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MASTERING MANUFACTURING: EXPLORING THE INFLUENCE OF ENGINEERING DESIGNERS' PRIOR EXPERIENCE WHEN USING DESIGN FOR ADDITIVE MANUFACTURING

Rohan Prabhu
Mechanical Engineering
The Pennsylvania State University
University Park, PA, 16802
rohanprabhu@psu.edu

Timothy W. Simpson
Mechanical Engineering, Industrial Engineering
The Pennsylvania State University
University Park, Pa, 16802
tws8@psu.edu

Scarlett R. Miller
Engineering Design, Industrial Engineering
The Pennsylvania State University
University Park, PA, 16802
scarlettmiller@psu.edu

Nicholas A. Meisel
Engineering Design
The Pennsylvania State University
University Park, PA, 16802
nam20@psu.edu (Corresponding Author)

ABSTRACT

Additive manufacturing (AM) processes present designers with unique capabilities while imposing several process limitations. Designers must leverage the capabilities of AM – through opportunistic design for AM (DfAM) – and accommodate AM limitations – through restrictive DfAM – to successfully employ AM in engineering design. These opportunistic and restrictive DfAM techniques starkly contrast the traditional, limitation-based design for manufacturing techniques – the current standard for design for manufacturing (DfM). Therefore, designers must transition from a restrictive DfM mindset towards a 'dual' design mindset – using opportunistic and restrictive DfAM concepts. Designers' prior experience, especially with a partial set of DfM and DfAM techniques could inhibit their ability to transition towards a dual DfAM approach. On the other hand, experienced designers' auxiliary skills (e.g., with computer-aided design) could help them successfully use DfAM in their solutions. Researchers have investigated the influence of prior experience on designers' use of DfAM tools in design; however, a majority of this work focuses on early-stage ideation. Little research has studied the influence of prior experience on designers' DfAM use in the later design stages, especially in formal DfAM educational interventions, and we aim to explore this research gap. From our results, we see that experienced designers report higher baseline self-efficacy with restrictive DfAM but not with opportunistic DfAM. We also see that experienced designers demonstrate a greater use of certain DfAM concepts (e.g., part and assembly complexity) in their designs. These findings suggest that introducing designers to opportunistic DfAM early could help develop a dual design mindset; however, having more engineering experience might be necessary for them to implement this knowledge into their designs.

Keywords: *prior experience; design education; design for additive manufacturing.*

1. INTRODUCTION

With recent advances in additive manufacturing (AM), there has emerged a consequent need for an AM-skilled workforce [1]. The lack of an AM-skilled workforce has often been referred to as a possible hindrance to the successful adoption of AM processes in industry applications [2–4]. Furthermore, researchers have argued that an AM-skilled workforce must not only be trained to operate AM processes, but also *design* parts suitable for these processes, i.e., design for AM (DfAM) [5]. Researchers have also emphasized that designers skilled in designing for AM must be adept in two aspects of DfAM: (1) accommodating AM limitations to ensure the feasibility of their solutions, and (2) leveraging the unique capabilities of AM to harness the creative potential afforded by these processes [6]. This dual DfAM approach starkly contrasts the current standard of limitation-based design for manufacturing (DfM) and concurrent engineering [7]. Therefore, designers must make special efforts to transition from a limitation-based design mindset towards adopting a dual design mindset, when employing their knowledge of manufacturing processes in design.

To facilitate the adoption of 'dual' DfAM among engineers and designers, researchers have proposed numerous design techniques and guidelines. These DfAM techniques can be broadly classified into two domains [7,8]: (1) restrictive DfAM – i.e., design guidelines to accommodate AM limitations, and (2) opportunistic DfAM – i.e., design techniques to leverage AM limitations. Some examples of restrictive DfAM guidelines include accommodating for: (1) support structures in overhanging sections [9], (2) warping due to thermal stresses [10], (3) material anisotropy [11,12], (4) surface roughness due to stair-stepping [13,14], and (5) feature size and accuracy [15]. On the other hand, some examples of opportunistic DfAM include leveraging the ability to (1) mass customize parts [16], (2) consolidate multiple components into fewer parts [17] and assemblies [18], (3) build complex geometries [19–21], (4) embed external components [22], and (5) build parts with multiple materials [23]. Researchers have also proposed consolidated tools in the form of worksheets [24,25], design principles [26–28], and heuristics [29] to convey these novel design concepts to designers and help them use these concepts in the design process.

These design tools have been shown to help designers use DfAM in the design process; however, designers' prior experience in engineering design and manufacturing could influence their ability to use DfAM knowledge in design. This influence of prior experience is particularly underscored when transitioning from a limitation-based design mindset towards adopting a dual design mindset. Moreover, designers' ability to implement some of these design techniques (e.g., geometric complexity) relies on auxiliary skills such as Computer-Aided Design (CAD). Designers with greater engineering experience could also present higher levels of experience with CAD and, therefore, be more successful in implementing DfAM knowledge in their solutions. However, little research has explored this relationship between designers' prior experience and their use of DfAM knowledge in engineering design, especially in the later stages of the design process. Our aim in this research is to investigate this research gap through an experimental study. Specifically, we compare changes in experienced and inexperienced designers' DfAM self-efficacy from before to after participating in a DfAM educational intervention. We also compare designers' use of DfAM concepts in their design outcomes. Through the findings of this study, we aim to inform the introduction of DfAM information to designers, taking into account their prior experience.

Next, we discuss prior research that informed this study, with the research questions and our corresponding hypotheses presented in Section 3. Our experimental methodology is discussed in detail in Section 4, the results of the experiment are discussed in Section 5, and the educational implications of these results are discussed in Section 6. Finally, we conclude the paper with a discussion of limitations, and potential directions for future research in Section 7.

2. RELATED WORK

Our aim in this research is to investigate the influence of designers' prior experience on their DfAM use in a design task. Before doing so, studies related to the role of prior experience in engineering design and in DfAM education are reviewed as discussed next.

2.1. Role of prior experience in design and problem-solving

Several researchers have argued for the influence of prior experience on designers' design strategies. For example, Ahmed-Kristensen et al. [30] compare differences between expert and novice designers' design processes. One of their main observations is that while experienced designers use deliberate design strategies such as referring to past designs, novice designers use a 'trial and error' approach. Similarly, Reimlinger et al. [31] compare novice and expert designers' use of design guidelines in the embodiment design stage. In their study, the authors observe that novices benefit more from the provision of design guidelines. Moreover, they observe that novices who perceive greater utility from the provision of guidelines also performed better in the design task. Given this influence of prior experience on designers' behaviors, it is important to understand how prior experience could influence designers' performance in DfAM tasks. This understanding is particularly important to successfully bring about a transition from a traditional, limitation-based DfM mindset towards a dual design mindset.

In addition to these studies linking prior experience to design behavior, researchers have also studied the relationship between prior experience and information retrieval in problem-solving. For example, Pellegrino [32] argues that to encourage successful learning, educators must understand students' prior mental models of the concepts, and if necessary, challenge faulty mental models. This influence of prior knowledge could particularly be in effect with DfAM education: students' prior knowledge of limitation-based traditional DfM concepts could hamper their future learning and use of dual DfAM concepts – comprising opportunistic and restrictive DfAM [33]. Similarly, researchers in learning and memory have demonstrated that the prior knowledge with a partial set of information influences individuals' future learning and recall of the remaining set of the information. This relationship between prior knowledge and information recall is often studied in the context of recall inhibition, i.e., the impaired recall of a set of information due to one's knowledge of a similar set of competing information [34,35]. Recall inhibition can influence one's ability to recall both, old information (i.e., retroactive inhibition [36]) or new information (i.e., proactive inhibition [37]).

Furthermore, researchers have demonstrated that the extent of recall inhibition is influenced by the similarity between the old and new information [38,39] as well as the semantic-relatedness between the two [40]. For example, a higher similarity between old and new information has been shown to correlate with a better recall of the old information [41,42]. Moreover, while this effect of similarity has been demonstrated on retroactive inhibition, this effect might not be seen in proactive inhibition [43]. *Therefore, designers' prior knowledge of traditional, limitation-based design for manufacturing concepts – gained through their engineering experiences – could result in better learning and recall of limitation-based restrictive DfAM concepts.*

Additionally, researchers have also demonstrated the relationship between one's familiarity with a partial set of information and their recall of similar information. Specifically, researchers have demonstrated that a stronger familiarity with a set of information could result in the weaker recall of similar information with weaker association [44,45]. Therefore, designers' prior experiences with restrictive DfAM – gained through both, their engineering experiences and experiences with AM – could further hamper their learning and recall of opportunistic DfAM concepts. *In light of these studies, designers' prior experience could influence their learning and use of DfAM knowledge in a DfAM educational intervention, and our aim in this research is to investigate these effects.* Before doing so, prior work exploring the influence of prior experience in DfAM education is reviewed as discussed next.

2.2. Studies on the influence of prior experience in design for additive manufacturing

As discussed in Section 2.1, an individual's prior experience influences both, their problem-solving strategies as well as their retrieval of information in problem-solving. Several studies have explored the effect of prior experience and expertise on designers' performance in DfAM tasks. For example, Laverne et al. [8] compare the effects of DfAM knowledge introduction between three groups of designers: (1) a control group with no DfAM knowledge, (2) novice designers presented with DfAM knowledge through memos and artifacts, and (3) novices paired with experts in AM. From the results, the authors demonstrate that the group consisting of AM experts generated fewer ideas compared to the other two groups. Furthermore, the authors demonstrate that the control group generated ideas of lower originality compared to the other two groups that possessed AM knowledge either through external cues or through the presence of AM experts.

Similarly, Fillingim et al. [46] discuss the effects of introducing DfAM knowledge through design heuristics on the performance of designers with varying levels of experience. They observe that industry professionals generated ideas of higher novelty compared to novice student designers when presented with DfAM heuristics. However, in their study, the authors only present designers with design heuristics on restrictive DfAM. Another similar study is presented by Hwang et al. [26] in which they compare the effects of presenting DfAM-based design principles on the ideation performance of inexperienced and experienced designers. From their experiment, they observe that experienced designers generated ideas of higher novelty compared to inexperienced designers when presented with DfAM principles. In contrast, inexperienced designers generated ideas of higher quality compared to inexperienced designers, with or without DfAM principles. These studies suggest that designers' prior experience influences the creativity of their designs in DfAM tasks, especially when presented with DfAM tools. Finally, Prabhu et al. [47] study the effects of prior experience on students' learning in formal DfAM educational interventions. Specifically, they observe that lower prior experience in DfAM corresponded to a greater perceived utility of the DfAM educational intervention. They also argue that designers with lower prior experience self-reported a greater use of opportunistic DfAM in the DfAM task.

Taken together, we see from these studies that prior experience influences designers' use of DfAM in design tasks, especially in the conceptual design stage. *However, little research has investigated the relationship between designers' prior experience and the extent of DfAM use in designs in the later stages of design.* Such an investigation is particularly important as designers' CAD skills could influence their design outcomes. For example, designers with more CAD experience could be more inclined to design parts with greater complexity and therefore, better use DfAM in their designs. Moreover, this ability to translate conceptual solutions into digital representations could also influence their DfAM learning and little research has investigated how designers' prior experience influences designers' learning of DfAM in formal DfAM educational interventions. Such an investigation is important as designers' prior experience, especially with traditional manufacturing and DfM could inhibit their ability to transition towards a dual design mindset. Our aim in this research is to investigate this research gap and towards this aim, we seek answers to the research questions discussed next.

3. RESEARCH QUESTIONS

Our aim in this research is to investigate the influence of designers' prior experience on their ability to DfAM. Towards this aim, we posed the following research questions (*RQs*)

- *RQ1: Do experienced and inexperienced designers vary in their baseline DfAM self-efficacy?* We hypothesized that inexperienced designers would report lower DfAM self-efficacy compared to experienced designers. This hypothesis was based on prior work that demonstrated a positive relationship between prior experience and self-efficacy [48].
- *RQ2: Do experienced and inexperienced designers vary in the changes in their DfAM self-efficacy after receiving DfAM education?* We hypothesized that inexperienced designers would report a greater increase in their DfAM self-efficacy compared to experienced designers. This hypothesis was based on prior research that suggested that novice designers benefited more from design guidelines compared to expert designers [31].
- *RQ3: Do experienced and inexperienced designers vary in their use of DfAM in a design task after receiving DfAM education?* We hypothesize that experienced designers would present greater use of DfAM concepts in their designs, as measured through objective assessment of their solutions. This hypothesis is based on prior research suggesting that experienced designers demonstrate greater use of AM principles in creative ideation [26]. Moreover, this hypothesis is based on prior work suggesting the influence of CAD skills in DfAM [49].

4. EXPERIMENTAL METHODS

To answer the research questions presented in Section 3, we performed an experiment in the form of an educational intervention comprising a DfAM lecture and a DfAM task. The study was approved by the Institutional Review Board and implied consent was obtained from the participants before conducting the experiment. The details of the experiment are discussed next.

4.1. Participants

One group of participants in the experiment were recruited from a freshman-level introductory undergraduate course on engineering design – comprising the inexperienced group of designers. A second group of participants was recruited from a graduate-level course on DfAM – comprising the experienced group of designers. While the freshman-level students were considered as the 'inexperienced' group, the graduate-level students were considered the 'experienced' group. In this paper, we used the year of study as a proxy for experience; however, future work must extend our findings with designers with experience in different aspects, such as the number of years working in the industry and the number of years of experience with AM or traditional manufacturing.

The experiment with the freshmen was conducted in the second half of the Spring semester to ensure that the participants had some experience in engineering design and CAD. On the other hand, the experiment with the graduate students was conducted in the first week of classes to minimize any extraneous effects due to the course content. Moreover, students from the DfAM-focused course could have a higher motivation to learn and use DfAM as given their choice to enroll in the course and this is a possible limitation of the study. Before the experiment was conducted, participants' prior AM, DfAM, and CAD experience was collected through a pre-intervention survey. The distribution of participants' prior experience is summarized in Figure 1. As seen in the figure, inexperienced designers demonstrated lower levels of prior experience in AM, DfAM, and CAD compared to the experienced designers.

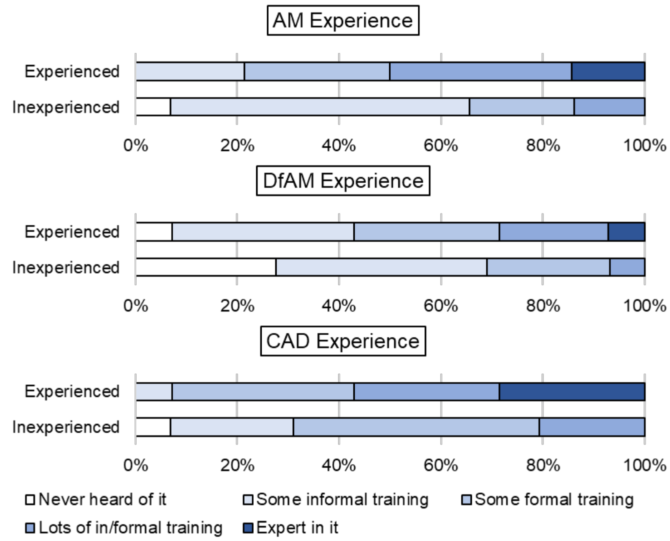

Figure 2 Comparing participants' previous experience

4.2. Procedure and metrics

The experiment comprised three main components: (1) a pre-intervention survey, (2) DfAM educational intervention, (3) a post-intervention DfAM task and survey. The details of each component and the metrics used are discussed next and the overall procedure is summarized in Figure 2.

4.2.1. Pre-intervention Survey

For the first part of the experiment, all students were asked to complete a pre-intervention survey. In the pre-intervention survey, participants were asked to complete the ten-item DfAM self-efficacy survey developed by Prabhu et al. [50]. Specifically, the survey measures self-efficacy with ten DfAM concepts with the first five being the opportunistic DfAM of (1) mass customization, (2) part consolidation, (3) geometric complexity, (4) functional embedding, and (5) multi-material printing, and the last five being the restrictive DfAM concepts of (1) support structures, (2) warping, (3) material anisotropy, (4) surface roughness, and (5) minimum and maximum feature size.

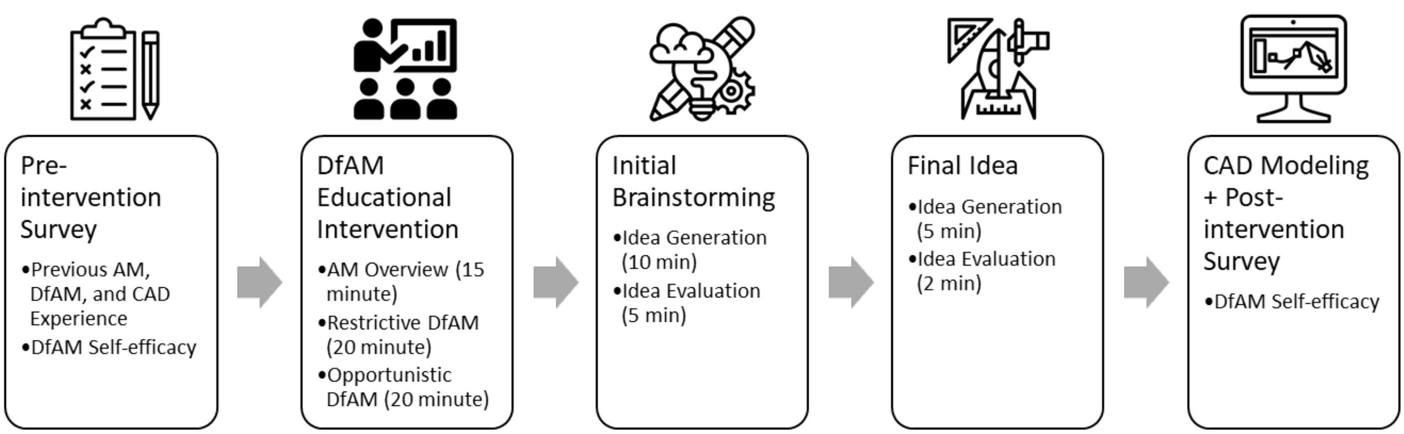

Figure 1 Procedure followed in the experiment

Participants self-efficacy was collected on a five-point scale based on Bloom's Taxonomy of Learning with 1 = 'Never heard about it' to 5 = 'Could feel comfortable regularly integrating it with my design process.' The participants' pre-intervention self-efficacy responses were collected to obtain a baseline and these responses were used to answer RQ1. Additionally, participants were also asked to report their prior experience with AM, DfAM, and CAD, on a scale of 1 = "Never heard about it" to 5 = "Expert in it". A summary of the participants' prior experience in AM, DfAM, and CAD is presented in Figure 1. The complete pre-intervention survey is freely accessible at [51].

4.2.2. DfAM Educational Intervention

Upon completing the pre-intervention survey, participants were given a series of lectures on AM and DfAM. First, all participants were given a 20-minute lecture providing an overview of the AM process. In this lecture, the instructor discussed the topics of (1) introduction to the material extrusion process – the AM process available to the students in the AM design challenge, (2) differences between additive and subtractive manufacturing processes, (3) the digital thread, (4) the Cartesian coordinate system and its relation to the print volume, and (5) materials available in material extrusion. After the AM overview lecture, participants were introduced to the DfAM content. The 20-minute restrictive DfAM lecture covered: (1) build time, (2) feature size, (3) support material, (4) anisotropy, (5) surface finish, and (6) warping. On the other hand, the 20-minute opportunistic DfAM lecture comprised: (1) geometric complexity, (2) mass customization, (3) part consolidation, (4) printed assemblies, (5) multi-material printing, and (6) embedding. The lecture slides can be accessed at [51]. The order of the lectures was based on prior work by Prabhu et al. [52] suggesting the greater effectiveness of teaching restrictive DfAM first, followed by opportunistic DfAM. Moreover, a short lecture-style intervention was chosen to ensure that all parts of the experiment could be completed in the allotted class time. The use of a short intervention is a possible limitation of our study and future work must investigate the use of a longer, distributed educational intervention. Additionally, it should be noted that the lectures were contextualized for the material extrusion AM processes, given that students had access to this type of process on campus. Future work must work towards extending these findings towards DfAM concepts for different AM processes.

4.2.3. Post-intervention DfAM Task and Survey

After receiving the DfAM educational lectures, the participants were asked to complete a DfAM task. The wind turbine tower design problem proposed by Prabhu et al. [53] was used in the study given its demonstrated effectiveness in DfAM educational interventions. Moreover, the design task was presented as a competition based on prior findings (see [54]) suggesting that competitive design tasks are more effective in motivating students to adopt DfAM in their design process and generate creative solutions. Finally, it should be noted that all participants were asked to individually complete the various stages of the design task as discussed next.

As part of the design task, participants were first given 10 minutes to brainstorm for solutions. Participants were asked to generate as many ideas as they liked to within that time and were asked to sketch their ideas and include a brief description. Next, participants were asked to evaluate the strengths and weaknesses of their ideas and based on these evaluations, come up with one final idea. In this stage, participants were given the freedom to select one of their initial ideas, combine several ideas into one, or come up with a completely new idea. Upon completing the final design sketches and descriptions, participants were asked to model their final design using computer-aided design (CAD). While a majority of the participants used Solidworks for generating their CAD models, they were given the freedom to use any software they were comfortable with. Furthermore, it should be noted that participants were not restricted in their use of any AM-specific add-ons or features that might have been present in the software. This freedom with the software used by the participants could have resulted in some potential confounding effects. Participants were given approximately one and a half hours to complete their CAD models. Participants were also asked to create a build layout of their design and submit a screenshot of their desired build layout. Examples of solutions generated by participants are presented in Figure 3. The participants' CAD files were evaluated for their DfAM use as discussed in Section 4.3.

Upon completing the DfAM task, the participants were asked to complete a post-intervention survey. In the survey, participants were asked to respond to the same ten-item DfAM self-efficacy scale as the pre-intervention survey. The differences between the participants' pre- and post-intervention survey responses were calculated and these change scores were analyzed to answer

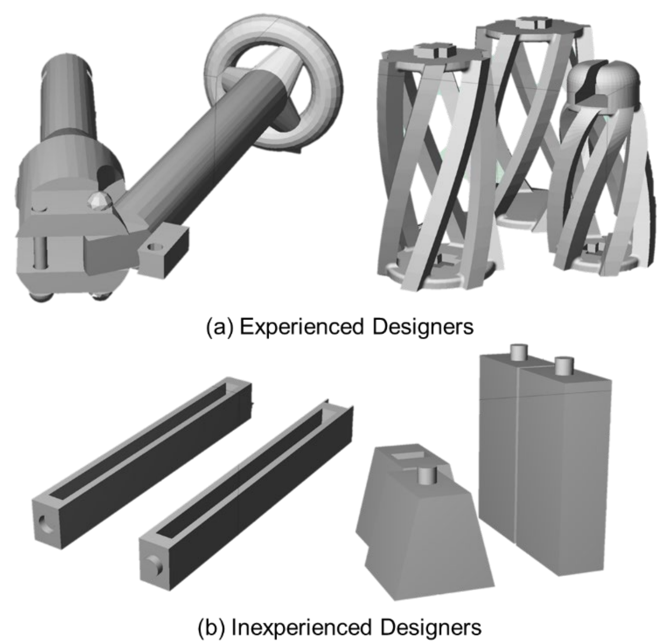

Figure 3 Examples of solutions generated by the participants

RQ2. Next, we discuss the procedures used to analyze the data collected in the experiment and the corresponding results.

4.3. Evaluating DfAM Use in Designs

Several researchers have proposed evaluation tools for assessing the extent of DfAM use in AM designs. These solutions range from the subjective measures proposed by researchers such as Blosch-Paidosh and Shea [29] and Prabhu et al. [55,56] to objective measures such as the DfAM Worksheet [24] and the GAPS worksheet [25]. Of these various methods proposed in the literature, the participants' final CAD files were assessed for their DfAM use using the ten metrics proposed by Prabhu et al. [57]. Specifically, the CAD files were evaluated on ten measures, namely, (1) part complexity, (2) assembly complexity, (3) number of parts, (4) part orientation, (5) assembly feature orientation, (6) smallest feature size, (7) smallest tolerance, (8) support material mass, (9) ease of support material removal, and (10) largest build plate contact area. These measures were used for evaluating the participants' designs given their emphasis on both, the opportunistic and restrictive domains of DfAM. One possible limitation of using these metrics is that they do not necessarily measure whether the various AM concepts were best used in the designs. Consequently, future work must explore the relationship between these objective measures and subjective measures of AM technical goodness such as those proposed in prior work [53,56]. Moreover, this direction of work could also investigate the relationship between the use of these objective metrics and design creativity as suggested in [58]. The scores on these metrics were compared to answer RQ3.

5. DATA ANALYSIS AND RESULTS

A total of 43 participants completed the pre-intervention survey with $N_E = 14$ in the experienced group and $N_{IE} = 29$ in the inexperienced group and these responses were used to answer RQ1. Additionally, 26 of these 43 participants ($N_E = 11$ and $N_{IE} = 15$) completed both, the pre- and post-intervention surveys and only these participants were used to answer RQ2. Finally, because only complete submissions with all STL files and designs that met the requirements of the design problem (e.g., fit in one build) were used to answer RQ3, there was a total of 25 designs in our sample ($N_E = 12$ and $N_{IE} = 13$). The specific statistical tests used to answer each research question and the corresponding results are discussed next.

5.1. RQ1: How do experienced and inexperienced designers vary in their baseline DfAM self-efficacy?

We hypothesized that experienced designers would report greater baseline self-efficacy with DfAM. To test this hypothesis, we first performed a series of independent-samples Mann-Whitney U Tests [59] due to the non-parametric nature of the data. We used participants' pre-intervention DfAM self-efficacy responses as the dependent variable and prior experience (i.e., experienced vs inexperienced) as the independent variable. From the results, summarized in Table 1, we see that experienced designers reported higher baseline DfAM self-efficacies compared to inexperienced designers. Furthermore, while this difference was statistically significant for all restrictive DfAM concepts, this difference was not observed in all opportunistic DfAM techniques. Specifically, we observe that experienced designers reported a higher baseline self-efficacy only with the opportunistic DfAM concepts of functional embedding and multi-material design. These results partially support our hypothesis that experienced designers would also report higher baseline self-efficacy with DfAM.

5.2. RQ2: How do experienced and inexperienced designers vary in their changes in DfAM self-efficacy after receiving DfAM education?

We hypothesized that inexperienced designers would report a greater increase in their DfAM self-efficacy compared to experienced designers. To test this hypothesis, we compared the changes between the pre- and post-intervention DfAM self-efficacy scores, between the experienced and inexperienced designers. Specifically, we performed a series of Mann-Whitney U Tests [59] with the DfAM self-efficacy change scores as the dependent variable and the prior experience as the independent variable. From the results, summarized in Table 2, we observed no differences in the changes in participants' DfAM self-efficacies ($p < 0.05$). Both experienced and inexperienced designers demonstrated similar change scores in their DfAM self-efficacies. This result refutes our hypothesis that inexperienced designers would demonstrate a greater increase in their DfAM self-efficacy and the implications of these results are discussed in Section 6.

Table 1 Comparing baseline DfAM self-efficacy between experienced and inexperienced designers

Self-efficacy Item	Std. Test Statistic	p	Mean Rank Inexperienced	Mean Rank Experienced
Mass Customization	1.94	>0.05	19.52	27.14
Part Consolidation	1.09	0.28	20.60	24.89
Free Complexity	0.92	0.36	20.83	24.43
Functional Embedding	2.60	<0.01	18.71	**28.82**
Multi-material Printing	2.01	0.04	19.41	**27.36**
Support Structures	3.54	<0.01	17.41	**31.50**
Warping	2.87	<0.01	18.28	**29.71**
Material Anisotropy	3.09	<0.01	17.98	**30.32**
Surface Roughness	2.59	0.01	18.66	**28.93**
Feature Size	3.59	<0.01	17.36	**31.61**

Significantly higher values in bold ($p < 0.05$)

Table 2 Comparing changes in DfAM self-efficacy between experienced and inexperienced designers

Self-efficacy Item	Std. Test Statistic	p*	Mean Rank Inexperienced	Mean Rank Experienced
Mass Customization	0.60	0.61	12.80	14.45
Part Consolidation	0.09	0.96	13.40	13.64
Free Complexity	1.68	0.12	11.47	16.27
Functional Embedding	-0.63	0.57	14.27	12.45
Multi-material Printing	-0.11	0.92	13.63	13.32
Support Structures	0.35	0.76	13.07	14.09
Warping	-0.87	0.41	14.57	12.05
Material Anisotropy	-1.23	0.26	14.97	11.50
Surface Roughness	-0.13	0.92	13.67	13.27
Feature Size	-2.78	<0.01	**16.93**	8.82

*exact p; Significantly higher values in bold (p < 0.05)

5.3. RQ3: How do experienced and inexperienced designers vary in their use of DfAM in a design task after receiving DfAM education?

We hypothesized that experienced designers would demonstrate greater levels of DfAM use – assessed using objective design evaluation metrics – compared to inexperienced designers. To test this hypothesis, we performed a series of independent samples t-tests with bootstrapping to 1000 samples. Bootstrapping was performed given the small sample size [60]. The scores on the DfAM utilization metrics were used as the dependent variable and prior experience was used as the independent variable. From the results, we see that only differences in the assembly complexity of the solutions were statistically significant (p < 0.05), with experienced designers generating solutions of higher assembly complexity.

However, as summarized in Figure 4 and Table 3, we see that experienced designers generated solutions of (1) greater part and assembly complexity, (2) fewer number of parts, (3) smaller feature sizes, (4) more appropriate tolerances (i.e., closer to the provided guideline of 0.5mm), and (5) lower build plate contact area. On the other hand, solutions by experienced designers also required more support material. It should be noted that not all of these differences were statistically significant. Of the observed differences, the differences in part and assembly complexity and smallest feature size were particularly noticeable; however, only differences in assembly complexity were statistically significant. These results partially support our hypothesis that experienced designers would demonstrate greater use of DfAM concepts in their designs. The implications of these results are discussed in Section 6.

Table 3 Comparing DfAM use in designs between experienced and inexperienced designers

DfAM Utilization Metric	F	p	η^2	Mean (SD) Inexperienced	Mean (SD) Experienced
Part Complexity	2.82	0.14	0.09	2.00 (0.71)	2.42 (0.67)
Assembly Complexity	4.69	0.04	0.17	1.54 (0.78)	**2.25 (0.87)**
Number of Parts	0.00	0.98	0.00	3.77 (1.92)	3.75 (2.86)
Part Orientation	0.31	0.58	0.01	2.23 (1.01)	2.00 (1.04)
Assembly Orientation	1.76	0.20	0.07	1.92 (0.95)	2.42 (0.90)
Smallest Feature Size	2.42	0.13	0.10	4.15 (3.45)	2.33 (2.20)
Smallest Tolerance	0.22	0.65	0.01	0.58 (1.74)	0.34 (0.34)
Support Material Mass	0.01	0.95	0.00	40.80 (86.34)	38.82 (49.67)
Support Material Removal	0.08	0.78	0.00	2.00 (0.58)	1.92 (0.90)
Largest Build Plate Contact	0.15	0.71	<0.01	5456.87 (3357.53)	4855.49 (4183.79)

Significantly higher values in bold (p < 0.05)

6. DISCUSSION AND IMPLICATIONS

Our aim in this research is to study the influence of designers' prior experience on their DfAM use in a design task, particularly in a formal DfAM educational intervention. Specifically, we aimed to study the relationship between designers' prior experience and (1) their baseline DfAM self-efficacy, (2) changes in their DfAM self-efficacy after receiving DfAM training, and (3) their use of DfAM in a design task. The three key findings from our results are that:

- Experienced designers reported higher levels of baseline self-efficacy with all restrictive DfAM concepts compared to inexperienced designers.
- Prior experience did not influence the changes in designers' DfAM self-efficacy from before to after participating in the DfAM educational intervention.
- Experienced designers designed parts with greater part and assembly complexity compared to inexperienced designers.

The first key finding is that experienced designers reported higher levels of baseline self-efficacy with all restrictive DfAM concepts compared to inexperienced designers. This finding suggests that as students gain engineering experience, they also are exposed to restrictive DfAM. In contrast, experienced designers do not report higher baseline self-efficacy with all opportunistic DfAM concepts. Specifically, we see that experienced designers only report higher baseline self-efficacy with the opportunistic DfAM concepts of functional embedding and multi-material printing, with no differences seen in the other opportunistic DfAM concepts. This result suggests that students are not exposed to opportunistic DfAM concepts to a similar

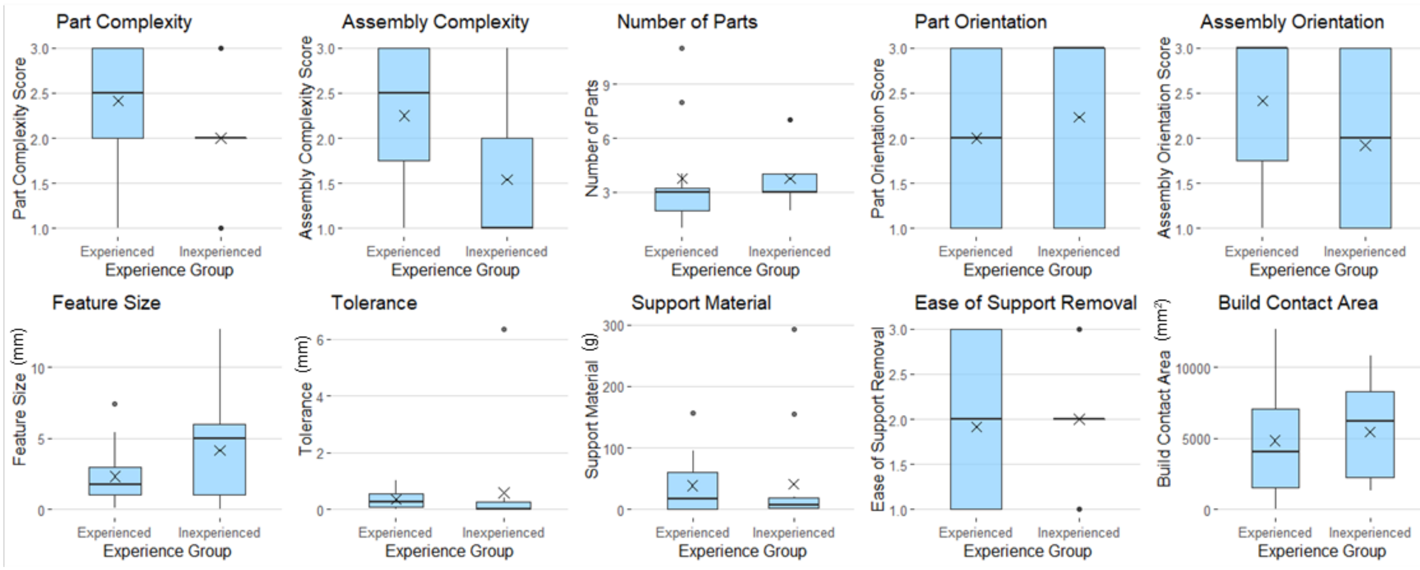

Figure 4 Comparing DfAM use in designs generated by experienced and inexperienced designers

extent as restrictive DfAM. This finding could be attributed to the higher emphasis on restrictive DfAM concepts in the DfAM tools and guidelines that expose designers to DfAM [61].

This finding is problematic because we see in prior research [62] that students' prior experience with restrictive DfAM concepts could hamper their future learning and use of opportunistic DfAM. Therefore, educators must make a special effort to train students in opportunistic DfAM, early in their academic careers. Such an emphasis on opportunistic DfAM training is particularly important as also see in prior research that students learn about restrictive DfAM more easily than opportunistic DfAM [55,56]. Introducing designers to opportunistic DfAM early in their academic journey could, therefore, help support and even reinforce their future learning and use of opportunistic DfAM concepts.

The second key finding is that prior experience did not influence the changes in designers' DfAM self-efficacy from before to after participating in the DfAM educational intervention. This is an important finding as it suggests that the educational intervention is equally effective in increasing designers' DfAM self-efficacy, irrespective of their prior experience. However, this result refutes our hypothesis that inexperienced designers would demonstrate a greater increase in their DfAM self-efficacy. This finding could be attributed to our use of a short, lecture-style intervention to convey DfAM knowledge to the designers. Our use of a lecture-style intervention could have limited its effectiveness in increasing designers' DfAM self-efficacy, especially for inexperienced designers. Inexperienced designers could potentially benefit from a longer educational intervention, that results in a greater increase in their DfAM self-efficacy. Therefore, future work must explore how educational interventions could be better formulated to result in more positive gains in inexperienced designers' DfAM self-efficacy. Moreover, in prior work, researchers have demonstrated that design tools such as design guidelines are an effective medium to introduce novice designers to new knowledge [31]. Therefore, future work must investigate the utility of design tools in formal educational interventions as a method to increase inexperienced designers' DfAM self-efficacy.

The third key finding is that experienced designers designed parts with greater part and assembly complexity compared to inexperienced designers. Additionally, experienced designers designed solutions with smaller features compared to inexperienced designers. For instance, in the example designs shown in Figure 3, the designs generated by experienced designers consist of complex assembly components and geometric features. In contrast, designs generated by inexperienced designers consist of primitive geometries with simple, primitively shaped assembly features. This finding suggests that experienced designers demonstrated greater use of DfAM, especially opportunistic DfAM, in their designs. This finding resonates with prior work where experienced designers presented with DfAM heuristics and principles generated ideas of higher novelty [26,46], potentially due to their use of opportunistic DfAM in their solutions [56].

Experienced designers' generation of designs with higher part and assembly complexity could be attributed to them having higher levels of CAD skills compared to inexperienced designers. Experienced designers' CAD skills could have enabled them to translate their complex conceptual ideas into digital representations. For instance, we present in Figure 5, examples of geometrically complex solutions, several of which were not observed in the final CAD submissions. This inference is informed by the results of the second RQ where both, experienced and inexperienced designers demonstrate similar increases in their DfAM self-efficacy. Despite gaining confidence in the various DfAM concepts, inexperienced students' ability to translate their solutions into digital representation could have been hampered by their lack of CAD

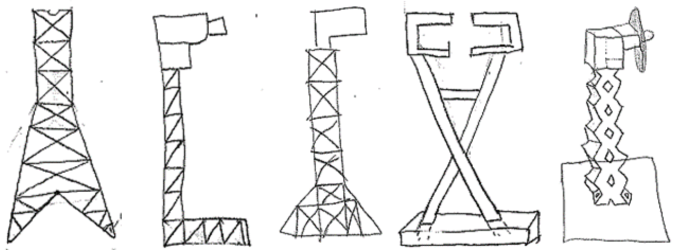

Figure 5 Examples of geometrically complex conceptual solutions generated by the inexperienced designers, some of which were not observed in the CAD submissions

skills. The reliance on CAD skills could be of particular concern when designing complex geometric and assembly features that require advanced modeling techniques.

This aspect of student success in implementing their solutions is particularly important as prior research (e.g., [63]) has demonstrated the influence of students' successes and failures in executing a task on their learning and future approach to solving similar tasks. Consequently, if students are not able to successfully translate their conceptual solutions into CAD models, they could potentially be averse to complex solutions when performing DfAM tasks in the future. Therefore, while introducing students to DfAM early could help encourage a dual design mindset early on, this mindset might not necessarily result in better use of DfAM in their design outcomes, especially in the later stages of the design process. While this is an important and novel finding, in making this inference we assume that inexperienced students generated complex solutions at the conceptual stage and struggled to translate these complex solutions into CAD models. This assumption was, however, not tested in our research and future work must compare students; conceptual ideas to their CAD models.

7. CONCLUSIONS, LIMITATIONS, AND DIRECTIONS FOR FUTURE WORK

Our aim in this research was to investigate the influence of designers' prior experience on their DfAM use in a design task. Specifically, we studied the relationship between designers' prior experience and (1) their baseline DfAM self-efficacy, (2) changes in their DfAM self-efficacy after receiving DfAM training, and (3) their DfAM use in a design task. From the results of our study, we see that experienced designers report higher levels of baseline self-efficacy with all restrictive DfAM concepts, but not necessarily with all opportunistic DfAM concepts. We also see that both, experienced and inexperienced designers report similar changes in their DfAM self-efficacy from before to after receiving DfAM training. Finally, we see that experienced designers generate ideas of higher part and assembly complexity compared to inexperienced designers. Taken together, these findings suggest that:

- Designers must be introduced to opportunistic DfAM concepts early in their academic career,
- However, designers' ability to use DfAM concepts in their designs might require additional engineering skills and experience.

Although the results of our study provide important insights into the influence of designers' experience on their DfAM self-efficacy and their DfAM use, our study has several limitations. First, given missing and ineligible data, we had a small sample size in our study. Future research must, therefore, extend our results to a larger sample. Furthermore, the participants in our study primarily comprised freshmen and graduate students with some participants in their senior year of study. Future research must, therefore, investigate designers with a wider range of prior experience including, possibly, designers with industry experience (e.g., see [56]). Second, only the CAD models for the students' solutions were evaluated in this study. As discussed in the findings of RQ3, students' ability to use DfAM in their solutions could have been limited by their CAD skills. Future research is needed to compare students' conceptual solutions to their CAD models. This direction of research could further elucidate the role of CAD expertise in students' use of DfAM at different stages of the design process. Finally, we used a lecture-style educational intervention to introduce designers to the various DfAM concepts. Prior work has demonstrated that design tools such as design guidelines are effective in introducing novice designers to new design knowledge and influencing design behavior [31]. Therefore, future work must explore our findings to study the use of DfAM tools in educational interventions, especially to increase novice designers' DfAM self-efficacy.

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REFERENCES

[1] Columbus, L., 2014, "Demand For 3D Printing Skills Is Accelerating Globally" [Online]. Available: https://www.forbes.com/sites/louiscolumbus/2014/09/15/demand-for-3d-printing-skills-is-accelerating-globally/#4393ca5e522e. [Accessed: 02-Feb-2018].

[2] Thomas-Seale, L. E. J., Kirkman-Brown, J. C., Attallah, M. M., Espino, D. M., and Shepherd, D. E. T., 2018, "The Barriers to the Progression of Additive Manufacture: Perspectives from UK Industry," Int. J. Prod. Econ., **198**(February 2017), pp. 104–118.

[3] Quinlan, H., and Hart, A. J., 2020, "Additive Manufacturing: Implications for Technological Change, Workforce Development, and the Product Lifecycle," (November).

[4] Bourell, D. L. (The U. of T. at A.), Leu, M. C. (Missouri U. of S. and T.), and Rosen, D. W. (Georgia I. of T.), 2009, *Identifying the Future of Freeform Processing*, The University of Texas at Austin, Austin, TX.

[5] Simpson, T. W., Williams, C. B., and Hripko, M., 2017, "Preparing Industry for Additive Manufacturing and Its Applications: Summary & Recommendations from a National Science Foundation Workshop," Addit. Manuf., **13**, pp. 166–178.

[6] Seepersad, C. C., Allison, J., and Sharpe, C., 2017, "The Need for Effective Design Guides in Additive Manufacturing," *Proceedings of the International Conference on Engineering Design, ICED*, pp. 309–316.

[7] Chekurov, S., 2019, "Categorization of Design for Additive Manufacturing Concepts," *Volume 14: Design, Systems, and Complexity*, American Society of Mechanical Engineers, pp. 1–8.

[8] Laverne, F., Segonds, F., Anwer, N., and Le Coq, M., 2015, "Assembly Based Methods to Support Product Innovation in Design for Additive Manufacturing: An Exploratory Case Study," J. Mech. Des., **137**(12), p. 121701.

[9] Hu, K., Jin, S., and Wang, C. C. L., 2015, "Support Slimming for Single Material Based Additive Manufacturing," CAD Comput. Aided Des., **65**, pp. 1–10.

[10] Zhu, Z., Dhokia, V., Nassehi, A., and Newman, S. T., 2016, "Investigation of Part Distortions as a Result of Hybrid Manufacturing," Robot. Comput. Integr. Manuf., **37**, pp. 23–32.

[11] Carroll, B. E., Palmer, T. A., and Beese, A. M., 2015, "Anisotropic Tensile Behavior of Ti-6Al-4V Components Fabricated with Directed Energy Deposition Additive Manufacturing," Acta Mater., **87**, pp. 309–320.

[12] Ahn, S., Montero, M., Odell, D., Roundy, S., and Wright, P. K., 2002, "Anisotropic Material Properties of Fused Deposition Modeling ABS," Rapid Prototyp. J., **8**(4), pp. 248–257.

[13] Boschetto, A., and Bottini, L., 2016, "Design for Manufacturing of Surfaces to Improve Accuracy in Fused Deposition Modeling," Robot. Comput. Integr. Manuf., **37**, pp. 103–114.

[14] Boschetto, A., Bottini, L., and Veniali, F., 2016, "Finishing of Fused Deposition Modeling Parts by CNC Machining," Robot. Comput. Integr. Manuf., **41**, pp. 92–101.

[15] Fahad, M., and Hopkinson, N., 2012, "A New Benchmarking Part for Evaluating the Accuracy and Repeatability of Additive Manufacturing (AM) Processes," 2nd Int. Conf. Mech. Prod. Automob. Eng., pp. 234–238.

[16] Pallari, J. H. P., Dalgarno, K. W., and Woodburn, J., 2010, "Mass Customization of Foot Orthoses for Rheumatoid Arthritis Using Selective Laser Sintering," IEEE Trans. Biomed. Eng., **57**(7), pp. 1750–1756.

[17] Schmelzle, J., Kline, E. V., Dickman, C. J., Reutzel, E. W., Jones, G., and Simpson, T. W., 2015, "(Re)Designing for Part Consolidation: Understanding the Challenges of Metal Additive Manufacturing," J. Mech. Des., **137**(11), p. 111404.

[18] Calì, J., Calian, D. A., Amati, C., Kleinberger, R., Steed, A., Kautz, J., and Weyrich, T., 2012, "3D-Printing of Non-Assembly, Articulated Models," ACM Trans. Graph., **31**(6), p. 1.

[19] Chu, C., Graf, G., and Rosen, D. W., 2008, "Design for Additive Manufacturing of Cellular Structures," Comput. Aided. Des. Appl., **5**(5), pp. 686–696.

[20] Rosen, D. W., 2007, "Computer-Aided Design for Additive Manufacturing of Cellular Structures," Comput. Aided. Des. Appl., **4**(1–6), pp. 585–594.

[21] Murr, L. E., Gaytan, S. M., Medina, F., Lopez, H., Martinez, E., MacHado, B. I., Hernandez, D. H., Martinez, L., Lopez, M. I., Wicker, R. B., and Bracke, J., 2010, "Next-Generation Biomedical Implants Using Additive Manufacturing of Complex Cellular and Functional Mesh Arrays," Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., **368**(1917), pp. 1999–2032.

[22] De Laurentis, K. J., Kong, F. F., and Mavroidis, C., 2002, "Procedure for Rapid Fabrication of Non-Assembly Mechanisms with Embedded Components," Proc. 2002 ASME Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf., pp. 1–7.

[23] Doubrovski, E. L., Tsai, E. Y., Dikovsky, D., Geraedts, J. M. P., Herr, H., and Oxman, N., 2015, "Voxel-Based Fabrication through Material Property Mapping: A Design Method for Bitmap Printing," CAD Comput. Aided Des., **60**, pp. 3–13.

[24] Booth, J. W., Alperovich, J., Chawla, P., Ma, J., Reid, T. N., and Ramani, K., 2017, "The Design for Additive Manufacturing Worksheet," J. Mech. Des., **139**(10), pp. 1–9.

[25] Bracken, J., Pomorski, T., Armstrong, C., Prabhu, R., Simpson, T. W., Jablokow, K., Cleary, W., and Meisel, N. A., 2020, "Design for Metal Powder Bed Fusion: The Geometry for Additive Part Selection (GAPS) Worksheet," Addit. Manuf., **35**, p. 101163.

[26] Hwang, D., Lauff, C. A., Perez, K. B., Camburn, B. A., and Wood, K. L., 2020, "Comparing the Impacts of Design Principles for Additive Manufacturing on Student and Experienced Designers," Int. J. Eng. Educ., **36**(6), pp. 1862–1876.

[27] Perez, K. B., Anderson, D. S., Hölttä-Otto, K., and Wood, K. L., 2015, "Crowdsourced Design Principles for Leveraging the Capabilities of Additive Manufacturing," Int. Conf. Eng. Des., (July), pp. 1–10.

[28] Yang, S., Page, T., and Zhao, Y. F., 2018, "Understanding the Role of Additive Manufacturing Knowledge in Stimulating Design Innovation for Novice Designers," J. Mech. Des., **141**(2), p. 021703.

[29] Blösch-Paidosh, A., and Shea, K., 2019, "Design Heuristics for Additive Manufacturing Validated

Through a User Study1," J. Mech. Des., **141**(4), pp. 1–40.
[30] Ahmed, S., Wallace, K. M., and Blessing, L. T. M., 2003, "Understanding the Differences between How Novice and Experienced Designers Approach Design Tasks," Res. Eng. Des., **14**(1), pp. 1–11.
[31] Reimlinger, B., Lohmeyer, Q., Moryson, R., and Meboldt, M., 2019, "A Comparison of How Novice and Experienced Design Engineers Benefit from Design Guidelines," Des. Stud., **63**, pp. 204–223.
[32] Pellegrino, J. W., 2006, "Rethinking and Redesigning Curriculum, Instruction and Assessment: What Contemporary Research and Theory Suggests," A Pap. Comm. by Natl. Cent. Educ. Econ. New Comm. Ski. Am. Work., (November), pp. 1–15.
[33] Sinha, S., Chen, H.-E., Meisel, N. A., and Miller, S. R., 2017, "Does Designing for Additive Manufacturing Help Us Be More Creative? An Exploration in Engineering Design Education," *Volume 3: 19th International Conference on Advanced Vehicle Technologies; 14th International Conference on Design Education; 10th Frontiers in Biomedical Devices*, American Society of Mechanical Engineers, pp. 1–12.
[34] Anderson, M. C., and Neely, J. H., 1996, "Interference and Inhibition in Memory Retrieval," Memory, pp. 237–313.
[35] Anderson, M. C., Bjork, R. A., and Bjork, E. L., 1994, "Remembering Can Cause Forgetting: Retrieval Dynamics in Long-Term Memory," J. Exp. Psychol. Learn. Mem. Cogn., **20**(5), pp. 1063–1087.
[36] Britt, S. H., 1935, "Retroactive Inhibition: A Review of the Literature," Psychol. Bull., **32**(6), pp. 381–440.
[37] Whitely, P. L., 1927, "The Dependence of Learning and Recall upon Prior Intellectual Activities," J. Exp. Psychol., **10**(6), pp. 489–508.
[38] Robinson, E. S., 1920, "Studies From the Psychological Laboratory of the University of Chicago: Some Factors Determining the Degree of Retroactive Inhibition," Psychol. Monogr., **28**(6), pp. 1–57.
[39] McGeoch, J. A., and McDonald, W. T., 1931, "Meaningful Relation and Retroactive Inhibition," Am. J. Psychol., **43**(4), p. 579.
[40] Blaxton, T. A., and Neely, J. H., 1983, "Inhibition from Semantically Related Primes: Evidence of a Category-Specific Inhibition," Mem. Cognit., **11**(5), pp. 500–510.
[41] Robinson, E. S., 1927, "The 'Similarity' Factor in Retroaction," Am. J. Psychol., **39**(1/4), p. 297.
[42] Harden, L. M., 1929, "A Quantitative Study of the Similarity Factor in Retroactive Inhibition," J. Gen. Psychol., **2**(4), pp. 421–432.
[43] Young, R. K., 1955, "Retroactive and Proactive Effects under Varying Conditions of Response Similarity," J. Exp. Psychol., **50**(2), pp. 113–119.
[44] Brown, J., 1968, "Reciprocal Facilitation and Impairment of Free Recall," Psychon. Sci., **10**(2), pp. 41–42.
[45] Karchmer, M. A., and Winograd, E., 1971, "Effects of Studying a Subset of Familiar Items on Recall of the Remaining Items: The John Brown Effect," Psychon. Sci., **25**(4), pp. 224–225.
[46] Fillingim, K. B., Nwaeri, R. O., Paredis, C. J. J., Rosen, D., and Fu, K., 2020, "Examining the Effect of Design for Additive Manufacturing Rule Presentation on Part Redesign Quality," J. Eng. Des., **0**(0), pp. 1–34.
[47] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2018, "The Earlier the Better? Investigating the Importance of Timing on Effectiveness of Design for Additive Manufacturing Education," *Volume 2A: 44th Design Automation Conference*, American Society of Mechanical Engineers, pp. 1–14.
[48] Robnett, R. D., Chemers, M. M., and Zurbriggen, E. L., 2015, "Longitudinal Associations among Undergraduates' Research Experience, Self-Efficacy, and Identity," J. Res. Sci. Teach., **52**(6), pp. 847–867.
[49] Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., and Martina, F., 2016, "Design for Additive Manufacturing: Trends, Opportunities, Considerations, and Constraints," CIRP Ann. - Manuf. Technol., **65**(2), pp. 737–760.
[50] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2018, "Teaching Design Freedom: Exploring the Effects of Design for Additive Manufacturing Education on the Cognitive Components of Students' Creativity," *Volume 3: 20th International Conference on Advanced Vehicle Technologies; 15th International Conference on Design Education*, American Society of Mechanical Engineers, pp. 1–14.
[51] "Design Thinking – Made By Design Lab" [Online]. Available: http://sites.psu.edu/madebydesign/design-thinking/. [Accessed: 24-Apr-2019].
[52] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Fresh in My Mind! Investigating the Effects of the Order of Presenting Opportunistic and Restrictive Design for Additive Manufacturing Content on Creativity," *Volume 3: 17th International Conference on Design Education (DEC)*, American Society of Mechanical Engineers, pp. 1–16.
[53] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Complex Solutions for Complex Problems? Exploring the Role of Design Task Choice on Learning, Design for Additive Manufacturing Use, and Creativity," J. Mech. Des., **142**(3).
[54] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Built to Win? Exploring the Role of Competitive Environments on Students' Creativity in Design for Additive Manufacturing Tasks," J. Eng. Des., **31**(11–12), pp. 574–604.
[55] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "Exploring the Effects of Additive Manufacturing Education on Students' Engineering Design Process and Its Outcomes," J. Mech. Des.,

142(4), p. 1.

[56] Prabhu, R., Bracken, J., Armstrong, C. B., Jablokow, K., Simpson, T. W., and Meisel, N. A., 2020, "Additive Creativity: Investigating the Use of Design for Additive Manufacturing to Encourage Creativity in the Engineering Design Industry," Int. J. Des. Creat. Innov., **8**(4), pp. 198–222.

[57] Prabhu, R., Miller, S. R., Simpson, T. W., and Meisel, N. A., 2020, "But Will It Build? Assessing Student Engineering Designers' Use of Design for Additive Manufacturing Considerations in Design Outcomes," J. Mech. Des., **142**(9), pp. 1–56.

[58] Prabhu, R., Masia, J. S., Berthel, J. T., Meisel, N. A., and Simpson, T. W., 2021, "Maximizing Design Potential: Investigating the Effects of Utilizing Opportunistic and Restrictive Design for Additive Manufacturing in Rapid Response Solutions," Rapid Prototyp. J.

[59] Mann, H. B., and Whitney, D. R., 1947, "On a Test of Whether One of Two Random Variables Is Stochastically Larger than the Other," Ann. Math. Stat., **18**(1), pp. 50–60.

[60] Efron, B., 1979, "Bootstrap Methods: Another Look at the Jackknife," Ann. Stat., **7**(1), pp. 1–26.

[61] Bracken, J. E., McComb, C., Simpson, T. W., and Jablokow, K. W., 2020, "A Review of Part Filtering Methods for Additive Manufacturing," *Proceedings of the ASME Design Engineering Technical Conference*, pp. 1–10.

[62] Prabhu, R., Simpson, T. W., Miller, S. R., and Meisel, N. A., 2021, "Fresh in My Mind! Investigating the Effects of the Order of Presenting Opportunistic and Restrictive Design for Additive Manufacturing Content on Students' Creativity," J. Eng. Des., pp. 1–26.

[63] Kapur, M., 2008, "Productive Failure," Cogn. Instr., **26**(3), pp. 379–424.