Title

Improving Outcomes and Participation in the Prototyping Process Using Design-for-Additive-Manufacturing Training

Journal

International Journal of Engineering Education, 36(4)

ISSN

0949149X

Authors

Budinoff, Hannah D
McMains, Sara

Publication Date

2020

Peer reviewed

Improving Outcomes and Participation in the Prototyping Process Using Design-for-Additive-Manufacturing Training

HANNAH D. BUDINOFF and SARA MCMAINS
Department of Mechanical Engineering, University of California, Berkeley, Berkeley, CA, USA.
E-mail: {hdb, mcmains}@berkeley.edu

University makerspaces provide students with resources to build and prototype, which is helpful in engineering design projects. In fall 2018, in a sophomore-level engineering class with a semester-long design project, we introduced a design-for-additive-manufacturing training activity with several goals in mind. We hoped to familiarize students with the interplay between design and manufacturing, reduce 3D printing failures leading to inefficient prototyping, and help novices build confidence with using 3D printing in our university makerspace. By evaluating individual homework assignments as well as team design project deliverables and grades for 58 students in the class, we seek to evaluate outcomes and participation in the prototyping process. The additive manufacturing training did not significantly decrease the occurrence of common manufacturability problems during team prototyping. However, we identified several interesting trends regarding participation. A moderate positive correlation was identified between a student's level of initial 3D printing experience relative to their team members' experience and the amount of prototyping responsibility that student undertook. Students who did not help prototype received lower peer review scores from their teammates than those who did. Although the participation was still unequal, the overall fraction of students who helped prototype in the semester with design-for-additive-manufacturing training was approximately 20% larger than the prior semester with no training, indicating that the training may be an effective way to foster more inclusivity in the prototyping process.

Keywords: university makerspaces; engineering design process; prototyping; engineering education; gender diversity; women in engineering; spatial visualization ability; design for manufacturing

1. Introduction

Makerspaces are becoming more integrated into engineering curriculums at universities [1]. Involvement in makerspaces has many benefits for students. Active participation in a makerspace improves confidence in design skills, especially in design for manufacturing (DFM) and prototyping [2], and provides students with experience that helps them once they enter the engineering workforce [3]. Hands-on engineering design experiences can help promote engineering and tinkering self-efficacy [4]. Makerspaces also enable students to cheaply create prototypes for design projects using technology like 3D printers without much or any prior experience, which can help enable more project-based learning throughout the engineering curriculum, another trend in engineering education [1,5].

Prototyping, which we use here to mean the physical realization of some aspect of a design, is an element central to the engineering design process. Although prototypes serve many purposes, they are frequently used early in the design process to provide a proof of concept, and later to refine the performance through use in testing [6]. Effective prototyping, as summarized in [7], can also reduce design fixation and lead to better design outcomes. Because of these benefits, and because of its centrality to the engineering design process, prototyping is a critical skill for engineering students to learn before entering the workforce.

However, there are potential roadblocks that may prevent students from reaping the numerous benefits of hands-on experiences, practice with prototyping, and participation in makerspaces. One potential problem is inefficient prototyping. A community-focused atmosphere and openness are important attributes that make makerspaces unique from other spaces on university campuses where Making was previously done (e.g., machine shops) [1]. Students perceive that it is easier to access makerspaces than traditional university machine shops [8]. Because of this openness and the prevailing encouragement of tinkering and trial and error in makerspaces, students may not have enough knowledge or guidance about a given process to make efficient use of their time and material resources during prototyping. For time-constrained and high-stress course design projects, they may waste time printing parts that are not compatible with their chosen manufacturing process. (One recent study showed approximately 20% of parts printed on a makerspace 3D printer failed due to poor design [9]).

Another issue is that not all students are likely to benefit equally from makerspace access. Many engineering design projects that involve prototyping are team projects. In a university setting, it is desirable that all students learn prototyping skills and gain familiarity with manufacturing processes, so it is important to consider how student characteristics may affect student participation in the prototyping process. There are several barriers to access for

Recommended citation: H.D. Budinoff and S. McMains, Improving Outcomes and Participation in the Prototyping Process Using Design-for-Additive-Manufacturing Training, *Int. J. Eng. Educ.*, **36**(4). 2020.

women and other marginalized groups, including a lack of similar role models [10]. We want to understand better the factors that enable students to participate and learn from makerspace and prototyping experiences.

One strategy that has been proposed to help promote equal participation in hands-on activities and makerspaces is to scaffold participation and mastery experiences [4,10]. For this reason and in an attempt to improve prototyping efficiency by helping students avoid unnecessary failures caused by design flaws, in fall 2018, midway through a semester-long team design project in a sophomore-level manufacturing and design class, we introduced a DFM training assignment. In previous semesters, the primary technology used by students to build their project prototypes was 3D printing, specifically fused filament fabrication (FFF, also known as fused deposition modeling), an additive manufacturing (AM) process. The training assignment educated students about design for additive manufacturing (DFAM) guidelines for FFF and asked them to apply the guidelines to redesign a part. It was hoped that students would learn from this training and apply the DFAM guidelines on their final project prototypes. In addition to evaluating if the training made the project prototyping process more efficient, our dataset also provides an opportunity to evaluate if all students participated in AM prototyping equally after the training.

Through a quantitative study of 58 students, we examine student outcomes and participation in the construction of design project prototypes in a university makerspace, with a focus on using AM. The impact of the DFAM training on issues with prototyping is analyzed. We highlight some potential barriers to active participation in makerspaces and the prototyping process and discuss strategies instructors in classes with a design component can use to ensure more equitable participation in design projects.

2. Related work

If the goal of design projects in engineering courses, especially projects early in the undergraduate curriculum, is to help students gain mastery over all aspects of engineering design, potential barriers should be mitigated to ensure all students have a chance to gain prototyping skills and experience. We will focus on a few potential barriers to equal access to prototyping or makerspace resources, namely: social factors; prior experience; and spatial visualization. Although each of these individual barriers has been the subject of prior study, here we consider the interplay between these variables, and experimentally assess whether or not additional knowledge of DFAM can mitigate their impact. Because this study seeks to evaluate the effect of DFAM training, research related to DFM, DFAM, and AM usage in engineering education is briefly surveyed as well.

2.1 Social factors impacting participation in makerspaces and design teams

The dominant conceptualization of Making is that it is a white, male, middle-class pursuit [10,11] which may cause students who do not fit that description to feel a lack of belonging. Makerspaces housed in universities may also reflect the masculine culture ingrained in academic engineering programs, which makes female students feel isolated and impacts their achievement [10]. Anxiety may also be a barrier to participation in a makerspace, with students who were more motivated and less anxious about engineering design participating more frequently in makerspaces [12].

In team projects, social factors also impact performance and influence which team members participate in different design activities. Stereotype threat and solo status (i.e., being the only member of a social category on a team) can cause underperformance compared with being in a group of similar peers [13]. Biases associated with gender can affect participation in team design projects, with females perceiving "significantly less emphasis to participate on hands-on construction" of their projects [14]. Compounding these biases is the tendency of students from under-represented groups to have lower self-efficacy, which may cause them to avoid volunteering for technical tasks [15]. Here, we seek to evaluate if more female students participate in prototyping activities in a group project after being provided with DFAM training.

2.2 Effect of prior experience on prototyping participation and performance

In high-stress team projects, students may adopt a divide-and-conquer strategy, where tasks are assigned based on team members' perceived strengths [15], which suggests that students less experienced with manufacturing are less likely to participate in constructing prototypes. Subdividing tasks is pervasive, since students view it as an efficient way to achieve design goals, and so students develop "specializations" that stick with them throughout their time at university [16]. One prior observational study found that teammates worked together for the majority of a design project but split up to complete prototyping because only particular team members could perform certain tasks well [7]. Because prototyping was found to take nearly half of the time spent on the design activity [7], students with less prototyping skill (or who are perceived to have less skill) may be excluded from the main design team for significant periods of the project. Fear of taking on hands-on responsibilities in a team project if a student has no prior experience has been identified as a barrier in interviews with students as well [4].

While assigning roles based on prior experience can be beneficial in industry teams, it is unclear if this strategy leads to better design outcomes in student teams [16]. A study of software engineering students found that specialization negatively impacted student's readiness for industry jobs [17]. Additionally, more experienced teams may not necessarily be more successful. One study found that neither the average team experience level nor the maximum experience level of any member on a team (measured as experience with CAD and time in industry) correlated to more success on a design project [18]. In this study, we investigate the role of prior experience on student participation and performance on design tasks.

2.3 Effect of spatial skills on prototyping participation and performance

Another factor that may influence participation is spatial visualization ability, i.e., the ability to mentally operate on 3D shapes. Spatial visualization ability (also called spatial skills) has been found to be related to learning and using 3D modeling packages [19] and creativity while designing in CAD [20]. Students with lower spatial skills have higher cognitive load while viewing 3D visualizations as compared to other students, which can interfere with learning [21]. Because the software programs used to prepare a part for 3D printing employ 3D visualizations, it may be harder for low visualizers to interact with the software to choose a suitable build orientation or to evaluate which features have overhanging faces. Although the impact of spatial skills on prototyping has not been extensively studied, there are indications that it may negatively affect students' prototyping skills [22], even using more traditional prototyping technologies.

We hypothesize that groups of students with lower spatial skills may find it more challenging to use AM for prototyping than groups with higher spatial skills. Women and students from certain underrepresented groups, who tend to have lower spatial skills [23,24], may find it harder to choose build orientations and learn DFAM guidelines that are heavily dependent on visualizing and rotating 3D shapes. Exposure to shop classes with hands-on manufacturing in middle school [25] and playing with construction games as a child [26] have been linked to higher spatial skills; consequently, social biases may impact differences between groups as well. Encouraging participation of low visualizers in 3D printing may be to their benefit because interacting with CAD and 3D printing has been shown to improve spatial skills [27,28], and improvements in spatial skills can help improve retention [29,30]. In this study, we explore interactions between spatial visualization ability and performance and participation in prototyping activities involving 3D printing.

2.4 DFM & DFAM training for students

Moving prototyping activities out of machine shops with heavily controlled and regulated access to manufacturing equipment into makerspaces may impact how students approach the design and prototyping process. Makerspaces are viewed as more collaborative and with easier access than machine shops [8]. This ease-of-access may lower student anxiety about needing to evaluate a design carefully before actually creating it. A recent study found that 18.2% of parts that students tried to 3D print in a university makerspace failed due to poor design [9]. With less controlled access and less supervision, students may not have enough knowledge or guidance to make efficient use of their time and material resources. The prototyping process may be focused on achieving successful manufacturing outcomes, rather than iterating on their design to improve design performance. One way to encourage more efficiency in the prototyping process is by teaching students DFM guidelines. DFM concepts are frequently taught via lecture but can also be learned from hands-on prototyping in makerspaces [2], reviewing DFM guidelines on a worksheet prior before being allowed to manufacture [9], and DFM software [31].

DFAM guidelines often take the form of short heuristics with pictorial examples of poor and acceptable geometry. Examples of part features that would be considered not in keeping with DFAM guidelines for FFF are walls thinner than approximately 2 mm, which tend to break, or internal cavities with overhanging faces that need support material, which is difficult or impossible to remove. Lists of DFAM guidelines have been developed in industry, but the effectiveness of DFAM in educational settings is only just beginning to be assessed [9,32]. Here, we look at the effectiveness of DFAM by evaluating common student issues with additively manufactured parts, both before and after a DFAM training. We also assess if DFAM training is an effective strategy for mitigating potential barriers for participation and performance in prototyping activities.

2.5 AM in engineering education

AM technologies have been integrated into many engineering programs at universities. A recent literature review found that AM has been used for various purposes at the university level, including incorporating AM skills and subject knowledge into new or existing classes, and to enable project-based learning [33]. In project-based classes, students are often tasked with solving an open-ended design problem as a team as an introduction to the engineering design process, and AM is a convenient and low-cost production technology for realizing their designs [33]. Alternatively, some project-based classes focus on instructing students about the science behind AM technologies, and use a design project as a convenient way to have students apply the AM-knowledge they've gained in the course [34,35]. Incorporating AM into courses has been shown to improve student engagement while also reducing design cycle times [33]. Prior examples of successful integration of AM topics into engineering education design projects at a university level demonstrate that this a promising way to help train students for future jobs. Wider adoption of AM in courses and the development of best pedagogical practices would also help AM to reach its full potential by helping to create a workforce better trained to take advantage of AM's unique characteristics [36]. Quantifying the factors that impact participation and performance in AM design projects, as we do here, is a first step towards achieving this goal.

3. Method

This study aims to assess how educating students about DFAM impacts the effectiveness of prototyping and to investigate the role of student characteristics on participation and performance on a design project. To investigate these topics, we evaluate performance and participation in several course components in a sophomore-level mechanical engineering class: a team design project; an AM-related homework assignment; and a DFAM training that was in the form of another homework assignment. Each component will be described in detail in subsequent subsections.

3.1 Participant characteristics

The study was conducted in an introduction to manufacturing and tolerancing course at a public R1 university. The sample discussed here includes 58 students (10 female) who were enrolled in the class in fall 2018. In fall 2017, students enrolled in this same course with the same professor were not given DFAM training, so that data is used for comparison when possible.

In fall 2018, to investigate possible correlations between student characteristics and performance or participation, we asked students about their prior experience and spatial skills. Before completing the AM-related homework assignment or the DFAM training, students were asked to describe their prior experience with 3D printing, rating their experience on an interval scale (1: "I have never heard of it"; 2: "I am familiar with it, but haven't 3D printed anything myself"; 3: "I have 3D printed one or two things"; 4: "I have 3D printed many things"; 5: "I own a 3D printer"). Students were also asked to respond to the question "Generally speaking, how confident do you feel in your ability to mentally visualize what an object will look like in 3D space based on only seeing 2D views of the object?" on an interval scale (1: "Not at all confident"; to 5: "Very confident"), which was meant to serve as an estimate for their spatial skills. Although not as accurate as measuring their spatial ability with a test designed for that purpose (e.g., the Purdue Spatial Visualization Test: Rotations, PSVT:R [37], or the Mental Cutting Test, MCT [38]), this approach was chosen due to time constraints and the difficulty of achieving uniform testing conditions. (Most of the students had taken the PSVT:R and/or MCT as part of a co-requisite class, but some had taken the spatial tests just a short time before, while for others it had been over a year.) A previous study found a significant correlation between students' perception of their spatial ability and their actual spatial ability as measured on these tests [39], so we expected our estimate would provide an adequate estimate of spatial ability.

3.2 Team design project

The course features a team design project, where student teams propose, design, and prototype a cell phone accessory. Students were randomly grouped into project teams for the first group lab assignment at the start of the semester. Although they were subsequently allowed to adjust the groupings, most students stayed with their initially assigned team. Project team size ranged from four to six students.

Almost all prototyping for the design project took place in the university makerspace (Fig. 1). All students had access to the makerspace. To use makerspace equipment like 3D printers, students must complete a basic online quiz that focuses on machine operation after reading some training material, a process that takes about 30 minutes. The makerspace provides no additional training on DFM or DFAM. Laser cutters, several types of 3D printers, and basic wood- and metal-working tools are all available in the makerspace.

Fig. 1. The university makerspace where prototyping took place features equipment such as 3D printers.

The final deliverable for the group project was a refined prototype of their design. All teams were assigned a score for the quality of their prototype by two evaluators, who rated each teams' final prototype on a scale of 1 to 10 for both workmanship and creativity, and summed these two metrics to calculate the overall quality score. The inter-rater reliability was acceptable (Krippendorff's α=.812). The two evaluators' ratings were averaged to determine the overall quality score, which is reported in this study as a percentage of the maximum score of 20. Peer review scores were calculated based on team member ratings for problem-solving, effort, reliability, team support, and overall effectiveness. Ratings from all of a student's team members were averaged to find that student's peer review score, with a maximum of 30 points. All teams also submitted a final project report, where they were asked to summarize manufacturing problems that they had to overcome during prototyping and which team member was responsible for which project activities, including prototyping.

3.3 Qualitative analysis of participation and prototyping problems

We wanted to identify common problems students encountered while prototyping using the makerspace 3D printers. As part of a homework assignment that took place before the DFAM training, students were asked to print a part and describe any manufacturability or quality issues that arose, submitting their responses and pictures of their printed part. The assignment was an individual homework assignment, not a team activity. Students who had already used a 3D printer could describe a part they had printed prior to their enrollment in this course. A primary analyst evaluated student submissions to identify common phenomena that students described. These phenomena were grouped into eight categories of manufacturability problems that were then used as a framework to code all student responses for the homework assignment. The framework was also used to refine the DFAM training to ensure that the most impactful problems were addressed by the DFAM guidelines included in the training.

The primary analyst used the same framework to code each team's final project report for prototyping problems. The final report also detailed team member contributions, stating what each team member was responsible for. When multiple students were listed with prototyping responsibilities, each student was assigned a fraction of the responsibility equal to the number of prototyping activities for which they were responsible.

3.4 DFAM training

In fall 2018, two months into the semester, the students were assigned a DFAM training exercise. The training was an individual activity rather than a team activity. The exercise was a homework assignment where students were asked to study DFAM design guidelines (a topic not covered in lecture), to apply those guidelines to redesign a pencil holder to avoid printing errors, and to recommend a build orientation. The training listed guidelines related to minimum feature size, warping, overhanging features, parts becoming dislodged from the build platform, and surface quality, and gave strategies such as reorienting the part or changing features to improve manufacturability. This training exercise is described in detail in [40]. Approximately half of the class used a MATLAB-based tool to complete the training exercise while others used a worksheet. The effect of the format of the tool is described in [40]. In this work, we analyze the overall effect of the training. After completing the DFAM training, students were asked to rate: their confidence in the success of the print; their effort level during the design task (measured using the NASA-RTLX [41]); and the usability, or ease of use, of the DFAM tool they were asked to use (measured using the System Usability Scale [42]).

3.5 Statistical tests

Our choices regarding statistical tests were guided by the relatively small sample sizes of some groups we wished to evaluate (for example, our sample contains only ten women). Because of the small sample sizes for certain groups and because this study was exploratory, we used a significance level of $\alpha=.10$ for all statistical tests. Associations between categorical variables were tested using a two-tailed Fisher's exact test. For calculating correlations between metrics, we used Spearman's rank correlation coefficient. To test for differences between groups, we used the non-parametric Mann-Whitney U test for independent samples, which does not have an assumption of normality. The effect size, r, for the Mann-Whitney U tests was calculated as the ratio of the z statistic over the square root of the total number of samples, with .1 seen as a small, .3 as a medium, and .5 as a large effect size.

4. Results

4.1 Student characteristics

Most students had some familiarity with 3D printing (Fig. 2). 58% (28/48) of men had used a 3D printer before while only 30% (3/10) of women had, but this difference in proportions was not found to be statistically significant (p = .16).

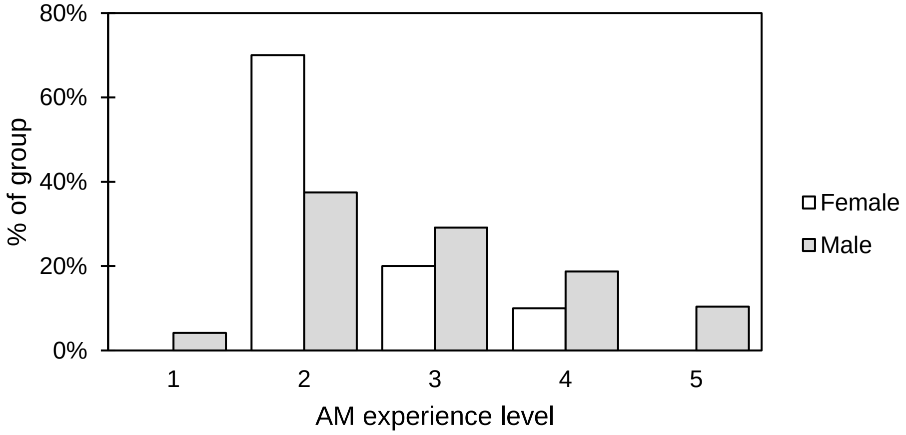

Fig. 2. Most students reported some familiarity with AM (experience levels range from 1: "I have never heard of it" to 5: "I own a 3D printer").

Students also reported varying levels of spatial skills (Fig. 3). Female students reported less confidence in their spatial skills, with 30% (3/10) of women reporting their confidence as neutral or not confident compared with 6% (3/48) of men, a difference in proportions that was statistically significant (p = .06). This self-reported data matches the distribution of spatial skills for the student population at our university, measured in a recent study using the Purdue Spatial Visualization Test: Rotations (PSVT:R) [43], and so we feel it is an acceptable estimate of actual spatial skills.

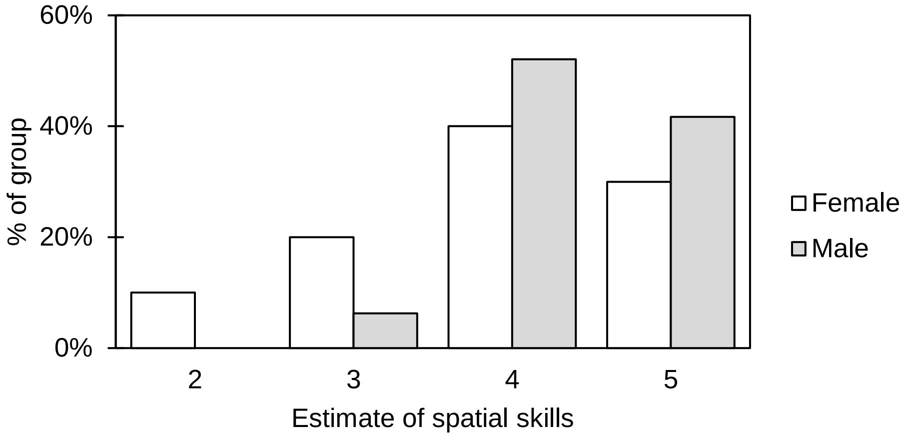

Fig. 3. Female students reported lower confidence in their spatial skills than men.

4.2 Manufacturability problems and prior experience

In the homework assignment prior to the DFAM training, students reported various types of manufacturability problems, which varied depending on their experience level. Inexperienced students who had never used a 3D printer before or only printed one or two parts (experience level < 4) struggled with basic manufacturability problems, such as part warpage, or parts becoming dislodged from the print platform. The most common problem students described was struggling to fully remove support material (e.g., in the words of one student, "The bottom surface support attaching the part to the build platform left a significant amount of leftover support material that had to be cut and sanded away, still leaving a rough and ununiform finish"). More experienced students described problems with dimensional accuracy (e.g., "Getting the correct fit between parts with the 3D printer's tolerances was the hardest part. This lead [sic] to multiple tries and errors."). Experienced students more frequently described parts they had printed for a prior project that required printing multiple interfacing parts. The frequency of the six most common problems encountered by all students is displayed in Fig. 4.

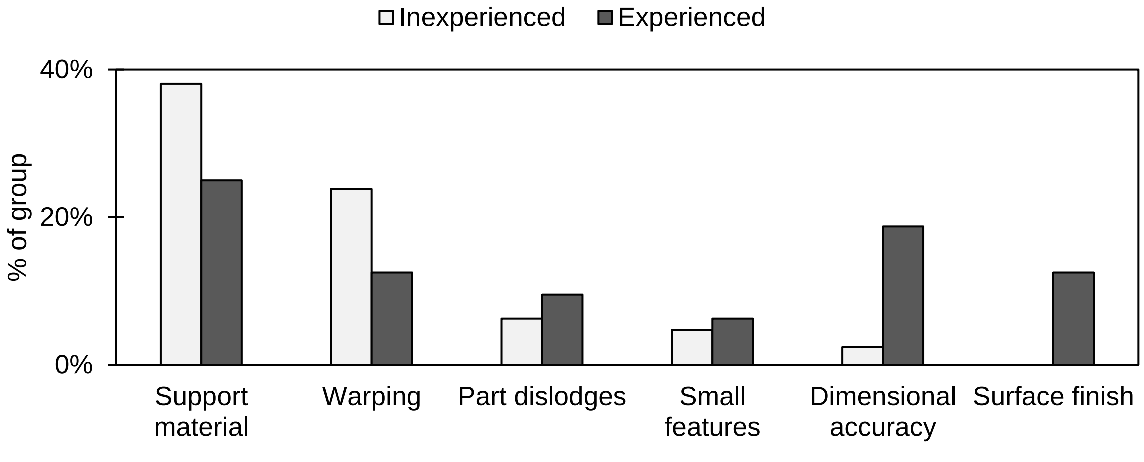

Fig. 4. Inexperienced students (experience level < 4) and experienced students (experience level ≥ 4) both encountered manufacturing problems using the 3D printers, but the types of problems they encountered differed.

4.3 DFAM training problem performance

In general, students performed relatively well on the DFAM training activity. The original part the students were tasked with redesigning had 3 DFAM guideline violations, and the average student redesign had 1.57 (*SD*=1.04) guideline violations, a 47.6% decrease. The most common guideline violations were a design or process plan that featured: support material in internal hole features (67% of students); a very long face printed on the build platform with a tendency to warp (18%); and features smaller than the minimum recommended feature size (22%). These values are equal or higher than the occurrence seen when students choose their own part to print (Fig. 4), but this is to be expected as the DFAM training problem was designed with several conflicting part features that were difficult to print.

We examined the impact of prior experience with 3D printing (distribution shown in Fig. 2) on performance on the redesign problem. There was no correlation between prior experience and performance on the redesign problem, with inexperienced and experienced students performing at a similar level. However, experience was correlated with students' self-reported task load for the assignment ($\rho = -.40$, $p = .005$) [40].

Spatial skills did seem to have some effect on students' performance on the DFAM activity. Key metrics are summarized in Table 1. Low visualizers (estimate of spatial skills < 4) rated the DFAM tools as more difficult to use (i.e., with lower usability) than high visualizers. This difference was statistically significant, and the effect size of this difference is medium to large. Similarly, low visualizers were less confident than high visualizers that their redesigned part would print successfully. The differences between high and low visualizers in the time or the task load required to complete the activity were not statistically significant.

Table 1. Low visualizers (*n*=6) found a DFAM activity to be more challenging and had less confidence in a successful print than high visualizers (*n*=43).

Metric	Measurement	Low visualizers median	High visualizers median	Effect size	*U*	*p*-value
Task load	NASA-RTLX average (range of 0-100)	55.8	49.2	0.21	80	.13
Ease of use/usability	SUS (range of 0-100)	44.4	72.2	0.42	32	.003
Time to complete problem	Self-reported (minutes)	119	100	0.09	107.5	.51
Confidence in a successful print	Self-reported (range of 1-5)	3.5	4.0	0.27	73.5	.06

4.4 Description of final project prototyping

Project teams made cell phone accessories such as a mount to hold a smartphone off the side of a laptop, a mount to hold a smartphone above bicycle handlebars, an earbud case mounted on the back of a smartphone, and a cooling fan to prevent smartphone overheating. 100% of teams used 3D printers in the university makerspace to prototype some part of their final design, 18.8% teams used the makerspace laser cutter, and 50% of teams used purchased parts or hardware. No other types of manufacturing technology were used.

4.5 Participation in final project prototyping

All project teams were relatively balanced in terms of team member AM experience, with average team experience ranging from 2.3 to 3.5. The overall level of involvement in prototyping for all students was 51.7%. The fraction of students who participated in prototyping was larger than the previous year when no DFAM training was assigned when 31.6% of students participated in prototyping. The difference between the rate of participation in fall 2017 and fall 2018 is statistically significant ($p = .04$).

Many inexperienced students participated in the prototyping process. A third (9/27) of the students who had not used a 3D printer before this class helped manufacture their team prototype. In an effort to normalize for the effect of teams having varying levels of experience, we calculated each individual student's experience level relative to the average experience level of his or her team. As shown in Table 2, approximately 26% of students in the class participated in prototyping even though they had less or equal experience than their team average.

Table 2. Students with AM experience were overrepresented among those who participated in prototype construction.

Participated in prototype construction?	% of students with as much or less experience as team average	% of students with more experience than team average
Yes	25.9%	25.9%
No	37.9%	10.3%

However, a positive correlation ρ =.38 (p = .003) was found between students' experience relative to their team's experience and the fraction of responsibility for prototyping that they accepted, i.e. the more experience a student had above the rest of their team, the larger their portion of the prototyping construction process tended to be (Fig. 5). Women, whose median initial experience level was lower coming into the class, participated in prototyping at similar or slightly lower levels as men (40% of women participated in prototyping, compared with 54% of men). However, it is interesting to note that 60% (6/10) of women had less or equal experience than their team average and did not participate in prototyping, versus 33% (16/48) of men, although this may be an artifact of the small sample size.

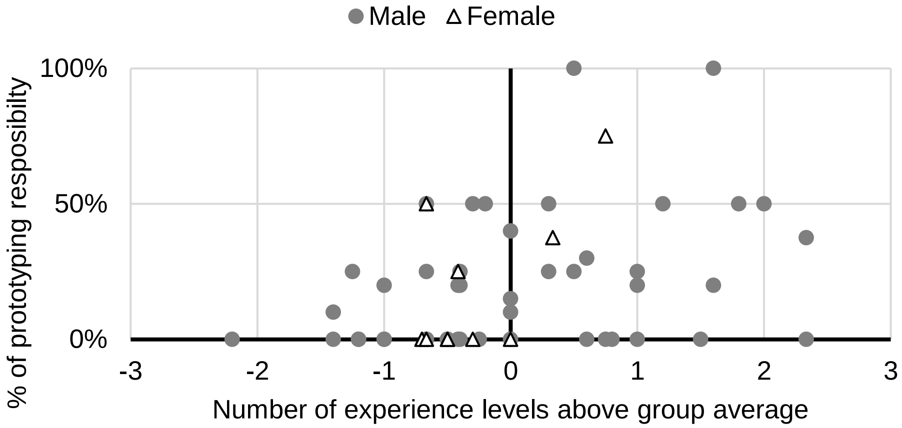

Fig. 5. There is a correlation between experience level relative to team members' experience and the fraction of prototyping duties that a student took on.

Spatial skills may have impacted who participated in prototyping. As seen in Fig. 6, a weak positive correlation was present between spatial skills and fraction of prototyping responsibility, but it was not statistically significant (ρ = .17, p = .21).

Fig. 6. The fraction of prototyping responsibility generally increases with spatial skills, but the correlation is not statistically significant.

4.6 Final project prototyping performance

In their final reports, most teams discussed struggling to interface multiple 3D printed parts in assembly due to not being able to predict the dimensional accuracy of their parts (e.g., “we tried and failed multiple times to fit various parts together”). Having to repeatedly prototype parts to achieve a level of stiffness or flexibility needed for their part functionality was another common problem. The DFAM training did not address dimensional accuracy or stiffness/flexibility. Manufacturability issues that were addressed in the DFAM training were relatively minor in severity or uncommon. No manufacturability issues with their design were reported by 9 out of the 16 teams (56%). In fall 2017, 5 of the 10 teams (50%) reported no manufacturability issues. Figure 7 compares the frequency of the most commonly occurring problems listed by teams in both semesters.

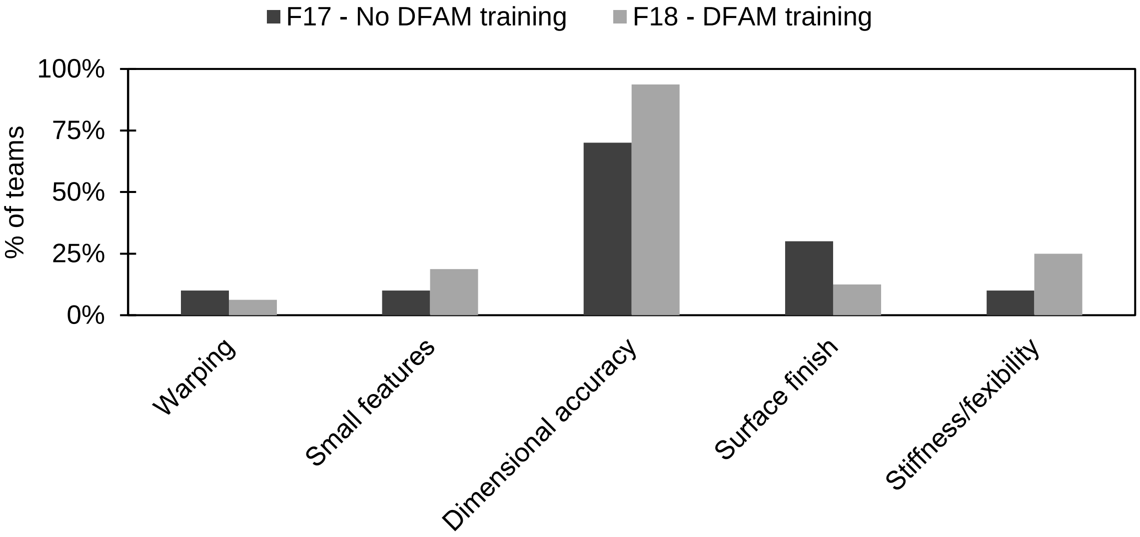

Fig. 7. A summary of commonly occurring AM problems described in the final project report, showing similar distributions of manufacturability problems in fall 2017 and fall 2018.

No significant correlation was found between average team member 3D printing experience and team prototype overall quality score ($\rho = .38$, $p = .14$). Additionally, there was no significant correlation between the fraction of team members who participated in prototyping and the team prototype overall quality score ($\rho = .18$, $p = .49$). However, 7 of the top 8 teams (as determined by their prototype overall quality score) had several team members participate in prototyping. The percentage of students participating was 40%, 100%, and 40%, for the first to third best scoring teams, respectively.

The variation in team member experience may have impacted individual team members' ability to contribute or be perceived by their team members to contribute. Students who were less experienced than their team average had lower peer review scores (Fig. 8) and much larger variation in their peer review scores. There was a significant difference between the scores of students who had less than or equal experience as their team average (*n* = 37, *Mdn* = 27.8) and those who had more (*n* = 21, *Mdn* = 28.8), *U* = 272, *r* = .25, *p* = .06.

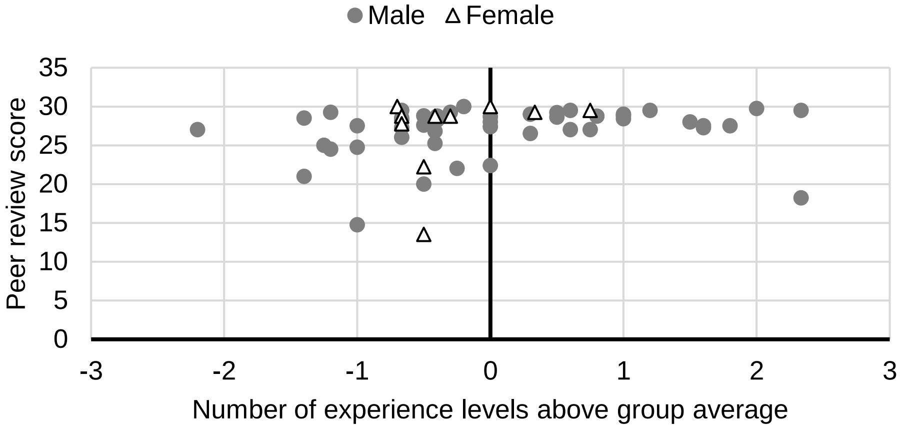

Fig. 8. Peer review scores showed a high degree of variation for students who were less experienced than their team.

A similar pattern is visible in Fig. 9, which shows how the fraction of prototyping responsibility is related to peer review scores. Students who did not help prototype or only helped a little had more variation in the peer review scores that they received. There was a significant difference between the peer review scores of students who helped prototype (*n* = 30, *Mdn* = 28.6) and those who did not (*n* = 28, *Mdn* = 27.6), *U* = 295.5, *r* = .25, *p* = .05.

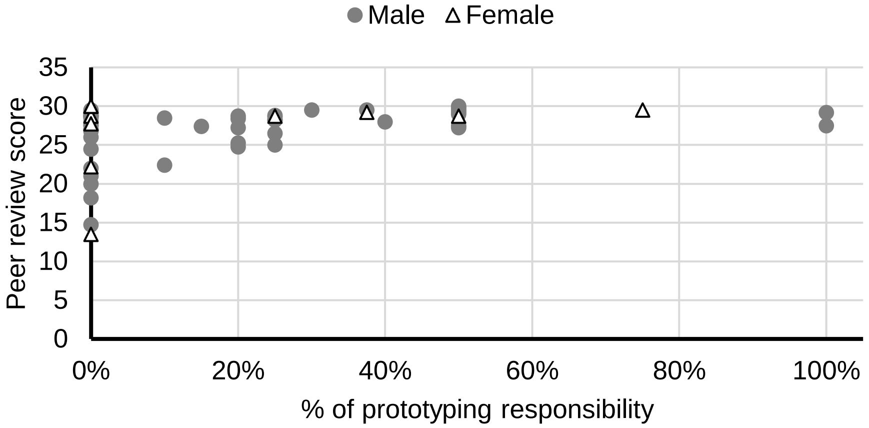

Fig. 9. Peer review scores tended to be higher for students who were responsible for more of the team prototyping.

Given the small sample size of female students, it is difficult to assess the impact of team gender composition on the performance of individual students. 40% (4/10) of the female students were on teams with other female students while 60% were on a team with no other female students (i.e., they had solo status). Non-solo female students received an average peer review score of 25.0 while solo female students received an average peer review score of 29.6 (indicating higher performance of solo-status students, rather than lower, as prior work found [13]). This difference is likely due in part to chance, given the small sample size, but could also be influenced by the fact that the solo female students had more initial experience and participated more in prototyping.

5. Discussion

5.1 Limitations

This study is exploratory and has some limitations. Because student characteristics such as low spatial visualization ability and gender are correlated, it is difficult to isolate the contribution of individual characteristics. Additionally, although we have a proxy for student's spatial visualization skills, our results would be strengthened if we had a direct measurement, such as the PSVT:R. Specific limitations and future work will be discussed in the subsequent subsections.

5.2 DFAM training activity performance

Both spatial skills and experience level were found to be related to differences in performance on the DFAM training activity. Students who reported lower spatial skills also reported less ease-of-use of using the training tools that explained DFAM guidelines and guided students on exploring the effect of build orientation. Students with lower spatial skills were also less confident about the success of their redesign. Experience was found to be correlated to the reported task load, with less experienced students tending to have to work harder on the training activity. These findings indicate that students with low spatial skills and with little 3D printing experience will likely be at a disadvantage while completing DFAM activities. This disadvantage may extend to more open-ended design projects as well. Instructors should be aware that activities with heavy CAD usage or activities that require students to mentally rotate 3D shapes can put low visualizers at a disadvantage. The relationships between ease-of-use and spatial skills and between workload and experience level offer instructors a potential strategy to help students. By increasing students' spatial skills and giving them more experience with 3D printing, instructors may help to make DFAM activities easier for those students, and helping to equalize any disadvantages. Because women tend to have lower spatial skills [23], this strategy may especially help women.

5.3 Prototyping performance

On the final project, several teams struggled with manufacturability issues that were addressed in the DFAM training. For example, several teams tried to print very thin walls, despite the training activity advising them to use larger thicknesses. This result is perhaps not completely surprising, as novices tend to employ more trial-and-error design strategies, whereas experienced engineers do more analysis before implementing a design [44]. Perhaps adding a hands-on 3D printing component to the training would be more effective at teaching DFAM guidelines. Another alternative could be requiring students to reference the guidelines before manufacturing a prototype, which would likely reduce manufacturability problems and help retention of the guidelines.

Another consideration for future semesters is the effect of when the training occurs. Based on the comments we received from our training and results described in other studies [32], students who are less experienced with AM find DFAM training to be more useful than those who are more experienced, so training should be given early in the semester. Also, it may be advisable to customize the training to the experience level of the students, so students who are very experienced with 3D printers can explore advanced topics, while novices focus on basic manufacturability training. Adapting the training to students with different experience levels would also address our finding that more advanced students, and most teams on the final project, struggled with different problems than students printing their first 3D printed part. Many experienced students and most teams struggled with dimensional accuracy. The DFAM training did not discuss dimensional accuracy, but it will in future semesters.

An encouraging result is that we did not identify a correlation between a team's average initial experience and the quality of their final prototype deliverable. This result agrees with another similar but independent study [18], which also found no correlation between experience and design outcomes on a student design project. It appears that a student design team's initial experience level does not dictate their success.

Also, we did not identify a correlation between performance and the fraction of team members participating in the prototyping process. Because specialization can be effective in industry teams, it would not have been surprising to find a negative correlation between performance and the fraction of students participating in prototyping, as specialization likely benefits student teams as well. However, we observed that student teams with at least a few students participating in prototyping performed better in our design project. Having multiple students involved in prototyping may have increased the time invested in prototyping iterations, improving the overall quality.

5.4 Participation in the prototyping process

Because this was not a controlled experiment with random assignment to different treatments, it is impossible to determine the exact efficacy of the DFAM training for encouraging participation. However, given that participation was 20% higher than the prior year when no DFAM training was offered, it seems likely that the training helped more students to participate. We hypothesize that this is because the DFAM activity served as a structured mastery experience, helping students to gain some specific knowledge that made them more confident about attempting hands-on construction with AM. In both years, each student was asked to 3D print a part in the makerspace, which could also encourage participation, as hands-on practice in makerspaces has been shown to improve students' confidence with 3D printing [45]. However, there are indications that certain student characteristics still impacted participation.

Prior experience, in particular, seemed to influence participation, which in turn influenced how a team member was perceived. Despite the DFAM activity and instructing all students to print a 3D printed part, initial inequality in experience was related to different outcomes for students. Students with lower experience levels coming into the class participated in prototyping at lower rates and received lower peer evaluation scores. Although it is difficult to assess causality, we feel that, given prior research ([15,16]), initial experience does impact who participates in prototyping. Including further structured mastery experiences in the course or refining our DFAM activity will likely help to encourage more students to participate.

To a lesser extent, spatial skills and gender may have also impacted participation in prototyping activities. Our study was limited in power by the small number of women and low visualizers included in our sample, so in future work, we will extend this study over multiple semesters to create a larger sample. Based on other research and our preliminary results, it appears that both gender and spatial skills may make a difference in prototype participation. Although these results were not all statistically significant, we observed that women had lower spatial skills, less initial experience, and participated in prototyping at a lower rate than men. It is difficult to resolve influencing factors such as gender, prior experience, and spatial skills because the factors tend to be related—women have lower spatial skills [23] and also feel less pressure to participate in prototyping [14].

Encouraging the participation of groups with lower spatial skills or lower initial experience with prototyping will likely disproportionately help women, which makes it an important educational goal, given the underrepresentation of women in engineering. We expect that the DFAM training can help women in particular by giving them a basic AM knowledge that could help them feel more comfortable asking for help, which has been cited as a barrier for women in makerspaces [10]. Including course activities with hands-on interaction with manufacturing equipment in a low-stress environment may be especially important for women, as well [46].

Regardless of gender, there are some instructional strategies that should help encourage participation in prototyping activities. Courses should be designed to help all students gain prototyping experience, improve their spatial skills, and improve their self-efficacy before beginning important design projects. By helping all students to start design projects on an equal footing, students from certain groups may be more likely to participate in prototyping and avoid being exiled from hands-on parts of a project due to early "specializations." Also, we observed that some teams described shifting responsibilities for prototyping between team members as the project progressed. Having faculty encourage this type of rebalancing as team members gain skills could be an effective strategy to ensure less experienced students are not marginalized [15].

5.5 Differences between Making and prototyping in makerspaces

Making and prototyping are different activities with different goals, although they share some attributes. Attributes that define Making include practical ingenuity, based on building and tinkering rather than analysis, and risk-taking, which encourages failure [47]. Prototyping is more focused on achieving design requirements, and especially in time-constricted projects, should be based on a foundation of good design and careful analysis. How can we help students develop an identity as a Maker [48] to develop self-efficacy and creativity, without compromising on teaching students skills like DFM or efficient prototyping, which they will need once they are in industry? Perhaps by sequencing courses that encourage Making with courses that teach more refined prototyping skills and DFM, a balance between these two objectives can be found. However, more research is needed to address how to best incorporate Making into the engineering curriculum without compromising on instilling engineering skills.

Another area that should be addressed in future work is the tendency of students using 3D printing as their go-to manufacturing process. We observed that all project teams used 3D printers, and only a small fraction used any alternative manufacturing process, despite having several other options. While this dependence on 3D printing is likely driven in part by the constraints of the design project, our observations indicated that students may have only developed designs that could be easily 3D printed, despite the fact that they were also required to describe their scaled-up manufacturing plan for mass production as part of the project. Reliance on 3D printing because of its ease of accessibility has been observed in other studies with students [9,49]. Students' reliance on 3D printing is likely to be an issue for any design project where students have makerspace access for prototyping. If the pedagogical purpose of project-based learning with prototyping is to expose students to a variety of manufacturing processes, we must better understand how to help students explore more processes and leverage their unique benefits, as they will need to do in industry. One promising strategy is exposing students to a structured prototyping framework while they complete their design project [49].

6. Conclusion

Encouraging students to construct prototypes for a team design project in a university makerspace has the potential to improve self-efficacy and build design and manufacturing skills relevant for employment in industry. We observed that, despite exposure to DFAM guidelines in a training activity, much of the prototyping students undertook for the design project focused on improving manufacturing outcomes with iterations that could have been avoided with proper DFAM. The DFAM activity was successful at fostering more inclusion, with 52% of students participating in prototyping, compared to only 32% the prior year. However, not all students tended to participate at the same rate. Students with less experience with AM than the rest of their team tended to participate less in prototyping and also received lower peer review scores. While including DFAM training helps encourage participation, our training needs to be refined to encourage better outcomes for all students and to address more advanced prototyping issues. Future work will further address the efficacy of DFAM training, team participation in prototyping, and fostering inclusivity in makerspaces.

Acknowledgements

The authors thank the students who volunteered to participate in this study. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1752814. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

References

[1] V. Wilczynski, Academic Maker Spaces and Engineering Design, *Proc. 2015 ASEE Annu. Conf. Expo.*, Seattle, WA, 14 June 2015.
[2] M. Galaleldin, F. Bouchard, H. Anis, and C. Lague, The Impact of Makerspaces on Engineering Education, *Proc. Can. Eng. Educ. Assoc.*, Halifax, Nova Scotia, 19 June 2016.
[3] M.N. Haji and M. Filippi, Academic makerspaces as preparation for careers in industry, *Proc. Int. Symp. Acadademic Makerspaces*, Palo Alto, CA, 3 August 2018.
[4] L. Hirshfield and D. Chachra, Experience is Not Mastery: Unexpected Interactions Between Project Task Choice and Measures of Academic Confidence and Self-Efficacy in First-Year Engineering Students, *Int. J. Eng. Educ.*, **35**(3), pp. 806–823, 2019.
[5] D. Clive, A. Agogino, O. Eris, D.D. Frey, L.J. Leifer, C.L. Dym, A. Agogino, O. Eris, D.D. Frey, and L.J. Leifer, Engineering Design Thinking, Teaching, and Learning, *J. Eng. Educ.*, **94**(1), pp. 103–120, 2005.
[6] K. Otto and K. Wood, Product Design: Techniques in Reverse Engineering and New Product Development, Pearson, New York City, NY, 2000.
[7] R. Bailey and M.E. McFarland, Prototyping and the engineer of 2020, *Int. J. Eng. Educ.*, **34**(2B), pp. 567–573, 2018.
[8] K. Youmans, I. Villanueva, L. Nadelson, J. Bouwma-Gearheart, A. Lenz, and S. Lanci, Makerspaces vs engineering shops: Initial undergraduate student impressions, *Proc. 2018 IEEE Front. Educ. Conf.*, San Jose, CA, 3 October 2018.
[9] J.W. Booth, J. Alperovich, P. Chawla, J. Ma, T. Reid, and K. Ramani, The Design for Additive Manufacturing Worksheet, *J. Mech. Des.*, **139**(10), 2017.
[10] W. Roldan, J. Hui, and E.M. Gerber, University Makerspaces: Opportunities to Support Equitable Participation for Women in Engineering, *Int. J. Eng. Educ.*, **34**(2B), pp. 751–768, 2018.
[11] S. Vossoughi, P.K. Hooper, and M. Escudé, Making through the lens of culture and power: Visions for educational equity, *Harv. Educ. Rev.*, **86**(2), pp. 206–232, 2016.

[12] R.J. Morocz, B. Levy, C. Forest, R.L. Nagel, W. Newstetter, K.G. Talley, and J.S. Linsey, Relating Student Participation in University Maker Spaces to their Engineering Design Self-Efficacy, *Proc. 2016 ASEE Annu. Conf. Expo.*, New Orleans, LA, 26 June 2016.

[13] D. Sekaquaptewa and M. Thompson, The Differential Effects of Solo Status on Members of High- and Low-Status Groups, *Personal. Soc. Psychol. Bull.*, **28**(5), pp. 694–707, 2002.

[14] J.J. Pembridge and M.C. Paretti, Differences between same-sex and cross-sex mentoring relationships in capstone design courses, *Proc. 2012 IEEE Front. Educ. Conf.*, Seattle, WA, 3 October 2012.

[15] L.A. Meadows, D. Sekaquaptewa, A. Pawley, S.S. Jordan, D. Chachra, and A. Minerick, Interactive Panel: Improving the Experiences of Marginalized Students on Engineering Design Teams, *Proc. 2015 ASEE Annu. Conf. Expo.*, Seattle, WA, 14 June 2015.

[16] L.C. Schmidt, Engineering Teams: Individual or Group Sport ?, *Int. J. Eng. Educ.*, **22**(3), pp. 659–664, 2006.

[17] S. Karunasekera and K. Bedse, Preparing Software Engineering Graduates for an Industry Career, *Proc. 20th Conf. Softw. Eng. Educ. Train.*, Dublin, Ireland, 3 July 2007.

[18] J. Jang and C.D. Schunn, Physical design tools support and hinder innovative engineering design, *J. Mech. Des.*, **134**(4), 2011.

[19] A. Hamlin, N. Boersma, and S. Sorby, Do Spatial Abilities Impact the Learning of 3-D Solid Modeling Software?, *Proc. 2006 ASEE Annu. Conf. Expo.*, Chicago, Illinois, 2006.

[20] Y. Chang, 3D-CAD effects on creative design performance of different spatial abilities students, *J. Comput. Assist. Learn.*, **30**(5), pp. 397–407, 2014.

[21] T. Huk, Who benefits from learning with 3D models? The case of spatial ability, *J. Comput. Assist. Learn.*, **22**(6), pp. 392–404, 2006.

[22] D. Koch, The Effects of Solid Modeling and Visualization on Technical Problem Solving, *J. Technol. Educ.*, **22**(2), pp. 3–21, 2011.

[23] Y. Maeda and S.Y. Yoon, A Meta-Analysis on Gender Differences in Mental Rotation Ability Measured by the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R), *Educ. Psychol. Rev.*, **25**, pp. 69–94, 2013.

[24] S.A. Sorby and N. Veurink, Spatial Skills Among Minority and International Engineering Students, *Proc. 2012 ASEE Annu. Conf. Expo.*, San Antonio, TX, 10 June 2012.

[25] S.A. Sorby, Developing 3-D Spatial Visualization Skills, *Eng. Des. Graph. J.*, **63**(2), pp. 21–32, 1999.

[26] J. Mataix, C. León, and J.F. Reinoso, Factors Influencing Spatial Skills Development of Engineering Students, *Int. J. Eng. Educ.*, **33**(2A), pp. 680–692, 2017.

[27] P.N. Chou, W.F. Chen, C.Y. Wu, and R.P. Carey, Utilizing 3D Open Source Software to Facilitate Student Learning of Fundamental Engineering Knowledge: A Quasi-Experimental Study, *Int. J. Eng. Educ.*, **33**(1B), pp. 382–388, 2017.

[28] H. Kwon, Effects of 3D printing and design software on students' overall performance, *J. STEM Educ.*, **18**(4), pp. 37–42, 2017.

[29] B.L. Kinsey, E. Towle, E.J. O'Brien, and C.F. Bauer, Analysis of Self-efficacy and Ability Related to Spatial Tasks and the Effect on Retention for Students in Engineering, *Int. J. Eng. Educ.*, **24**(3), pp. 488–494, 2008.

[30] S.A. Sorby and B. Baartmans, The development and assessment of a course for enhancing the 3-D spatial visualization skills of first-year engineering students, *J. Eng. Educ.*, **89**(3), pp. 301–307, 2000.

[31] B. Riggs, C. Poli, and B. Woolf, A Multimedia Application for Teaching Design for Manufacturing, *J. Eng. Educ.*, **87**(1), pp. 63–69, 1998.

[32] R. Prabhu, S.R. Miller, T.W. Simpson, and N.A. Meisel, The Earlier the Better? Investigating the Importance of timing on Effectiveness of Design for Additive Manufacturing Education, *Proc. ASME 2018 IDETC/CIE Conf.*, Quebec City, Canada, 26 August 2018.

[33] S. Ford and T. Minshall, Where and how 3D printing is used in teaching and education, *Addit. Manuf.*, **25**, pp. 131–150, 2019.

[34] P.H.P. Chiu, K.W.C.L. Wai, T.K.F. Ki, and S.H. Cheng, A Pedagogical Model for Introducing 3D Printing Technology in a Freshman Level Course Based on a Classic Instructional Design Theory, *Proc. 2015 IEEE Front. Educ. Conf.*, El Paso, TX, 21 October 2015.

[35] J. Go and A.J. Hart, A framework for teaching the fundamentals of additive manufacturing and enabling rapid innovation, *Addit. Manuf.*, **10**, pp. 76–87, 2016.

[36] Y. Huang, M.C. Leu, J. Mazumder, and A. Donmez, Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations, *J. Manuf. Sci. Eng.*, **137**(1), 2015.

[37] R.B. Guay, *Purdue Spatial Visualisation Test: Rotations, Purdue Research Foundation,* West Lafayette, IN, 1977.

[38] *CEEB Special Aptitude Test in Spatial Relations*, developed by the College Entrance Examination Board, USA, 1939.

[39] E. Towle, J. Mann, B. Kinsey, E.J. O'Brien, C.F. Bauer, and R. Champoux, Assessing the Self Efficacy and Spatial Ability of Engineering Students from Multiple Disciplines, *Proc. 2005 IEEE Front. Educ. Conf.*, Indianopolis, IN, 19 October 2005.

[40] H.D. Budinoff, Geometric Manufacturability Analysis for Additive Manufacturing, Doctoral Dissertation, Mechanical Engineering, University of California, Berkeley, 2019.

[41] S. Hart and L. Staveland, Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research, *Adv. Psychol.*, **52**, pp. 139–183, 1988.

[42] J. Brooke, SUS-A quick and dirty usability scale, P.W. Jordan, B. Thomas, I.L. McClelland, B. Weerdmeester (Eds.), *Usability Eval. Ind.*, Taylor & Francis, 1996: pp. 189–194.

[43] H.D. Budinoff, A. Ford, and S. McMains, Effects of gender, effort, and spatial visualization abilities in an engineering graphics class, *Proc. 2019 ASEE ASEE Annu. Conf. Expo.*, Tampa, FL, 15 June 2019.

[44] S. Ahmed, K.M. Wallace, and L.T.M. Blessing, Understanding the differences between how novice and experienced designers approach design tasks, *Res. Eng. Des.*, **14**, pp. 1–11, 2003.

[45] D.R. Haidar, Student self-assessment of modern making skills, *Proc. Int. Symp. Acadademic Makerspaces*, Palo Alto, CA, 3 August 2018.

[46] P. Dickrell, Building Skills in Engineering: Hand and Power Tool Workshops for Confidence and Retention, *Proc. 2018 ASEE Annu. Conf. Expo.*, Salt Lake City, UT, 24 June 2018.

[47] M. Lande, S.S. Jordan, and S. Weiner, Making People and Projects : Implications for Designing Making-Based Learning Experiences, *Proc. 2017 ASEE Pacific Southwest Sect. Conf.*, Tempe, AZ, 20 April 2017.

[48] S. Weiner, M. Lande, and S. Jordan, The Engineer of 2020, in the Making: Understanding how Young Adults Develop Maker Identities and the Implications for Education Reform, *Int. J. Eng. Educ.*, **34**(2B), pp. 833–842, 2018.

[49] J. Menold, T.W. Simpson, and K. Jablokow, The prototype for X framework: exploring the effects of a structured prototyping framework on functional prototypes, *Res. Eng. Des.*, **30**(2), pp. 187–201, 2019.

Hannah D. Budinoff is a researcher interested in additive manufacturing, geometric manufacturability analysis, and design for manufacturing. She is also interested in engineering education and received a best paper award from the American Society of Engineering Education Engineering Design Graphics Division in 2019 for work focused on the interaction of gender, spatial skills, and effort in an engineering graphics course. She recently completed her PhD in mechanical engineering at the University of California, Berkeley, where she was awarded an NSF Graduate Research Fellowship.

Sara McMains directs the Computer-Aided Design and Manufacturing Lab in the Department of Mechanical Engineering at the University of California, Berkeley. Her pedagogical research interests include engineering design visualization and auto-grading of engineering drawings. Her other research interests include Geometric DFM (Design for Manufacturing) feedback, computational geometry, geometric and solid modeling, CAD/CAM, GPU algorithms, computer aided process planning, additive manufacturing, computer vision, and machine learning. She received her A.B. from Harvard University in Computer Science, and her M.S. and Ph.D. from UC Berkeley in Computer Science with a minor in Mechanical Engineering. Her research has been recognized with various best paper awards (Usenix, ASME DETC, ACM Solid and Physical Modeling Symposium, NAMRC), the Audi Production Award, and the NSF CAREER Award.