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Authors
Kershaw, Trina
Holtta-Otto, Katja
Lee, Yoon Soo

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The Effect of Prototyping and Critical Feedback on Fixation in Engineering Design

Trina C. Kershaw[1], Katja Hölttä-Otto[2], & Yoon Soo Lee[3]
tkershaw@umassd.edu, kotto@umassd.edu, ylee@umassd.edu
Departments of [1]Psychology, [2]Mechanical Engineering, and [3]Design, University of Massachusetts Dartmouth
285 Old Westport Road, North Dartmouth, MA 02747 USA

Abstract

Design fixation is a common problem in engineering. In two experiments, we implement two educational interventions, prototyping and critical feedback, to help reduce design fixation, which is defined as adherence to one's own design. We found that constant prototyping across the design process reduced fixation in the final product. Surprisingly, we also found that not receiving feedback reduced fixation in the final product. Implications for engineering design education are discussed.

Keywords: fixation; engineering; prototyping; feedback; metacognition; education

One of the greatest challenges facing future engineers is to create innovative products to stay competitive in the real world (Duderstadt, 2008). Unfortunately, there is considerable evidence that current engineering curricula may not support creativity. Graduating engineers are often less innovative than entering freshman (Yang, 2008) and the standard design process tools often lead to safe rather than innovative solutions (Cooper, 2005). Engineers tend to stick with the same idea throughout the design cycle (Ulrich & Eppinger, 2004), often even if the idea has severe flaws. In the following paper, we review possible hindrances to creativity in engineers, and describe two educational interventions that we hope can lead to greater creativity in engineering design.

The Problem of Design Fixation in Engineering

Being stuck is common in design. One means of measuring 'stuckness' is measurement of design fixation, the unintentional adherence to a set of features or concepts limiting the output of conceptual design (Janson & Smith, 1991). Design fixation is typically measured as similarity to the design brief the designers were shown in the beginning of the design project. However, designers can also show fixation on concepts learned outside of the experimental setting (Purcell & Gero, 1996) or to the initial idea they had (Sachs, 1999). Design fixation is a prevalent problem in engineering, yet it is often unrecognized by the person committing it; even teachers of engineering design are unaware of their own fixation (Linsey et al., 2010).

Numerous creativity methods have been proposed to overcome design fixation. These methods generally focus on one-time generation of ideas at the beginning of the design process, which is not enough (cf. Mehalik & Schunn, 2006) because innovative design should be a continuous string of divergent and convergent thinking (Dym et al., 2005). For example, Genco et al. (2010) used the 6-3-5 method (Pahl & Beitz, 1996) to compare the concepts for a next-generation alarm clock of freshmen and senior mechanical engineering students. They found that freshmen and senior groups produced concepts with similar, high levels of feasibility. However, freshmen students were less fixated on the sample alarm clocks than seniors. Instead of just attempting to promote divergent thinking at the beginning of the design process, engineers need to avoid fixation throughout the design process.

Avoiding Fixation through Prototyping

The typical engineering design process involves coming up with a few ideas, quickly selecting one, and taking that idea through the design cycle (Ulrich & Eppinger, 2004). Prototyping is a common part of engineering design. We loosely define prototyping as a representation of a design idea before the final artifact exists (Lim et al., 2008). In the beginning of the process rough prototypes can be used to capture latent customer needs and to prove a concept. During the design process the level of detail of the prototypes improves and they are used for communicating concepts to the client, testing the usability, and exploring and evaluating the design (Lim et al., 2008). A prototype can ensure the final product will work as desired and it can answer questions that would be otherwise hard to answer.

Prototyping has many benefits, and thus prototyping is common in most design projects. Design requires the mental manipulation of complex relationships among design features, thus taxing cognitive capacity (Youmans, 2011). Prototypes could reduce fixation by releasing cognitive load. Youmans found that using prototypes reduced fixation compared to situations in which participants, both design experts and undergraduate psychology students, were unable to manipulate objects. The point at which prototypes are used during the design process might also influence creativity. For example, Jang and Schunn (2010) found that engineering designers who used prototypes during the ideation phase produced more innovative designs. However, use of prototypes during the concept refinement phase had no impact on innovation. Despite these reported positive effects of prototyping, there is evidence that exposure to prototypes can lead to design fixation during concept generation (Christiansen & Schunn, 2007; 2009). We varied the point at which prototyping occurred during the design process in Experiment 1.

Avoiding Fixation through Reflecting on Critical Feedback

Assessment of engineering design is typically focused on problem solving skills, communication, and meeting of the stakeholder needs (McKenzie et al., 2004) instead of on self-reflection about the design process. Since a student is typically grade driven (Cross & Steadman, 1996), it is better in the eyes of the student to steer toward known working solutions than to explore the design space more openly. It is likely that this same behavior is prominent also in industry.

In contrast to engineering designers, other designers (graphic, industrial, and architectural) receive more critical feedback. The third author developed a participatory Peer Crit which she uses in her design courses (Lee, 2010). During the crit process, students explain and defend their design choices. This process often leads to the restructuring of their designs when they are not able to explain their design choices. The crit leads to metacognitive awareness of the design process. Reflective thinking is one of the traits of good engineering design (Cross & Steadman, 1996), and enables effective inquiry between divergent and convergent questions (Dym et al., 2005).

In order to test the effect of critical feedback on fixation during the design process, we varied the type of feedback that participants received in Experiment 2.

Experiment 1: Prototyping Method

Participants

Participants were 50 students enrolled in introductory psychology classes at the University of Massachusetts Dartmouth who received research credit for their participation. While the students had different majors, none of the participants were engineering majors. We chose participants from a research pool to pilot the prototyping intervention prior to its implementation in engineering classes. No demographic data were collected about the participants.

Materials

Participants were asked to design a device to move balls from one box to another, referred to as the Balls and Boxes problem. The problem sheet showed the start state to have two boxes set 10" apart from each other, with five balls in box 1 and box 2 empty. The end state of the problem showed five balls in box 2.

During the introductory and sketch phases (sketching could occur during the Concept Generation Phase, the Concept Refinement Phase, or both) of the experiment, participants were provided with a stack of blank paper and a set of colored markers. During the prototype (which could occur during the Concept Generation Phase, the Concept Refinement Phase, or both) and Final Build phases of the experiment, participants were given a bin of materials to build their designs. These materials consisted of 15 popsicle sticks, seven pipe cleaners, six rubber bands of varying sizes, two thick paper napkins, a small jar of playdough, assorted k-nex plastic building toys (including sticks and wheels), a two meter long piece of string, and a pair of scissors. Two square plastic bowls were used to represent the boxes of the Balls and Boxes problem, and five ping pong balls were used to represent the balls in the problem.

Procedure

Each participant was a member of only one condition (see Table 1 for the *n* in each condition). Participants were run in groups of two to six. They were told that they would be following a standard design process to solve the balls and boxes problem. All participants were told that they would build a prototype at some point during the process, and were told that a prototype worked like one's intended device, but might not look like it, might not be made from the same material, and was generally not made using the same manufacturing methods as the intended device. Participants then went through a four-phase design process, consisting of initial idea generation, concept generation, concept refinement, and final build. Table 1 shows the experiment flow for each phase within each condition. The phases are explained in greater detail below.

Initial Idea Generation Phase Participants were given two minutes to generate multiple ideas for moving the balls from one box to another. Participants were asked to sketch ideas, instead of writing a list.

Concept Generation Phase Participants were given up to 12 minutes to either sketch or prototype one or more of their ideas. They were told to draw as much as possible, but that they could use words to clarify aspects of the sketch. Participants were instructed to notify the experimenter as soon as they had an idea or ideas they wanted to share. Once alerted, the experimenter then began the first Feedback Phase with the participant.

Participants who were building prototypes were given a bin that contained all the materials listed above. Individuals in the *multiple early prototype* condition were given two bins. The balls and boxes were set up on the table. Participants in the *multiple early prototype* condition were asked to build two or more prototypes; all other participants were asked to build at least one. All participants were reminded that they were building a representation of the device, not the device itself.

Concept Refinement Phase Participants were given 12 minutes to modify their ideas by adding, taking away, or changing some element of the current design. They were also told that they could come up with a new design. Participants were reminded that after this phase, they would need to be ready to produce their final design during the Final Build phase. Depending upon the experimental condition they were in, participants either sketched or prototyped during this phase. The sketch and prototype

Table 1: Experiment Conditions and Phases

Condition	*N*	Experiment Phase					
		Initial Idea Gen.	Concept Gen.	Feedback	Concept Refine.	Feedback	Final Build
Experiment 1							
• Multiple Early Prototype	7	X	2+ protos	tech	sketch	tech	X
• Constant Prototype	10	X	1 proto	tech	1 proto	tech	X
• Early Prototype	12	X	1 proto	tech	sketch	tech	X
• Late Prototype	10	X	sketch	tech	1 proto	tech	X
• No Prototype	11	X	sketch	tech	sketch	tech	X
Experiment 2							
• No Feedback	8	X	sketch	none	sketch	none	X
• Technical Feedback	11	X	sketch	tech	sketch	tech	X
• Full Crit	10	X	sketch	full crit	sketch	full crit	X

procedures were the same as during the Concept Generation Phase. Participants were again instructed to notify the experimenter once they had an idea or ideas to share. Once alerted, the experimenter began the second Feedback Phase with the participant.

Feedback Phases Participants received feedback on their designs twice, after the Concept Generation and Concept Refinement Phases. Participants were asked to explain how their designs worked and then asked if their designs met each of the technical criteria, such as being at least six inches away from the balls, etc. The experimenter then pointed out any technical failures of the design.

Final Build Phase Participants were given 12 minutes to build their final concept. They were told to be prepared to explain how it worked and solved the Balls and Boxes Problem. Participants were reminded that their final build functioned as a prototype, and therefore was only a representation of the device itself. Participants were again instructed to notify the experimenter as soon as they had a prototype to share. After reviewing the participant's final build, the experimenter explained the purpose of the study and thanked the individual for his/her participation.

Analysis of Feedback Reaction

We developed a coding scheme to describe the ways in which participants could respond to the feedback. We compared their designs before and after each feedback sessions by examining the differences between the designs produced during the Concept Generation and Concept Refinement phases, and the differences between the designs produced during the Concept Refinement and Final Build phases.

The feedback reaction coding categories are detailed in Table 2. Participants could react in multiple ways to the feedback. For example, they could add padding to a device in order to protect the balls from damage, yet ignore the experimenter's reminder that the user needs to be at least six inches away from the balls. In this example, the response would be coded as *fix failure* for the addition of padding, and *ignore feedback* for not making a change to comply with the six inches rule.

Initial coding was completed by all three authors. Coding agreement was high. The third author completed the final coding, as reported in the Results section.

Table 2: Feedback Reaction Coding

Feedback Reaction	Coding Description
No Change	Sticks with current design. E.g. Final Build is the same as Concept Refinement.
Ignore Feedback	Ignores feedback about a particular feature. E.g. Remind about 6" distance from the balls or boxes, but participant leaves the distance alone.
Fix Failure	Modifies an aspect of a current feature to fix a criterion failure. This can be done by modifying, adding, or taking away a feature. E.g. Raise box 1 in order to make it easier for balls to travel to box 2.
Change Design	Changes a feature in order to improve the design, but not to fix a failure. This can be done by modifying, adding, or taking away a feature. E.g. Make claw more stable by adding extra prong.
Create New Concept	Abandons current design and creates something new.

Results

The frequency of the coding categories was not evenly distributed across the feedback reactions (Table 3). Some categories, such as *ignore feedback*, were rare. *Fix failure* was more prevalent during the first feedback reaction than the second. In contrast, *no change* was more likely to occur during the second feedback reaction.

Table 3: Percent of Feedback Reactions, Experiment 1

Coding Category	Feedback 1	Feedback 2
No Change	14%	48%
Ignore Feedback	6%	4%
Fix Failure	28%	6%
Change Design	52%	38%
New Concept	16%	2%

Feedback reactions with 6% or less occurrence were eliminated for the next analysis, in which we examined the types of feedback reactions in each condition. The percent of feedback reactions by condition is shown in Table 4. We ran chi-square analyses to compare the frequency of each feedback reaction between the Concept Generation and Concept Refinement phases among the prototype conditions. We found no difference between the prototype conditions in the *no change* (χ^2 [4, N = 50] = 4.23, p = .38), *fix failure* (χ^2 [4, N = 50] = 1.80, p = .77), or *create new concept* reactions (χ^2 [4, N = 50] = 2.51, p = .64). A chi-square test comparing the frequency of the change feedback reaction among the groups was marginally significant, χ^2 (4, N = 50) = 8.93, p = .06. Examination of the adjusted standardized residuals (ASR) indicated that the locus of this significant result was due to the *multiple early prototype* (ASR = 1.9) and *late prototype* (ASR = -2.3) groups.

Table 4: Percent of Feedback 1 Reactions between Concept Generation and Concept Refinement Phases by Condition, Experiment 1

Condition	No Change	Fix Failure	Change Design	New Concept
Multi-early	14.3%	21.4%	23.1%	12.5%
Constant	0%	21.4%	15.4%	25%
Early	14.3%	28.6%	30.8%	12.5%
Late	42.9%	14.3%	7.7%	37.5%
No Prototype	28.6%	14.3%	23.1%	12.5%

We also examined the feedback reactions that were shown within each group between the Concept Refinement and Final Build phases (Feedback 2). Only changing the design and making no change were examined because the other categories had 6% or less prevalence. Participants in the *early prototype* group (31.6%) made up the largest percentage of participants who changed their designs. Participants in the *constant prototype* and *late prototype* groups were equally likely to change their designs (21.3%), followed by participants in the *multiple early prototype* condition (15.8%) and the *no prototype* condition (10.5%). A chi-square test comparing the frequency of the change feedback reaction among the groups was not significant, χ^2 (4, N = 50) = 2.67, p = .61.

Participants in the *no prototype* condition made up the largest percentage (37.5%) of participants who made no change between the Concept Refinement and Final Build phases. The other percentages of participants making no change were as follows: *early prototype* = 25%, *multiple early prototype* = 16.7%, *late prototype* = 12.5%, and *constant prototype* = 8.3%. A chi-square test comparing the frequency of the no change feedback reaction among the groups was marginally significant, χ^2 (4, N = 50) = 9.73, p = .05. Examination of the adjusted standardized residuals (ASR) indicated that the locus of this significant result was due to the *constant prototype* (ASR = -2) and *no prototype* (ASR = 2.5) groups.

Experiment 2: Type of Feedback Method

Participants

Participants were 29 students enrolled in introductory psychology classes at the University of Massachusetts Dartmouth who received research credit for their participation. While the students had different majors, none of the participants were engineering majors. We chose participants from a research pool to pilot the feedback intervention prior to its implementation in engineering classes. No demographic data were collected about the participants.

Materials and Procedure

Participants in Experiment 2 used the same materials and followed the same procedure as in Experiment 1, following a design process through the Initial Idea Generation, Concept Generation, Concept Refinement, and Final Build phases (see Table 1). Unlike the participants in Experiment 1, they received different types of feedback during the Feedback Phases, and only produced sketches, not prototypes, during the Concept Generation and Concept Refinement phases. Sketch instructions for Experiment 2 were the same as Experiment 1.

Feedback Phases Participants received feedback on their designs twice during the experiment, after the Concept Generation and Concept Refinement Phases. All participants were first asked to explain how their designs worked. Participants in the *no feedback* condition were only thanked for explaining their designs, and were not given any additional feedback. Participants in the *technical feedback* condition followed the same procedure from Experiment 1.

Participants in the *full crit* condition were given technical feedback, and then asked a series of questions to encourage reflection upon their design. The questions were as follows:
1) Why do you think this product has the restrictions that it does (such as keeping a certain amount of space in between the person and the balls and boxes)?
2) Imagine this device in a real life environment with a real person packaging these products. What is the sequence the user goes through in order to use this device?
3) What are the strengths of your device?
4) What are the weaknesses of your device?
5) How could you improve this device?

Analysis of Feedback Reaction

We coded participants' feedback reactions in the same manner as in Experiment 1 (see Table 2).

Results

As in Experiment 1, we first examined the frequency of the feedback reaction types during the first and second feedback phases. As shown in Table 5, some of the feedback reactions were not seen in the data, such as *ignore feedback*. *Fix failure*, *change design*, and *new concept* were more frequent during the first feedback reaction, while *no change* was more frequent during the second feedback reaction.

Table 5: Percent of Feedback Reactions, Experiment 2

Coding Category	Feedback 1	Feedback 2
No Change	7%	69%
Ignore Feedback	0%	0%
Fix Failure	31%	3%
Change Design	66%	21%
New Concept	10%	0%

Feedback reactions with 7% or less occurrence were eliminated for the next analysis, in which we examined the types of feedback reactions that were shown in each condition (see Table 6).

Table 6: Percent of Feedback 1 Reactions between Concept Generation and Concept Refinement Phases by Condition, Experiment 2

Condition	No Change	Fix Failure	Change Design	New Concept
No Feedback	0%	22.2%	36.8%	66.7%
Tech. Feed.	100%	22.2%	31.6%	33.3%
Full Crit	0%	55.6%	31.6%	0%

The *technical feedback* condition was the only group that made no change between the Concept Generation and Concept Refinement phases. A chi-square test comparing the conditions was not significant, χ^2 (2, N = 29) = 3.52, p = .17. Participants in all conditions fixed failures, with the *full crit* condition showing the highest prevalence of this feedback reaction. A chi-square test comparing the conditions was not significant, χ^2 (2, N = 29) = 2.67, p = .26.Changing one's design was the most likely, and occurred fairly equally in each condition. A chi-square test comparing the conditions was not significant, χ^2 (2, N = 29) = 2.43, p = .30.Participants in the *no feedback* and *technical feedback* conditions created new concepts, while participants in the *full crit* condition did not. A chi-square test comparing the conditions was not significant, χ^2 (2, N = 29) = 3.03, p = .22.

We also examined the feedback reactions that were shown within each group between the Concept Refinement and Final Build phases (Feedback 2). Only changing the design and making no change were examined because the other categories had 3% or less prevalence. Participants in the *technical feedback* condition made up 45% of the no change category, followed closely by the *full crit* condition (40%), with the category being far less prevalent among the feedback reactions of the *no feedback* group (15%) A chi-square test comparing the conditions was marginally significant, χ^2 (2, N = 29) = 5.12, p = .07. Examination of the adjusted standardized residuals (ASR) indicated that the locus of this significant result was due to the *no feedback* group (ASR = -2.3).

In contrast, no participants in the *full crit* condition made changes to their designs between the Concept Refinement and Final Build phases, while 33.3% of the change category consisted of participants in the *technical feedback* and 66.7% of category consisted of participants in the *no feedback* condition. A chi-square test comparing the conditions was significant, χ^2 (2, N = 29) = 6.84, p = .03. Examination of the adjusted standardized residuals (ASR) indicated that the locus of this significant result was due to the *no feedback* (ASR = 2.4) and *full crit* (ASR = -2) groups.

General Discussion

While there was variety in the feedback reactions shown in Experiment 1 and Experiment 2 between the Concept Generation and Concept Refinement stages, none of the group differences reached significance except for the change category within Experiment 1, in which more participants in the *multiple early prototype* condition made changes to their designs than participants in the *late prototype* condition. We saw more group differences in the feedback reactions shown between the Concept Refinement and Final Build stages. In Experiment 1, many participants in the *no prototype* condition made no changes to their designs, while few participants in the *constant prototype* condition made no changes. This could be because lack of a prototype can make it hard to identify failures or other areas of improvements, and the designer is thus more likely to stick with same concept. This is in line with Youmans' (2011) finding that a designer may be better able to handle complex problems by reducing the cognitive load via prototyping.

When prototyping is not required, participants were most likely to just build their final refined concepts. Sketching did not give them enough information to make changes to Final Build. This supports use of prototypes in general.

It remains to be tested which prototyping strategy leads to the most creative final concepts. Jang and Schunn (2010) found that prototyping during ideation, but not during concept refinement, correlated with high levels of creativity of the final output. While this point was not examined per se, we found that prototyping, when used throughout the design process, led to more changes, presumably improvements.

In Experiment 2, participants did not build prototypes until the final build, and they differed by the type of feedback received. We found that participants in the *technical feedback* condition accounted for 45% of the no change feedback reactions between Concept Refinement and Final Build, followed closely by the *full crit* condition (40%). Participants in the *no feedback* group only accounted for 15% of this category. In the change category, participants from the *no feedback* condition accounted for 66.7% of the no change category for the period between the Concept Refinement and Final Build stages, with the remaining 33.3% of this feedback reaction coming from the *technical feedback* condition. No participant from the *full crit* condition fell within this category. This result was surprising, in that one might expect more detailed feedback to lead to less design fixation. One possibility is that participants who receive feedback may feel that their designs were validated by the experimenter, and thus they can stop making changes, while participants who do not receive feedback are forced to engage in self-reflection because their ideas have not been validated by someone else. However, additional data collection and analyses are needed to further elucidate the effects of critical feedback.

While our results are not conclusive, it is likely that critical feedback will help the overall design process, particularly in educational settings. Critical feedback could help engineering professors change the way they give feedback. Encouraging self reflection may help students to focus on the quality of their designs rather than ease of building in the belief that the easy build would result in a good grade. This could help solve the problem of senior level engineering students performing worse compared to their freshman counterparts in terms of innovativeness of their designs (Genco et al., 2010). We are currently implementing the crit process in the senior design class to test this hypothesis.

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