Design Heuristics Idea Generation Tool Can Help to Mitigate Fixation. We predicted that the first idea generation phase using individual brainstorming could induce fixation effects as observed in other studies; if so, continuing in a second idea generation phase using design heuristics would determine whether a design ideation tool could mitigate existing fixation effects. Using design heuristics to prompt students to consider more varied designs may improve outcomes by avoiding similarities to an initial example, whether provided or self-generated. This would indicate that idea generation tools can be helpful in reducing design fixation in the same design session.

Participants. One hundred and twenty-two male (65.9%) and 63 female engineering students at a major research university in the Midwest participated in the study. The students' ages ranged from 17 to 18 years of age ($M = 17.9$; standard deviation (SD) = 0.46). The students were recruited through a free, 2-day workshop offered to incoming engineering students and were not compensated for their time. As this was an educational workshop, all students received the same training on Individual Brainstorming and the design heuristics tool for idea generation. The original study by Jansson and Smith [9] included 56 engineering students (25 in study 1; 31 in study 2) divided into two groups and did not include statistical analyses of group differences. By including a larger sample in the present study ($n = 185$), we were able to employ statistical tests of the factors (source of example, type of idea generation) in our study.

Materials. Two design problems from Jansson and Smith's [9] study of fixation on provided examples were employed in this study:

No-spill cup problem: "Design a disposable, spill-proof coffee cup. The design should be operable with one hand, durable and should not include a mouthpiece or straw."

Bike rack problem: "Design a car-mounted bicycle rack that addresses the following needs: (1) Easy mounting of the bicycle, (2) Easy mounting of the rack, (3) Cannot harm bike or car, and (4) Must be versatile for all bikes and cars."

For the example-provided conditions, each problem was paired with an example concept sketch and a description of flaws in its design presented on a single page. This text read as follows.

No-spill cup problem: "Below is an example of a spill proof coffee cup. Please note, the straw will leak when the cup is rotated 90 deg from the angle shown. The cup will leak if squeezed and the hot liquid emerging from the straw will burn one's mouth."

Bike rack problem: "Below is an example of a present day bike rack. The bicycle is set in the rails and the vinyl coated hook is attached to the seat tube of the bike, and then the hook is tightened down by hand with a wing nut. One should note the difficulty of mounting the middle bikes on the rack."

The example design concept sketches provided [9] are shown in Fig. 1.

For the self-generated example condition, only the problem description was presented. Just as in the Jansson and Smith [9] study, students in the control condition did not see any example design concept or description of flaws.

Separate concept sheets for recording each new design were provided. The top of each sheet included a boxed space for sketching, and below it, a prompt was presented: "Describe the concept in detail. How does it work? What are the unique features, mechanisms, and details?" For the second idea generation phase using design heuristics, each concept sheet included an additional prompt: "Did you use any specific strategies or Design Heuristics cards? If so, write the number of each card you used. If you did not use any, write "none.""

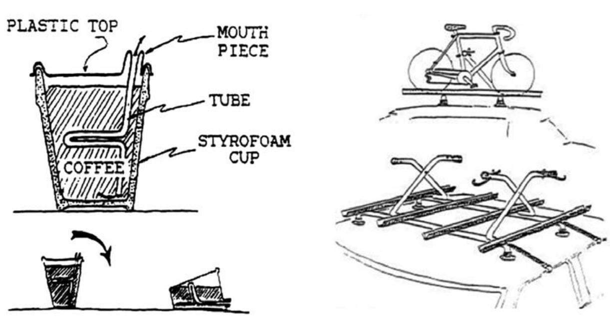

Fig. 1 (*a*, *b*) **Example concepts provided for the two problems: no-spill cup (left) and bike rack (right) [9]**

The design heuristics were presented individually on 3×5 cards in a format shown to be effective in enhancing concept generation in first-year engineering students [19,65]. Each card describes one heuristic and shows a graphical illustration on one side and two example consumer products illustrating the heuristic on the other (Fig. 2).

This design heuristic, "Redefine Joints," suggests modifying the way that product parts are connected by removing, covering, or changing the orientation of joints. In the product on the bottom right, the chair back and seat are joined together inside an overwrapping fabric. This heuristic may lead to the development of concepts that improve the visual consistency of the product and enhance the safety of product operation.

The set of 77 design heuristics cards is listed in Fig. 3. Each heuristic is a distinct cognitive strategy to use in generating new concepts [19]. However, in our second hypothesis, we did not make predictions regarding specific heuristics (shown on each card); instead, we expected that any of the strategies could support exploration of more diverse solutions. Thus, and additionally for ease of administration, the cards were selected at random into five subsets drawn from decks of the 77 cards. Each student's pack of design heuristics cards contained 15 of the 77 cards. With only 30 min to create new concepts, pilot testing found that 15 cards per pack were enough to ensure students always had new cards available if desired.

A post-study questionnaire presented demographic and other reflection questions about the concepts generated in the study.

Procedure. Students were assigned at random to one of four 95-min design workshops held in separate rooms. Two workshops ran concurrently followed by another two concurrent workshops with different students. Two trained proctors familiar with idea generation and design heuristics led the workshops. In each workshop, students were given a large envelope including all of the materials needed for the study. In a 2×2 experimental design, each student was assigned at random to one of two design problems (no-spill cup or bike rack) and one of two fixation source conditions (example provided or self-generated example). So, each student saw only one problem and were either presented with an example solution or generated their own initial solution. All four workshops followed the same procedure and timeline for the study (shown in Fig. 4).

Students worked individually in all of the tasks in the study. First, students were introduced to the presented problem. Then, students saw either a provided example concept or they generated their

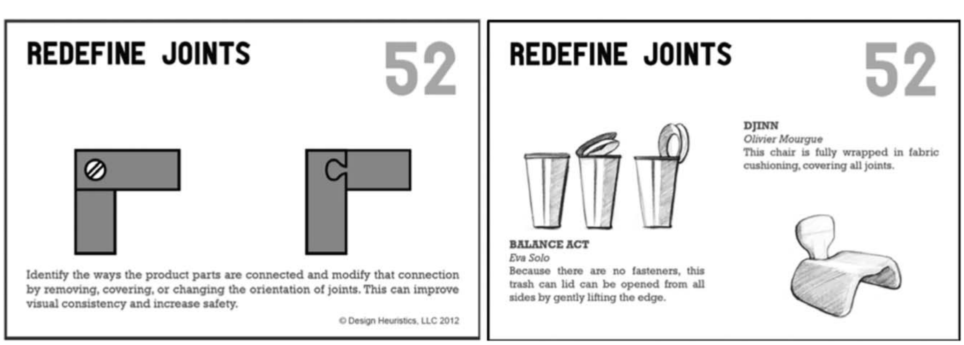

Fig. 2 Example of a design heuristics card showing its definition on the front (left) and two example products where the "redefine joints" heuristic is illustrated on the back (right)

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. 3 The 77 design heuristics card titles used as prompts in the second idea generation phase

own initial concept on a colored concept sheet for the same time period (6 min). Next, students were provided a short (3 min) introduction to idea generation, including a definition of divergent thinking and the goal of creating multiple, diverse concepts for design tasks. The students were provided guidelines for the idea generation phases that would follow, including to generate varied alternative concepts and to sketch concepts without worrying about their drawing skills. The instructors did not mention fixation (or other idea generation difficulties). Students were asked to draw, describe, and number each of their concepts on a different (white) concept sheet to record each idea.

Then, students began the first phase of idea generation using individual brainstorming. A short (3 min) introduction to brainstorming (based on Ref. [73]) presented steps as described in Fogler and LeBlanc [37] but modified for an individual designer:

(1) postpone and withhold your judgment of ideas
(2) encourage wild and exaggerated ideas
(3) quantity counts at this stage—not quality
(4) build consecutively on your ideas
(5) every idea has equal worth.

Students practiced this idea generation method on a practice problem ("design a seating device") for 3 min. Then, students were asked to create concepts for their assigned design problem using individual brainstorming for 30 min. Students were free to follow the Individual Brainstorming method presented or to use another method (such as natural ideation).

Next, a second idea generation phase took place using design heuristics. A short (10 min) lesson explained how to use the design heuristics cards to generate new concepts for a design problem. The instructors discussed the card format, front and back, and students were encouraged to select and combine heuristics as they wished. The students practiced using heuristics to "design a seating device." Then, students worked individually with a packet of 15 cards to generate more concepts for their original problem (30 min). Students were free to follow the design heuristics method or to use their own method. Students

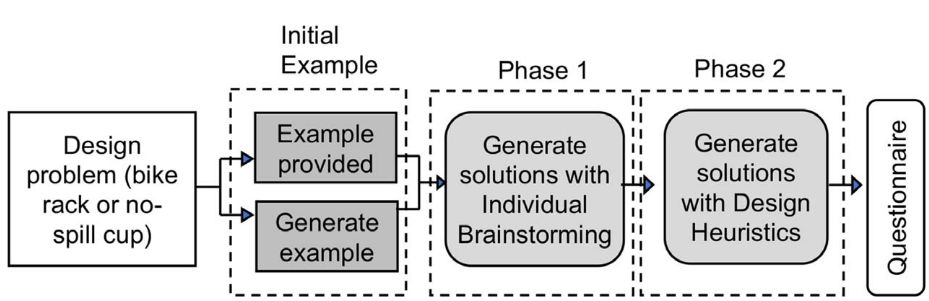

Fig. 4 Schematic of study procedure showing common steps. Half of the students were provided with an example concept, while others generated their own initial concept.

were also asked to indicate on each concept sheet whether they had used any of the design heuristics, and which ones by number (shown on each card).

At the conclusion of the second phase of idea generation, each student completed a final questionnaire (10 min) where they assessed their concepts and answered some open-ended demographic and reflection questions.

Measuring Fixation. Each student's concept set ($n = 166$) was coded for fluency (the number of different concepts generated in each phase). Nineteen students' concept sets (17 male; 2 female) were removed from the analyses because students failed to follow instructions or the completed concepts were illegible or uninterpretable.

Fixation studies often use a "degree of copying" approach to scoring [13], where repetitions of specific elements from the provided example are counted [6,28,74]. Jansson and Smith [9] defined fixation for the no-spill cup problem as including "a straw "or "a mouthpiece" (see Fig. 1) (as in the provided example design) and reported the example-provided group created 16% more "straw" designs and 29% more "mouthpiece" designs compared with the control group (Study 3). Jansson and Smith [9] did not provide statistical comparisons in their report.

For the present study, this approach was not possible because students in the two groups had *different* initial examples and therefore a different set of design elements that may be repeated. If, for example, an initial concept a student created had no mouthpiece or straw, scoring for those elements cannot detect other fixation that may have occurred. In addition, the "degree of copying" approach may fail to capture deeper conceptual, form-based, or more general similarities between concepts; and, defining fixation as any use of "a straw" means counting even very novel straws as fixation. Example ideas generated by participants who saw the example are shown in Fig. 5.

Vasconcelos and Crilly [11] document a variety of other evaluation metrics for fixation in published studies, including "repeated solutions" and ideas [28,45], "explicit linkage" and "new concepts" [40,42], timestamps and "non-redundant ideas" (e.g., Ref. [44], self-reports [6,75], and originality [25,76]. To measure fixation using the same procedure in both the provided and self-generated example groups, we used overall similarity judgments by independent coders, following Chrysakou and Weisberg [45]. In their study, similarity was scored (0/1) based on the occurrence of the same shapes, patterns, and features (e.g., type of car, roof of the car, tire railings, attachment mechanism) when similar to the example design. We selected this overall concept similarity coding procedure because of the need for ease and consistency given the large number of similarity comparisons ($n = 1308$) required.

Two independent coders (a senior undergraduate and a master's student) experienced in qualitative research rated the overall similarity of each generated concept to that student's initial concept (either provided or self-generated). The coders were blind to the study hypotheses, and blind to the idea generation phase (individual brainstorming or design heuristics) for each concept set because we removed the question and response about design heuristics use from each concept sheet. The two coders worked independently through each of the 166 concept sets in a randomized order and analyzed each student's set separately. The coders were instructed to provide a holistic rating for every concept in the set based on its "overall similarity to the initial concept in the set." For each student's concept set, the coders considered the first concept in each set—either the provided example or an initial concept generated by the student—and then rated every other concept in that set as "similar" or "not similar" to that set's initial concept. The concepts from the two phases were mixed together and placed in a randomized order. The reliability of the coders' ratings was examined using Cohen's kappa coefficient [77], which reached a moderate level [78] of agreement ($\kappa = .456$), suggesting that the coders' ratings are largely similar with some exceptions. Based on availability, discrepancies were then resolved by a third independent coder also blind to generation phase and hypotheses.

The coders judged an average of 1.6 concepts (range 0–6; SD = 1.52) per student as similar to the provided example, out of an average of 7.49 concepts (range 2–14, SD = 2.9). Overall, an average of 28% of the concepts were rated as "similar" to the initial one in the concept set, and only 12% ($n = 22$) of the students had no concepts rated as similar to their first (provided or self-generated) example. We computed similarity ratios for each student in both phases separately using the number of concepts rated as similar to their initial concept (either self-generated or provided) divided by the total number of concepts that student generated in each phase.

Results

Hypothesis 1: Providing Examples Leads to More Fixation. A first comparison mirrors that in Jansson and Smith's [9] study: Do students in the provided example condition show evidence of fixation on the example? Jansson and Smith [9] compared concept similarity to an example that was provided to one group and withheld from the control group. In study 1 (the Bike Rack

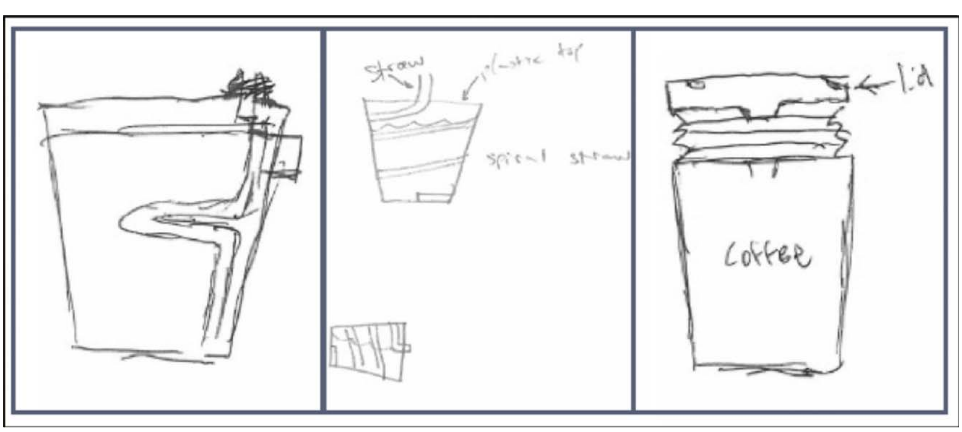

Fig. 5 Three example concepts for the "no-spill cup" problem from students who saw the provided example: (left) a small change to the provided example in a "Button [that] shifts tube to align with opening;" (middle) changes straw to a spiral limiting spills when tipped; (right) using the Design Heuristic "Flatten," a different means of preventing spills uses accordion folds: "The lid flattens so it meets the liquid section"

problem), they observed more fixation (58%) in the provided example group compared with 27% in the control group (where no example presented); in study 3 (no-spill cup problem), 28% of concepts in the provided example condition and 5.5% in the control condition were scored as similar. Their results support the conclusion that more fixation occurs with the provided example. Since our study used the same paradigm, we expected similar findings, matching many other demonstrations of fixation on provided examples (see reviews by Refs. [10,11,21].

However, Jansson and Smith [9] did not examine fixation on initial (self-generated) concepts in their control group. When accounting for potential fixation to initial concepts, contrary to our hypothesis, students' concepts sets showed *more* fixation to their own initial concept (the control group—32%) compared with those provided with an example (24%).

We compared these fixation rates (for this first individual brainstorming phase only) in a 2 × 2 ANOVA with problem and fixation source as between group variables, and the ratio of similar concepts to total number of concepts per student (in phase 1) as the dependent measure. This fixation ratio was used to account for the varied concept set sizes generated across students [16]. The results showed a main effect of fixation source where more fixation occurred in the self-generated example condition ($M = 0.32$, SD = 0.24) than in the Provided Example condition ($M = 0.24$, SD = 0.28), $F(1, 165) = 4.4$, $p < 0.04$. Contrary to our hypothesis and the findings in Jansson and Smith [9] and other studies, fixation on a provided example was *less* than that observed when students generated their own initial example.

The no-spill cup ($M = 0.23$, SD = 0.23) produced less fixation than the bike rack ($M = 0.33$, SD = .29) problem, $F(1, 165) = 5.6$, $p < 0.02$. The no-spill cup problem may have been easier for students due to their greater familiarity with the product. There was no observed interaction between example condition and problem, $F(1, 165) < 1$, ns (see Fig. 6).

Examples of ideas developed when provided the example solution are shown in Fig. 7 and examples of ideas developed when participants generated a first idea are shown in Fig. 8.

Because both groups demonstrated substantial fixation on their initial examples (from 19% to 38%), a second idea generation phase offered the opportunity to observe whether fixation from either source could be mitigated.

Hypothesis 2: Using an Idea Generation Tool Can Help to Mitigate Fixation. We compared fixation across the two idea generation phases to identify whether the use of a support tool (design heuristics) might reduce the observed fixation effects. Because the two phases produced different numbers of concepts, we considered fixation effects in two separate frequency analyses. First, 72% of concepts rated as similar (to either provided or self-generated examples) occurred in the first individual brainstorming phase ($n = 199$; $M = 1.2$; SD = 1.2), while 28% ($n = 76$; $M = 0.46$; SD = 0.45) were identified in the second phase using design heuristics. Since the individual brainstorm phase produced 62% of the total concepts generated, it contributed a significantly greater proportion of similar concepts than expected by chance, $X^2 = 17.51$, $p < 0.0001$. Following an individual brainstorming phase where fixation occurred in both groups, the use of the design heuristics generation tool during a subsequent idea generation phase reduced fixation on initial examples.

Second, we considered whether the individual brainstorming phase differed from the design heuristics phase in the frequency of similar concepts. We compared similarity ratios in both phases for each student (the number of concepts rated as similar to their initial concept divided by the total number of concepts generated). We found that the brainstorm concepts were more frequently identified as similar to their initial example ($M = 0.43$, SD = 0.31) compared with design heuristics concepts ($M = 0.28$, SD = 0.35), $t(165) = 3.33$, $p < 0.001$. These results suggest that although individual brainstorming produced more concepts, these concepts were also more similar to the initial example seen (provided or self-generated) than were later concepts produced in the design heuristics phase.

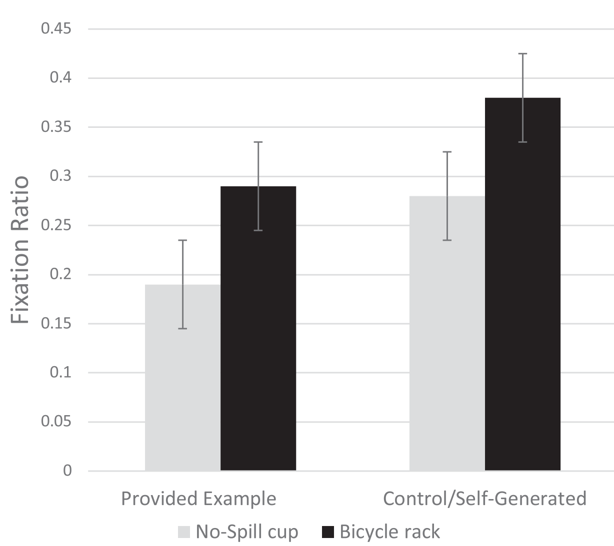

Fig. 6 The effects of fixation source (example provided or self-generated example) and problem in the individual brainstorming phase on fixation ratio (number of concepts similar to the initial example divided by total number of concepts per student)

Fluency in Idea Generation. While our focus was design fixation, we also analyzed the concepts with regard to the fluency of ideas produced. This allows for an exploration of trade-offs; that is, when reducing fixation through the use of an idea generation tool, are other qualities disadvantaged?

The design heuristics phase resulted in fewer concepts generated (520; $M = 2.94$; standard error (SE) = 0.11) than in the initial Individual Brainstorming phase (888; $M = 4.67$; SE = 0.11), $F(1, 165) = 201.36$, $p < 0.001$, with 76% of students generating more concepts using individual brainstorming. This difference may be due to fatigue since the individual brainstorming phase came first. As more time is devoted to idea generation, creative exhaustion may occur, limiting the generation of additional concepts [79].

However, the students' concepts in the second phase using the design heuristics tool suggest they continued to generate successful concepts, albeit at a slower pace. Only 12% ($n = 61$) of the concepts from the design heuristics phase failed to list a specific heuristic card as the concept source. Though first-time users of design heuristics, students listed at least one design heuristic for 360 concepts, and more than one for 99 concepts, suggesting they were successful in using the design heuristics method. In addition, using this tool may require additional time as the student reads, understands, and applies the cards, taking time away from concept generation [64]. Even so, while producing fewer concepts in this second phase, using the design heuristics resulted in fewer concepts similar to their initial example.

Considering fluency as a dependent measure (the number of concepts generated), a 2 × 2 × 2 ANOVA with a mixed design compared the effects of fixation source, problem, and generation phase. For both the brainstorm and design heuristics phases, the self-generated example conditions produced more concepts, and this advantage held across problems (see Fig. 9).

This fluency advantage for self-generated examples was larger in the individual brainstorming phase, $F(1, 165) = 6.21$, $p < 0.05$, and with the no-spill cup problem, $F(1, 165) = 6.12$, $p < 0.05$. Finally, there was no three-way interaction ($F(1, 165) = 1.30$, ns), with a similar pattern of results across the two idea generation phases. These fluency results show a consistent pattern: Students generated more concepts with the no-spill cup problem over the bike rack problem, with their own initial example solution rather than a provided example, and when individual brainstorming over using

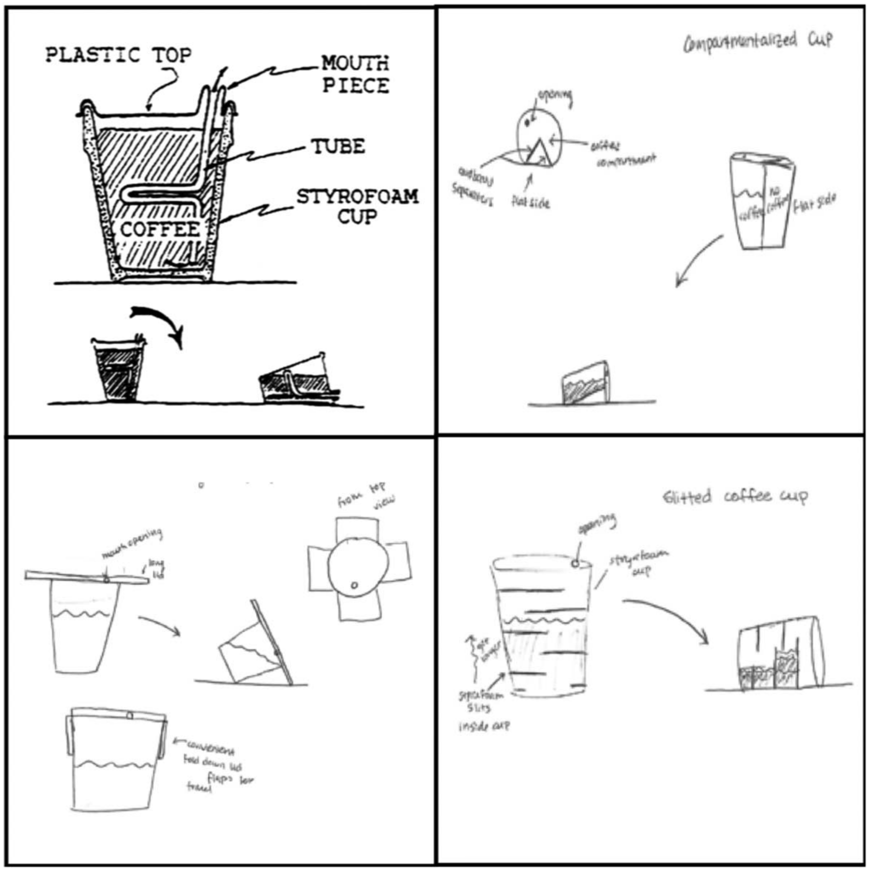

Fig. 7 A student's initial provided example for the no-spill cup problem (upper left) alongside three concepts they created during brainstorming. The two on the right were coded as similar to the initial concept (likely because they use internal compartments), and the one below it (using an expanded lid to keep the cup more upright when on its side) as dissimilar.

design heuristics. Each of these independent variables contributed separately and in combination to influence fluency in concept generation.

Discussion

We summarize our findings by addressing the effects of each factor included in the experiment. First, the source of the initial example solution (whether it was self-generated or provided with the problem) affected fixation: Seeing a provided example solution led to *less* fixation than observed when students generated their own initial example. The students who self-generated examples produced more concepts than those provided with an example; however, more of the self-generated concepts were similar to the initial example, an index of greater fixation. Those provided with an example along with the problem were actually *less* fixated on it compared with the fixation observed in the control group. This pattern of results was robust, observed across two idea generation methods (individual brainstorming and design heuristics) and two problem contexts (no-spill cup and bike rack problems).

Previous studies [9,11] observed a higher fixation rate with provided examples compared with a control condition where no example was provided; however, these studies did not include a measure of fixation on the first-generated solution in the control group; as a result, these studies may have underestimated fixation occurring in the control condition. The body of evidence for fixation effects from provided examples appears definitive [11,21]; however, provided example fixation may be much less pervasive than fixation arising from one's own initial concept. Prior studies have identified a bias in favor of designers' own initial ideas [18], and the negative impact of initial ideas on selection preferences has been demonstrated [10]. Our results suggest it is important to consider how this "first idea" bias may impact idea generation outcomes whether or not example solutions are provided.

Second, following a first idea generation phase with identified fixation effects, students' use of the design heuristics method successfully reduced fixation to initial examples. The results showed that fewer concepts were judged as similar to either the example or first idea generated when students used the design heuristics tool to support idea generation. This may be because generation support tools such as morphological analysis [80] and design heuristics [65] have been shown to increase the diversity of ideas [64], moving designers away from ideas already proposed (whether an example idea or an initial idea). These findings suggest that using an idea generation tool, such as design heuristics can help in moving designers away from fixation on their initial ideas to consider alternatives. Across both design problem contexts, design heuristics supported a shift away from existing fixation tendencies, with students generating less similar ideas than when individual brainstorming. This finding adds to prior demonstrations of the benefits of idea generation tools in mitigating fixation [15,16] by showing that introducing a tool support phase following fixation can mitigate it within the same session.

These findings allow the re-examination of conclusions from the seminal Jansson and Smith [9] study. While their findings showed more fixation with a provided example, no comparison with self-generated examples was performed. In this study, comparing these two potential sources of fixation showed that self-generated examples resulted in more fixation than provided examples. Many other studies have also documented fixation on a

Fig. 8 A student's initial self-generated concept for the no-spill cup problem (upper left) alongside three concepts they created during brainstorming. The two on the right (both using a domed lid) were coded as similar to the initial concept, and the one below it (with a narrow neck) as dissimilar.

provided example (see reviews by Refs. [11,21]) and others have noted designers' preferences for their own initial ideas [18]. However, our study is the first to show that both provided and self-generated examples produce design fixation in the same design task, and that self-generation produces more fixation. The finding that generating an initial concept can produce more fixation than provided examples suggests that replication and extension studies and considering multiple measurement methods for fixation and idea diversity [11] may help to identify other factors leading to design fixation.

Limitations. While our experimental design allowed inferences about causes of fixation, conducting a study of this scale involves trade-offs in ecological validity. Design tasks in the world typically involve much longer time spans, multiple idea generation sessions distributed in time, working within teams of other designers, and addressing more complex and more contextualized design problems; certainly, all of these factors are likely to influence fixation [22].

We also gave explicit instructions on individual brainstorming to all participants following Osborn's original description [73]; because these suggestions include "Build upon earlier ideas," it is possible students felt encouraged to use the initial example as a basis for later concepts. Only one design ideation tool (design heuristics) was tested due to the need to provide equivalent educational experiences across students attending the workshop and the limited time available. Other design tools that support idea generation through exposure to external cues (rather than relying on the designers' memory as in brainstorming) may work well to relieve existing fixation, such as design-by-analogy [15,16]. There is growing evidence that some specific idea generation methods are more effective than others [64]. Further studies are needed to identify the cognitive processes involved in successfully generating diverse ideas in the presence of existing fixation, impact on reducing design fixation. Other studies have documented ways to reduce fixation through the use of other idea generation techniques [16,22].

An additional constraint in our study was replicating the paradigm from Jansson and Smith [9] in order to compare fixation from provided examples to that of a control group. To do so, all participants completed the individual brainstorming phase first using a similar procedure to Jansson and Smith [9]. The second idea generation phase was added on with the intent of determining whether design tools like design heuristics can help to overcome existing fixation. Because this design tool phase always followed brainstorming, this ordering limits possible comparisons. The second idea generation phase occurred further removed in time from the exposure to the initial example; as a consequence, memory and fixation on the initial example may have faded. Participants may have felt more "warmed up" by the second phase and performed better; or, they may have felt more fatigue, leading to generating fewer solutions. And, having already generated designs in the first phase, lower output resulted in the design heuristics phase. Gray et al. [79] found that providing an initial period where students can "exhaust" their own ideas followed by use of generation tools enhances idea generation.

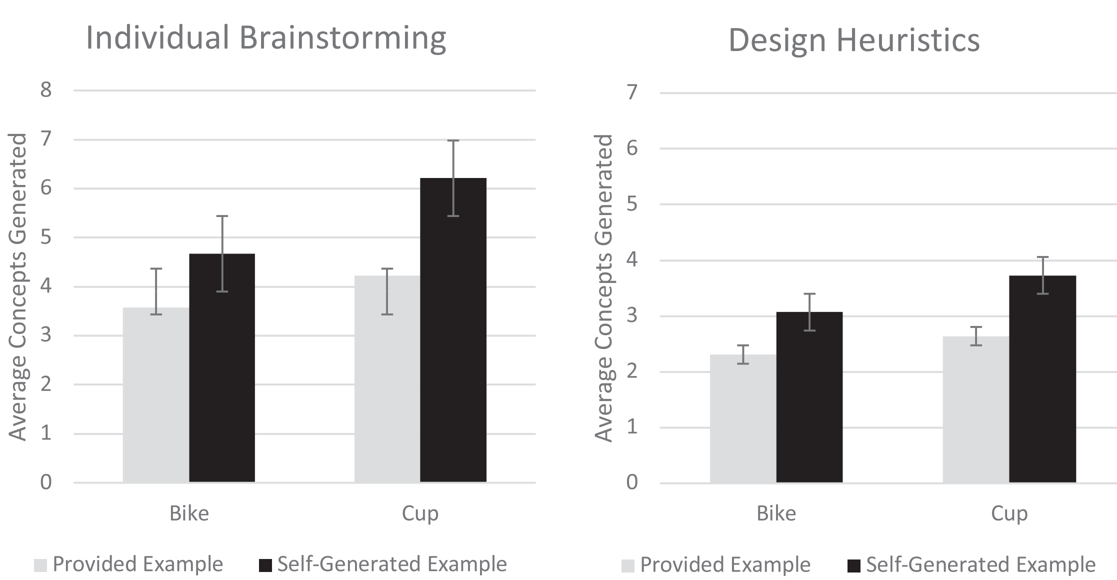

Fig. 9 Fluency (mean, SE) in idea generation across phases shows that students in the self-generated example condition generated more concepts than those in the provided example condition in both individual brainstorming and design heuristics phases and across both problems

In our study, measuring fixation in the same way as Jansson and Smith [9] was not possible because their scoring method was based on the provided example. For students in the self-generated example condition, each had a different, unique first concept; consequently, we would need to define comparable feature repetition scoring based on each individual's initial generated concept. Scoring each with a different criterion may fail to capture fixation and introduce differing standards for each. Our measurement method involved completing holistic similarity judgments over many concept sets, likely introducing inconsistencies given the large number of comparisons required, as the inter-rater reliability obtained was only moderate. Future studies should attend to methods for assessing similarity and quality of concepts for larger scale experiments.

The results in this study were obtained in an educational setting (a university workshop for students entering engineering), which added constraints on the time available (a single 95 min session). Because of the educational intent of the workshop, we provided the same training to all participants (in both individual brainstorming and design heuristics methods) during the study. In other situations with longer session periods, more complex or knowledge-rich problems, and group rather than individual idea generation sessions, different findings may be observed. Further, this study followed Jansson and Smith's [9] research study, where the realism of the design task and problems is compromised for experimental control.

Finally, we chose to focus on beginning designers because they may be particularly vulnerable to provided examples given their newly developing generation skills. Beginning engineers may have less prior knowledge of existing designs, along with little exposure to methods for generating diverse ideas. The observed findings may differ from studies with more advanced student engineers [17,39] and with expert engineers with more experience [26,28]. Further research is needed to address how prior domain knowledge influences fixation. Further, the students were assigned to example groups without considering gender, and race and ethnicity data were not collected, limiting generalization of these findings across demographic groups.

Implications. Studies of design fixation have burgeoned since Jansson and Smith's [9] seminal study, and identification of sources, cognitive processes, and design settings impacting fixation continue to develop [11,21]. The results of the present study provide two concrete suggestions. First, including an example solution with the design problem may serve to *reduce* fixation that arises when not presented; without one, generating your own initial example may promote "falling in love" with it [18]. Without a provided example, students in our study created more new concepts, but more of them were similar to the first example they themselves had generated. Perhaps the introduction of a concept from an outside source—not one you created—motivates a search for new ideas. Further studies are needed to compare how these factors contribute to cognitive limitations observed in idea generation [21,22].

Second, as proposed by Crilly and Cardoso [22], turning to a different idea generation approach may help to reduce fixation by "restarting" idea generation. Design heuristics was a new tool for these students, but they were able to make use of it with minimal training to continue adding new solutions to their concept sets. Changing the idea generation tool may also help with idea "exhaustion" by punctuating the session with differing approaches to idea generation [79]. Our results suggest that design heuristics are a helpful and accessible method for overcoming existing fixation within the same design session. Other interventions and design tools during idea generation may hold similar potential for shifting designers from fixation toward more variety in the concepts created [22].

For designers, increasing awareness of the potential for fixation on initial examples (both provided and self-generated) appears important in improving the generation of diverse concept sets. If designers are aware of the impact of initial examples on later designs, they may choose to take steps (such as making use of an idea generation tool) to break fixation. These findings suggest learning to recognize one's own fixation may be an important metacognitive skill in managing the search for creative outcomes in design.

Conclusions

Since Jansson and Smith's [9] seminal study, design fixation has been demonstrated as a pervasive problem in engineering design [11,21,22]. Design problems are often presented with example solutions in educational settings in order to ensure that important information is understood (such as design requirements, concrete implementations, or simply existence proofs of solution), particularly with beginning and novice engineers. While extensive research has demonstrated fixation arising from a provided example solution, the results of this study demonstrated that fixation from one's own initial idea may be an even bigger problem. Without a provided example, a first concept created by the designer may take on a special prominence and lead to fixation. While fixation on initial examples appears even more ubiquitous than expected, our study showed that fixation effects can be reduced through the use of an idea generation tool added within the same design session. Methods supporting idea generation through external prompts (like design heuristics) appear to be good candidates for mitigating the consequences of fixation, leading to the generation of more varied and more creative designs.

Acknowledgment

Many thanks to Greg Caputo for his assistance with the data collection and organization, the two instructors who conducted the workshop sessions, our three coders, and the beginning engineers who participated in our workshop.

Funding Data

- National Science Foundation (Grant No. #0927474; Funder ID: 10.13039/501100008982).
- National Science Foundation (Grant Nos. #1140256, #1323251, and #1322552; Funder ID: 10.13039/501100008982).

References

[1] Brophy, D. R., 2001, "Comparing the Attributes, Activities, and Performance of Divergent, Convergent, and Combination Thinkers," Creat. Res. J., **13**(3–4), pp. 439–455.

[2] Liu, Y.-C., and Bligh, T., 2003, "Towards an 'Ideal' Approach for Concept Generation," Des. Stud., **24**(4), pp. 341–355.

[3] Ullman, D. G., Dietterich, T., and Stauffer, L., 1988, "A Model of the Mechanical Design Process Based on Empirical Data," Artif. Intell. Eng. Des. Manuf., **2**(1), pp. 33–52.

[4] Ball, L. J., Evans, J., and Dennis, I., 1994, "Cognitive Processes in Engineering Design: A Longitudinal Study," Ergonomics, **37**(11), pp. 1753–1786.

[5] Cross, N., 2001, "Design Cognition: Results From Protocol and Other Empirical Studies of Design Activity," *Design Knowing and Learning: Cognition in Design Education*, C. M. Eastman, W. M. McCracken, and W. C. Newsletter, eds., Elsevier, Amsterdam, pp. 79–104.

[6] Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., and Schunn, C., 2010, "A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty," ASME J. Mech. Des., **132**(4), p. 041003.

[7] Kohn, N., and Smith, S., 2011, "Collaborative Fixation: Effects of Others' Ideas on Brainstorming," Appl. Cognit. Psychol., **25**(3), pp. 359–371.

[8] Condoor, S., and Lavoie, D. J., 2007, "Design Fixation: A Cognitive Model," Proceedings of ICED 2007, the 16th International Conference on Engineering Design, Paris, France, July 28–31, pp. 345–346.

[9] Jansson, D. G., and Smith, S. M., 1991, "Design Fixation," Des. Stud., **12**(1), pp. 3–11.

[10] Youmans, R., and Arciszewski, T., 2014, "Design Fixation: Classifications and Modern Methods of Prevention," Artif. Intell. Eng. Des., Anal. Manuf., **28**(2), pp. 129–137.

[11] Vasconcelos, L. A., and Crilly, N., 2016, "Inspiration and Fixation: Questions, Methods, Findings, and Challenges," Des. Stud., **42**(C), pp. 1–32.

[12] Luchins, A. S., 1942, "Mechanization in Problem Solving: The Effect of Einstellung," Psychol. Monogr., **54**(6), pp. i–95.

[13] Shah, J. J., Smith, S. M., Vargas-Hernandez, N., Gerkens, D. R., and Wulan, M., 2003, "Empirical Studies of Design Ideation: Alignment of Design Experiments With Lab Experiments," Proceedings of the ASME 2003 International Design Engineering Technical Conferences and Computers and Information in

Engineering Conference. Volume 3b: 15th International Conference on Design Theory and Methodology, Chicago, IL, Sept. 2–6, ASME, pp. 847–856.
[14] Bilalić, M., McLeod, P., and Gobet, F., 2010, "The Mechanism of the Einstellung (Set) Effect: A Pervasive Source of Cognitive Bias," Curr. Dir. Psychol. Sci., **19**(2), pp. 111–115.
[15] Linsey, J. S., Moreno, D. P., Yang, M. C., Herna, A. A., and Wood, K. L., 2015, "A Step Beyond to Overcome Design Fixation: A Design-by-Analogy Approach," Proceedings of the Design Computing and Cognition Conference '14, pp. 607–624, Springer, Cham, Switzerland.
[16] Moreno, D. P., Blessing, L. T., Yang, M. C., Hernández, A. A., and Wood, K. L., 2016, "Overcoming Design Fixation: Design by Analogy Studies and Nonintuitive Findings," Artif. Intell. Eng. Des., Anal. Manuf., **30**(2), pp. 185–199.
[17] Viswanathan, V., Esposito, N., and Linsey, J., 2012, "Training Tomorrow's Designers: A Study on Design Fixation," ASEE Annual Conference, San Antonio, TX.
[18] Nikander, J. B., Liikkanen, L. A., and Laakso, M., 2014, "The Preference Effect in Design Concept Evaluation," Des. Stud., **35**(5), pp. 473–499.
[19] Daly, S. R., Christian, J. L., Yilmaz, S., Seifert, C. M., and Gonzalez, R., 2012, "Assessing Design Heuristics in Idea Generation Within an Introductory Engineering Design Course," Int. J. Eng. Educ., **28**(2), pp. 463–473.
[20] Yilmaz, S., Daly, S. R., Seifert, C. M., and Gonzalez, R., 2016, "Evidence-Based Design Heuristics for Idea Generation," Des. Stud., **46**(C), pp. 95–124.
[21] Sio, U. N., Kotovsky, K., and Cagan, J., 2015, "Fixation or Inspiration? A Meta-Analytic Review of the Role of Examples on Design Processes," Des. Stud., **39**(C), pp. 70–99.
[22] Crilly, N., and Cardoso, C., 2017, "Where Next for Research on Fixation, Inspiration and Creativity in Design?" Des. Stud., **50**(C), pp. 1–38.
[23] Abdelall, E. S., Frank, M. C., and Stone, R. T., 2018, "Design for Manufacturability-Based Feedback to Mitigate Design Fixation," ASME J. Mech. Des., **140**(9), p. 091701.
[24] Zahner, D., Nickerson, J. V., Tversky, B., Corter, J. E., and Ma, J., 2010, "A Fix for Fixation? Representing and Abstracting as Creative Processes in the Design of Information Systems," Artif. Intell. Eng. Des., Anal. Manuf., **30**(2), pp. 185–199.
[25] Youmans, R. J., 2011, "The Effects of Physical Prototyping and Group Work on the Reduction of Design Fixation," Des. Stud., **32**(2), pp. 115–138.
[26] Crilly, N., 2015, "Fixation and Creativity in Concept Development: The Attitudes and Practices of Expert Designers," Des. Stud., **38**(C), pp. 54–91.
[27] Purcell, A. T., and Gero, J. S., 1996, "Design and Other Types of Fixation," Des. Stud., **17**(4), pp. 363–383.
[28] Moreno, D. P., Hernandez, A. A., Yang, M. C., Otto, K. N., Holtta-Otto, K., Linsey, J. S., Wood, K. L., and Linden, A., 2014, "Fundamental Studies in Design-by-Analogy: A Focus on Domain-Knowledge Experts and Applications to Transactional Design Problems," Des. Stud., **35**(3), pp. 232–272.
[29] Kim, J., and Ryu, H., 2014, "A Design Thinking Rationality Framework: Framing and Solving Design Problems in Early Concept Generation," Hum. Comput. Interact., **29**(5–6), pp. 516–553.
[30] Rowe, P., 1987, *Design Thinking*, MIT Press, Cambridge, MA.
[31] Rietzschel, E. F., Nijstad, B. A., and Stroebe, W., 2007, "Relative Accessibility of Domain Knowledge and Creativity: The Effects of Knowledge Activation on the Quantity and Originality of Generated Ideas," J. Exp. Soc. Psychol., **43**(6), pp. 933–946.
[32] Cross, N., 2004, "Expertise in Design: An Overview," Design Studies, **25**(5), pp. 427–441.
[33] Guindon, R., 1990, "Designing the Design Process: Exploiting Opportunistic Thoughts," Hum. Comput. Interact., **5**(2), pp. 305–344.
[34] Sachs, A., 1999, "'Stuckness' in the Design Studio," Des. Stud., **20**(2), pp. 195–209.
[35] Niku, S. B., 2009, *Creative Design of Products and Systems*, John Wiley & Sons, Inc., New York.
[36] Smith, R. P., and Tjandra, P., 1998, "Experimental Observation of Iteration in Engineering Design," Res. Eng. Des., **10**(2), pp. 107–117.
[37] Fogler, S. H., and LeBlanc, S. E., 2008, *Strategies for Creative Problem Solving*, Pearson Education, Inc., MA.
[38] Dugosh, K. L., and Paulus, P. B., 2005, "Cognitive and Social Comparison Processes in Brainstorming," J. Exp. Soc. Psychol., **41**(3), pp. 313–320.
[39] Viswanathan, V., Tomko, M., and Linsey, J., 2016, "A Study on the Effects of Example Familiarity and Modality on Design Fixation," Artif. Intell. Eng. Des., Anal. Manuf., **30**(2), pp. 171–184.
[40] Perttula, M., and Sipilä, P., 2007, "The Idea Exposure Paradigm in Design Idea Generation," J. Eng. Des., **18**(1), pp. 93–102.
[41] Dahl, D. W., and Moreau, P., 2002, "The Influence and Value of Analogical Thinking During New Product Ideation," J. Mark. Res., **39**(1), pp. 47–60.
[42] Perttula, M. K., and Liikkanen, L. A., 2006, "Exposure Effects in Design Idea Generation: Unconscious Conformity or a Product of Sampling Probability," Nord Design, Reykjavik, Iceland, Aug. 16–18, pp. 42–55.
[43] Moss, J., Kotovsky, K., and Cagan, J., 2007, "The Influence of Open Goals on the Acquisition of Problem-Relevant Information," J. Exp. Psychol. Learn. Mem. Cogn., **33**(5), pp. 876–891.
[44] Siangliulue, P., Chan, J., Gajos, K. Z., and Dow, S. P., 2015, "Providing Timely Examples Improves the Quantity and Quality of Generated Ideas," ACM SIGCHI Conference on Creativity and Cognition, New York, June 22–25, ACM, pp. 83–92.
[45] Chrysikou, E. G., and Weisberg, R. W., 2005, "Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task," J. Exp. Psychol. Learn. Mem. Cogn, **31**(5), pp. 1134–1148.
[46] Thaler, R., 1980, "Toward a Positive Theory of Consumer Choice," J. Econ. Behav. Organ, **1**(1), pp. 39–60.
[47] Viswanathan, V., and Linsey, J., 2011, "Design Fixation in Physical Modeling: An Investigation on the Role of Sunk Cost," Proceedings of the International Conference on Design Theory and Methodology, Washington, DC, Aug. 28–31, pp. 119–130.
[48] Campbell, D. T., 1960, "Blind Variation and Selective Retention in Creative Thought as in Other Knowledge Processes," Psychol. Rev., **67**(6), pp. 380–400.
[49] Cross, N., 2000, *Engineering Design Methods: Strategies for Product Design*, 3rd ed., Wiley, Chichester, UK.
[50] Higgins, J. S., Maitland, G. C., Perkins, J. D., Richardson, S. M., and Piper, D. W., 1989, "Identifying and Solving Problems in Engineering Design," Stud. High. Educ., **14**(2), pp. 169–181.
[51] Pahl, G., and Beitz, W., 1996, *Engineering Design: A Systematic Approach*, Springer-Verlag, Berlin.
[52] Thompson, L., 2003, "Improving the Creativity of Organizational Work Groups," Acad. Manage. Exec., **17**(1), pp. 96–109.
[53] Wilson, C. E., 2006, "Brainstorming Pitfalls and Best Practices," Interactions, **13**(5), pp. 50–63.
[54] Litchfield, R. C., 2009, "Brainstorming Rules as Assigned Goals: Does Brainstorming Really Improve Idea Quantity?," Motiv. Emotion, **33**(1), pp. 25–31.
[55] Perkins, D., 1997, "Creativity's Camel: The Role of Analogy in Invention," *Creative Thought*, T. Ward, S. Smith, and J. Vaid, eds., American Psychological Association, Washington, DC, pp. 523–528.
[56] Zwicky, F., 1969, *Discovery, Invention, Research Through the Morphological Approach*, Macmillan, New York, NY.
[57] Gordon, W. J. J., 1961, *Synectics*, Harper & Row, New York.
[58] Eris, O., 2004, *Effective Inquiry for Innovative Engineering Design*, Springer, New York.
[59] de Bono, E., 1999, *Six Thinking Hats*, Back Bay Books, Boston.
[60] Finke, R. A., Ward, T. B., and Smith, S. M., 1992, *Creative Cognition: Theory, Research, and Applications*, The MIT Press, Cambridge, MA.
[61] Eberle, B., 1995, *Scamper*, Prufrock, Waco, TX.
[62] Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., and Sierakowski, R., 2009, "Innovations in Design Through Transformation: A Fundamental Study of Transformation Principles," ASME J. Mech. Des., **131**(8), p. 081010.
[63] Altshuller, G., 1997, *40 Principles: TRIZ Keys to Technical Innovation*, Technical Innovation Center, Inc., Worcester, MA.
[64] Daly, S. R., Seifert, C. M., McKilligan, S., and Gonzalez, R., 2016, "Comparing Ideation Techniques for Beginning Designers," ASME J. Mech. Des., **138**(10), p. 101108.
[65] Daly, S. R., Yilmaz, S., Christian, J. L., Seifert, C. M., and Gonzalez, R., 2012, "Design Heuristics in Engineering Concept Generation," J. Eng. Educ., **101**(4), pp. 601–629.
[66] Yilmaz, S., Colleen, M. S., and Seifert, C. M., 2011, "Creativity Through Design Heuristics: A Case Study of Expert Product Design," Des. Stud., **32**(4), pp. 384–415.
[67] Daly, S. R., Christian, J., Yilmaz, S., Seifert, C. M., and Gonzalez, R., 2011, "Teaching Design Ideation," Proceedings of the American Society for Engineering Education (ASEE) Annual Conference (AC 2011-1569), Washington, DC, June 26–29, American Society for Engineering Education.
[68] Christian, J. L., Daly, S. R., Yilmaz, S., Seifert, C. M., and Gonzalez, R., 2012, "Design Heuristics to Support Two Modes of Idea Generation: Initiating Ideas and Transitioning Among Concepts," Paper Presented at the Annual Conference of American Society of Engineering Education, San Antonio, TX, June 10–13.
[69] Kramer, J., Daly, S. R., Yilmaz, S., Seifert, C. M., and Gonzalez, R., 2015, "Investigating the Impact of Design Heuristics on Idea Initiation and Development," Adv. Eng. Educ., **4**(4), pp. 1–26.
[70] Yilmaz, S., Christian, J. L., Daly, S. R., Seifert, C. M., and Gonzalez, R., 2013, "Can Experienced Designers Learn From New Tools? A Case Study of Idea Generation in a Professional Engineering Team," Int. J. Des. Creat. Innov., **1**(2), pp. 82–96.
[71] Yilmaz, S., Daly, S. R., Seifert, C. M., Gonzalez, R., and Gray, C. M., 2015, "Expanding Evidence-Based Pedagogy With Design Heuristics," The Proceedings of the ASEE Annual Conference, NSF Grantees Poster Session, Seattle, WA, June 14–17, ASEE.
[72] Leahy, K., Seifert, C. M., Daly, S. R., and McKilligan, S., 2018, "Overcoming Design Fixation in Idea Generation," International Conference of Design Research Society, Limerick, Ireland, June 25–28, pp. 2764–2775.
[73] Osborn, A., 1957, *Applied Imagination: Principles and Procedures of Creative Problem-Solving*, Scribner, New York.
[74] Viswanathan, V., and Linsey, J., 2012, "Training Tomorrow's Designers: A Study on the Design Fixation," ASEE Annual Conference and Exposition, Conference Proceedings, San Antonio, TX, June 10–13.
[75] Yilmaz, S., Seifert, C. M., and Gonzalez, R., 2010, "Cognitive Heuristics in Design: Instructional Strategies to Increase Creativity in Idea Generation," Artif. Intell. Eng. Des., Anal. Manuf., **24**(3), pp. 335–355.
[76] Goncalves, M., Cardoso, C., and Badke-Schaub, P., 2012, "Find Your Inspiration: Exploring Different Levels of Abstraction in Textual Stimuli," 2nd International Conference on Design Creativity, Glasgow, UK, Sept. 18–20, The Design Society, pp. 1–8.
[77] Cohen, J., 1960, "A Coefficient of Agreement for Nominal Scales," Educ. Psychol. Meas., **20**(1), pp. 37–46.
[78] Landis, J. R., and Koch, G. G., 1977, "The Measurement of Observer Agreement for Categorical Data," Biometrics, **33**(1), pp. 159–174.
[79] Gray, C. M., McKilligan, S., Daly, S. R., Seifert, C. M., and Gonzalez, R., 2017, "Using Creative Exhaustion to Foster Idea Generation," Int. J. Technol. Des. Educ., **1**, pp. 177–195.
[80] Allen, M., 1962, *Morphological Creativity*, Prentice-Hall, Upper Saddle River, NJ.