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A Study on the Role of Computer-aided Design in Design Creativity and Education

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Abstract

The efficiency and popularity of computer-aided design (CAD) packages have been continually improving over the past couple of decades. Most of the graduating engineers are proficient in their use and prefer using CAD models instead of simple freehand sketches to communicate their ideas. While these CAD models can enable better visualization of the initial designs, some of the prior studies highlight a few disadvantages of using those for the initial stages of engineering design. Some of the critical concerns raised by observational studies include constrained thinking and design fixation while using CAD models. Motivated by the scarcity of empirical evidence regarding the use of CAD models in engineering design practice and education, this paper reports a study conducted in a freshman design classroom where students are instructed to generate a creative idea using CAD models as their medium of representation. One group of students are given a simple example while another is given one with more detailed features. The presence of example features in the designs they generated is compared against that of a control group. The results show that while generating ideas in a CAD package, the students fixate on example designs and this fixation is more significant when the example is more detailed. Unlike physical prototypes, CAD models do not offer immediate feedback on the designs which might prompt students to keep their ideas with fixated features.

Introduction

Generation of novel ideas has been considered as an integral part of the engineering design process. One of the critical factors that influences the generation of innovative design ideas has been identified as the fidelity of the representation used for communicating the ideas (Viswanathan & Linsey, 2013b; Yang, 2005). The literature shows that an ideal design representation conveys the maximum amount of information while keeping the resources needed at a minimum (Macomber & Yang, 2011). Because of this reason, sketching is considered to be an ideal medium for design communication (Macomber & Yang, 2011; Yang, 2009; Yang & Cham, 2007). Several studies show that sketching promotes creative thinking, which is an advantage over the other forms of representation (Goel, 1997; Goldschmidt, 1994; Lawson, 2005). Sketching provides immediate visual feedback to designers (Contero, Varley, Aleixos, & Naya, 2009) and is very simple and economical to use (Jonson, 2002, 2005).

In spite of the advantages that sketching can offer, the use of sketching has been decreasing in the engineering curriculum across the nation. The new graduates from engineering programs are more proficient in the Computer-aided Design (CAD) packages (Veisz, Namouz, Joshi, & Summers, 2012), some of which are claimed to be "ideal" for the product design process, according to their developers (Ullman, 2002). As defined by Westmoreland et al., (2011), a CAD model is a visual image created by a solid modeling package such as SOLIDWORKS, Creo or Siemens NX. By their very nature, a CAD model is less ambiguous compared to a sketch and can communicate information that is less subjective (Veisz et al., 2012). A CAD model can also include a lot of hidden details such as dimensions of the part, hidden lines, hidden parts, etc. and offer the po-

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tential to rotate the component to view it from different orientations. These properties make the representation of complex geometries easier through CAD models compared to sketching.

This study stems from the observation that many of the engineering students prefer to use CAD packages to simple free-hand sketching when they are ready to generate ideas for a new design problem. In most of the engineering programs, CAD packages are taught at the freshman level. Many of these courses do not place enough emphasis on sketching (based on discussion with colleagues who teach similar classes). However, some of the prior studies do show many disadvantages of using CAD models at the initial stages of the design process. CAD modeling is a slow process compared to a simple free-hand sketch (Thilmany, 2006) and the time spent for creating the CAD model can also have a negative impact on the ideas generated in the initial stages of design (Veisz et al., 2012). Through their observational case study (B. F. Robertson, Walther, & Radcliffe, 2007) and an extensive survey of CAD users (B. Robertson & Radcliffe, 2009), Robertson and colleagues found that the use of CAD models could lead to design fixation and constrained thinking. In a more recent study, Atilola and Linsey (2015) showed that the use of examples presented in a CAD format helped designers in identifying the key design features compared to a hand sketch. Considering the advances in CAD packages over the past few years, it is difficult to predict if these results still hold true. Considering the increasing popularity of CAD as a primary tool for early stage design, it is critical to understand its impact on design creativity.

This paper presents the results from a controlled study, where the participants are instructed to generate ideas using a CAD software package. The participants are given a fixating example, and the effects of this example in the ideas generated are studied. The further sections of this paper outline the relevant background literature, the procedure followed and a discussion of the results of the study.

Background

Design Fixation

As noted by several prior studies, design fixation is the blind and often counter-productive copying of ideas from the designs one is familiar with, or the previous ideas one has generated (Jansson & Smith, 1991; Purcell & Gero, 1991, 1996). At the initial stages of design, many novel ideas are sought; hence, design fixation might act as a hindrance. Previous research has identified several factors that might influence the presence of design fixation in engineering idea generation – these include the presence of an example, the fidelity of the medium used for communicating the example (Viswanathan & Linsey, 2013b), expertise of the designers (Linsey et al., 2010; Viswanathan & Linsey, 2013a), additional information available to the designers (Linsey et al., 2010), fidelity of the medium of communication (Viswanathan, et al., 2014; Viswanathan & Linsey, 2012; Viswanathan & Linsey, 2013) etc., to name a few.

Representations in Engineering Design

The type of representation used for conveying design ideas has been a focus in many recent studies. The amount of information that designers can gather from various representations varies (Casakin & Goldschmidt, 1999; Kavakli & Gero, 2001; Kokotovich & Purcell, 2000; Suwa & Tversky, 1997). A study by Macomber and Yang (2011) has shown that customers prefer hand sketches with sufficient details compared to CAD models. According to architects, CAD models typically provides the impression of a more finished design rather than the initial ideas (Schumann, et al., 1996).

A few empirical studies have examined the role of more tangible models such as a physical prototypes as a medium of communication in engineering idea generation. Viswanathan and Linsey have shown that as designers spend more time to represent their initial ideas, they are more likely to fixate on those initial ideas (Viswanathan &

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Linsey, 2013c), a phenomenon that is known as the "sunk cost effect." A few other studies have shown that when ineffective examples with fixating features are present in an educational setting, the building of physical models can help to eliminate resulting unwanted features present in their initial ideas (Kiriyama & Yamamoto, 1998; Vimal Viswanathan et al., 2014; Youmans, 2011).

One of the most positive aspects of CAD models, as often cited, is that they allow designers to visualize and manipulate their ideas very quickly (Schrage, 1999). This is consistent with the argument that high fidelity representations can communicate more information (Veisz et al., 2012). CAD models may allow designers to "play around" with their ideas and makes the communication between the design team's members easier (Paulus & Nijstad, 2003; Roy, 1993).

While the advantages of using CAD models in engineering design are self-evident, some non-empirical studies have demonstrated their problems in generating novel designs (Council, 2003; Hanna & Barber, 2001). One of the most prominent among those was the observational case study on practicing designers by Robertson et al. (2007), that identified four impacts of designing with CAD models: enhanced communication, thinking constrained by the capabilities of the CAD package, bounded idea generation, and design fixation. While the first one was the positive aspect of the use of CAD models, the last three represented potential limitations concerning creative idea generation. They observed that most of the creative ideation occurred away from computers and the CAD packages did not offer the most promising environment for idea generation.

In light of these findings, Lawson (2005) suggested the need for an empirical investigation into the use of CAD models in design. The study described in this paper investigates the effect of a CAD modeling package in the generation of ideas for a design problem presented in a freshman design course. More specifically, the study addresses the following research questions:

> **RQ1**: Do designers fixate on examples when they generate ideas using CAD modeling?
>
> **RQ2**: Do the number of features copied from examples and the number of the newly generated novel features correlate with each other?
>
> **RQ3**: What type of examples are most suitable for teaching design courses – simple or more detailed?

Method

A simple controlled experiment was designed and implemented in a freshman design class to investigate the research questions described above. The details of the experimental design are given in the below subsections.

Class Structure and Participants

A freshman level design class taught at San Jose State University (SJSU) is selected as the testbed for this study. This course is one of the first classes that first-year students across most of the engineering majors take at SJSU. Titled "Design and Graphics," this class introduces the fundamentals of engineering drawing to the freshmen. It has a lecture-lab format. The lecture session meets for 1 hour, and the lab meets for 2 hours and 45 minutes per week. In the lab component of the course, the students are given various activities to be completed in a CAD software throughout the semester. The lab sessions are facilitated by teaching assistants (TAs). The students are expected to complete their lab exercises (10 of them) before they are assigned a project. The project consists of a creative problem, and the students are expected to submit the CAD model of their idea at the completion of the project. For this study, the project was modified to accommodate various experimental conditions.

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All the participants in this experiment had a freshman or sophomore standing at SJSU. During the semester in which the investigation was conducted, seven lab sections with approximately 25 students each were taught. Out of these, three sections were used for the experiment. The designs generated by the participants were collected without any identifying information; so the exact demographic distribution was not available. However, typically the lab sections have a very diverse student population (concerning ethnicity, work experience, and age) with approximately 10% female students.

Before the data collection for the experiment, it was verified that more than 95% of the participants in each section had completed the majority of the lab activities. These lab activities were expected to prepare them with the tools necessary to complete the exercise in their project. Further, the activity they performed as a part of the study was supposed to be simpler compared to some of their previous tasks. With these, it could be safely assumed that all the participants possessed sufficient CAD knowledge to complete the study activities comfortably.

Design Problem

The design problem instructed the students to create the CAD model for a table with innovative features. The problem statement told them to generate a design that fits within the dimensions 56 in x17 in x 24 in (length x width x height). The table was expected to be in wood grain finish. No other restrictions were placed on their design. The students were encouraged to use their imagination to come up with the most innovative design and were explicitly instructed not to reuse any of the example features (if one was available). They were also informed that the grading of the project would be based on the creativity of their design.

Experimental Conditions

The three sections that participated in the experiment received three different types of examples for completing the design activity. The first group (Investigational Group 1 – IG1) received the hand-made sketch of a table with very detailed features, as shown in Figure 1. In addition to the flat top surface and the legs of a regular table, this contained some features like an arch that supported the top surface and additional minor details of the features. The second group (Investigational Group 2 – IG2) received the example of a typical table with drawers, as shown in Figure 2. Most of the participants were expected to be familiar with this simple table. Besides, the location of the experiment also had similar tables. The third group was kept as the "control" group (CG), and they received no example for their design activity.

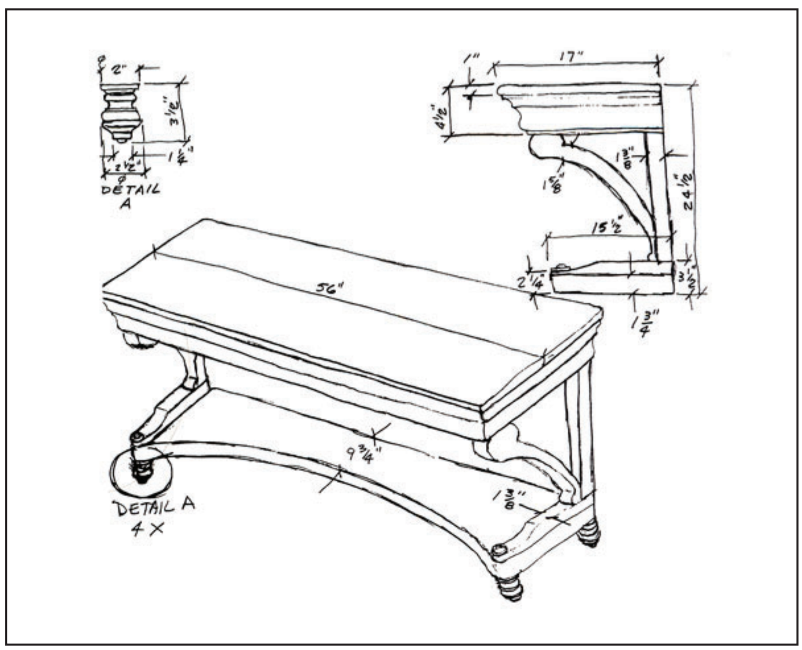

Figure 1. The example provided to the "detailed example" experimental group (IG1). This table design had very elaborate design features.

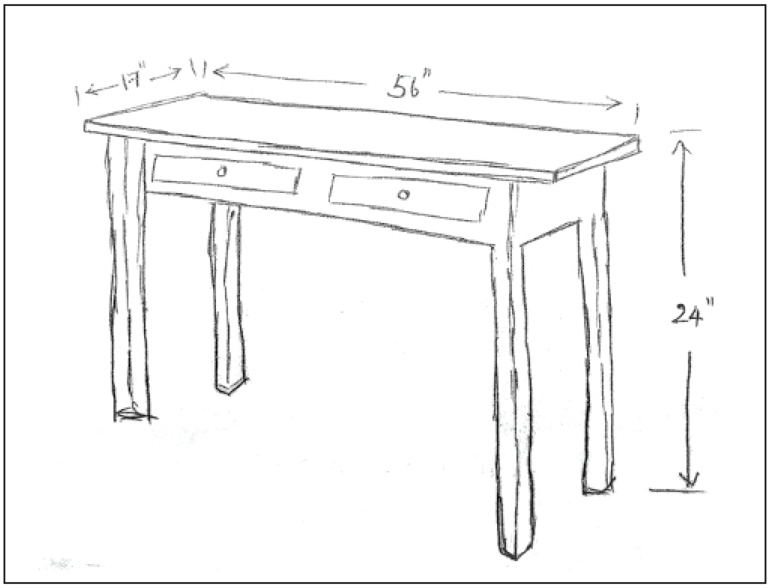

Figure 2. The "simple example" group (IG2) received this hand-sketch of a simple table with two drawers.

Procedure

The experiment was conducted during a single lab session that lasted 2 hours and 45 minutes. The students were introduced to their design problem during the first 10 minutes of the design activity. They were given an instruction sheet along with the example, depending on their experimental condition. The instructions were further explained to them along with the statement that their grade for the project would depend on the creativity of their final design. The students used Creo™ to complete the exercise. They were expected to upload the CAD model of their final design to a link provided on their learning management system. The students were instructed to complete this task strictly as an individual activity. The TA was available throughout the time of the experiment to answer any questions that the students had.

The data from a total of 63 students were considered for the analysis with 24 students each in IG1 and IG2 and 15 in CG. Some of the students submitted the assembly file for their table without including their part files making their data unusable. So their data were excluded from the analysis. Please note that the students were not required to do an assembly for the table. They could create one as a single part file.

Analysis

The first step in the analysis process was to examine the examples given in IG1 and IG2 to identify their design features. Some of the main features of the example used in IG1 were the arch support column connecting the table top and the leg, thick top with an additional pattern at the edges, other details of the table foot and the two-column support. The main features of the example used in IG2 were the flat rectangular top, the presence of storage drawers, and four legs with a rectangular cross-section. Each table design from the three sections was then analyzed to find the number of features reused from the example in the student's table design. Each of the feature reused from the example was considered to be a "fixating feature" and received a score of negative one. The features which were not present in the given example were considered as "novel features" and were given one point each.

Results and Discussion

The designs created by the students in IG1 and IG2 showed a clear indication of design fixation. Some examples are shown in Figure 3. These example designs are from IG1. The top row shows designs with a high degree of fixation on the example, and the bottom row shows the more creative designs.

Total Number of Design Features

It was observed that the students in IG1 generated ideas with more number of overall design features, on average in comparison with the other

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Figure 3. Examples of designs created by the participants in IG1. The top row shows some of the designs with a high degree of fixation and the bottom row shows designs with a relatively low degree of fixation.

two group's as shown in Figure 4. This meant that when students in IG1 saw the example, they decided to create designs with many additional features similar to their example compared to IG2. The simple example in IG2 contained a certain minimum number of features and the students in this group decided to stick with similar features in their designs.

A one-way Analysis of Variance (ANOVA) was conducted to analyze these data, statistically. The data were not homogeneous but were normally distributed, making the use of ANOVA possible (Tabachnick & Fidell, 2007). The results showed that the total number of design features varied significantly across the experimental groups ($F = 11.53$; $p < 0.01$). Post-hoc tests showed that IG1 had a significantly higher number of design features compared to the other conditions ($p < 0.01$ for both comparisons).

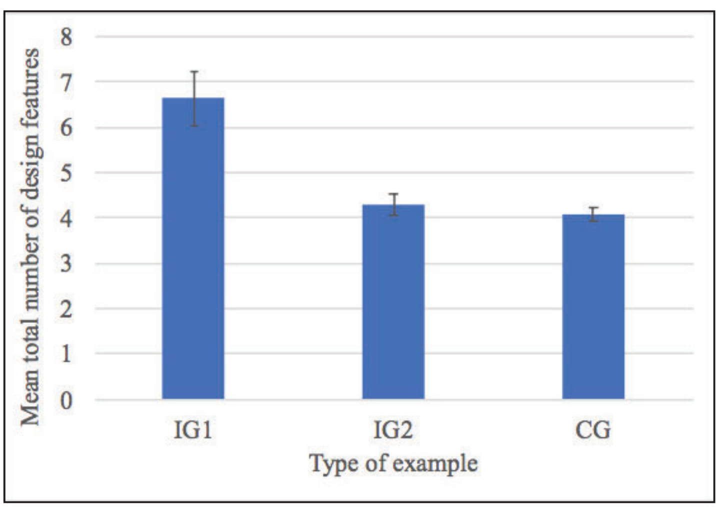

Figure 4. The mean number of design features present in each experimental conditions. All error bars represent (±1) S.E.

Number of Novel and Fixating Design Features

Another metric used for comparison across the conditions was the number of fixating features present in the designs created by the participants. Figure 5 shows the average number of fixating and creative features present in each experimental condition. As shown in the figure, the average number of fixating features in IG1 was higher compared to the two other groups. IG2 and CG had a similar number of fixating features. The simple example provided to the participants was the same as the one participants could visualize as soon as they think about a table. Besides, many tables similar to this example were present in the classroom where the experiment was conducted. This may explain the

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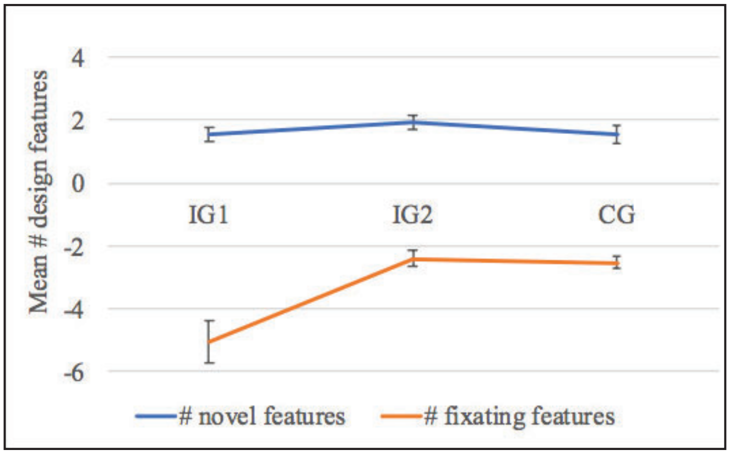

Figure 5. The mean number of fixating and creative features present in the designs across the experimental conditions. All error bars represent (±1) S.E.

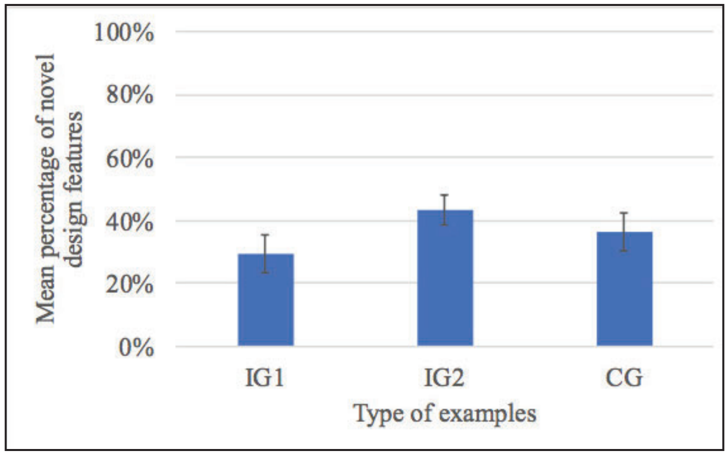

Figure 6. Figure 6. Participants who received the detailed example created ideas with a lower percentage of novel ideas. All error bars represent (±1)

presence of the same number of fixating features in both groups.

A one-way ANOVA showed that the experimental condition was a significant factor that influenced the presence of fixating features in a design ($F = 10.38$; $p < 0.01$). Follow-up post-hoc tests show that the designs in IG1 contained a significantly higher number of example features compared to the CG and IG2 groups ($p < 0.01$ for both comparisons). This showed that the detailed example caused significantly greater fixation compared to the simple one.

As shown in Figure 5, the average number of novel features in the designs remained the same across the experimental conditions. Based on Figure 4 and 5, it could be concluded that the participants in IG1 generated ideas with the same number of novel features as in the other conditions, but they included more fixating features from their example. A one-way ANOVA shows that the number of novel designs remained the same across all experimental conditions.

In other words, when a very detailed example was present, the students generated ideas that have significantly lower novel features (as a fraction of the total number of features included in each design), as shown in Figure 6. A one-way ANOVA confirms that this difference is statistically significant ($F = 1.80$; $p = 0.14$).

RQ1: Do designers fixate on examples when they generate ideas using CAD modeling?

The data from this controlled experiment provides supporting evidence for the claim that designers fixate when they use CAD models as their medium of communication (B. Robertson & Radcliffe, 2009). Regardless of the type of example, the participants copied features from it, even after they were informed that the grading was based on the creativity of their ideas. It was observed that the fixation on examples was higher when the example was more detailed. As evident from Figure 3, many participants blindly copied the detailed features in their example. It can be argued that the fixation on a simple table was unavoidable, as all the participants were quite familiar with it and the similar extents of fixation in both control and simple example groups provided supporting evidence for this argument.

Despite the increased efficiency of CAD packages, many of them are still somewhat slow compared to freehand sketching. In other words, the time commitment needed to model a design using a

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CAD software is significantly higher compared to sketching. This longer time requirement might lead to the sunk cost effect, as suggested by the prior literature (Viswanathan & Linsey, 2013c). While the sunk cost is even higher in physical prototyping, often the feedback available from the testing of these models helps in mitigating fixation to unwanted features. The CAD modeling packages still lack on this front. For example, most of the CAD packages allow one to assemble components with dimensions that may be impossible to assemble in practice.

RQ2: Do the number of features copied from examples and number of the newly generated novel features correlate with each other?

In this study, no correlation was observed between the number of novel features and the number of fixating features present in a design. From Figure 5, it could be observed that the average number of novel features remained the same across all the experimental conditions, while the average number of fixating features varied. It could be argued that the inclusion of each kind of features in a design was independent of the other.

RQ3: What type of examples are most suitable for teaching design courses – simple or more detailed?

As the number of novel features remained the same across the experimental conditions, it could be argued that the simple example might be a better choice to teach design with the help of CAD models. The increased number of features in CG1 were resulting from the fixation on the example, and in a CAD model, the participants did not get any immediate feedback as in the case of physical models. A previous study has shown that when participants are fixated on the ineffective features of an example, the building of a physical model of their design helped them to learn from those fixating features (Viswanathan, et al., 2014). This mitigation of fixation and learning effects from the fixating features are mainly attributed to the immediate feedback that the students obtain when they test their physical models. In the case of the virtual prototyping, this type of feedback is not available; hence, to teach design using CAD, it would be more beneficial to use simpler examples with less detailed features.

Conclusions

The study described in this paper aims to understand the design fixation associated with the use of computer-aided virtual representations in design education and practice. Based on the observation, the majority of our graduating students from the engineering programs are accustomed to CAD packages, and they prefer modeling parts in CAD to quick and straightforward free-hand sketching. In this empirical study, a small class project in a freshman level design class has been modified to introduce different examples in different sections, and these examples are used as the fixating stimuli. It was observed that regardless of the type of example they received, the participants fixated on the features present in the example design. The average number of novel features in the designs remained the same across the two conditions that received examples and the control. However, when more details are provided in the example, the participants fixated more on those detailed features. In the absence of any real-time feedback in CAD models, unlike in physical experimentation and testing, the results tend to support the use of simple examples in the classes that use CAD models to teach design concepts.

Limitation of the Study & Future Work

The results of this study show that when designers use CAD models to represent their initial ideas, they tend to fixate on the features of an example that is available to them. However, it does not explore how the extent of this fixation compares with the other types of representations (such as freehand sketches and physical models). We are

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currently designing a controlled study to explore any differences across these representations.

In this study, we did not investigate the familiarity and skill levels of participants with CAD modeling packages. It is possible that some of the participants (we estimate less than 10% of the class) are trained on one of the CAD modeling packages before their enrollment in the design and graphics class and it may be easier for them to ideate using Creo™. The variation in the skill levels may influence the experimental results. This factor will be further investigated in future work.

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