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The Impact of Appropriate Prototyping Tool Choices on Achieving Functionality for Novices*

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Balancing coverage of design process, teaming, and prototyping is a challenge for instructors in their pursuit of creating the perfect engineering design course. Previous studies have demonstrated that teaming and process-based skills can be acquired in a short period of time by applying a training model. Prototyping skills can also be taught but there is a quandary regarding *which* tools and machines are critical to student success. In this study we evaluated prototypes produced in a first-year team-based engineering design course. Pre- and post-course surveys on prototyping skill and evaluations of end-of-semester prototypes were used to explore which prototyping tools meaningfully contribute to producing *functional* final prototypes. Several fascinating results have been uncovered through this exploration of student prototyping, including student skills growth and overreporting skill growth, as well as prototyping progress as a critical factor determining design functionality. Our study shows that when considering which prototyping skills to teach in a first-year design course the question is not how many prototyping skills to teach, but how few an instructor can get away with.

Keywords: prototyping; novice; design process

1. Introduction

The field of engineering design encompasses a broad range of tasks from project identification to the implementation of a final product. Professional engineers must work effectively in teams, applying computation, computer aided design, and an assortment of manufacturing tools to create, prototype, and test their designs. To prepare students for these industry demands, engineering education employs project-based courses from first-year design to capstone design. Using real-world projects, courses of this type seek to give students an authentic introduction to a multitude of topics including professional skills, design skills, and prototyping skills.

Meeting these broad course objectives requires careful planning and a suitable educational model. Effective skills training should teach underlying concepts, demonstrate proper usage of tools, dedicate time for learners to practice, and, most importantly, provide feedback to the learners [1]. These components of instruction allow students to develop both the declarative and procedural knowledge needed for mastery of a skill [2]. Well-implemented training can lead to safer practices, increased performance, and fewer mistakes. When skills are taught effectively in a class, students see positive results both individually and as teams [3]. To teach complex skills, instructors must incorporate several types of information and tasks, some of which are ill-suited for traditional classroom instruction [4].

A burgeoning approach to this challenge in engineering design education is incorporating aspects of the maker movement, which models learning through the process of creating tangible artifacts, or prototypes [5]. This active, procedural form of learning is favorable for understanding and retaining information [6, 7]. The generation of prototypes is a vital endeavor for designers, serving to resolve uncertainties, gather feedback, and convey ideas to others [8]. Building upon their utility for learning and communicating in a design project, prototypes also serve a critical role in decision-making [9]. In a learning context, the process of constructing low-fidelity prototypes allows students to develop momentum by breaking down an imposing project into manageable components. This tactic is shown to bolster students' morale and confidence while enhancing the quality of the resulting products [8].

Although prototyping is clearly a powerful and productive exercise for students, novice designers are often unaware of the vast range of forms and applications of prototypes [10]. Prototypes may include any representation of an idea, from a hand drawing to a high resolution integrated

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model, and can be constructed with physical or digital materials in multiple dimensions [11]. Therefore, when teaching students how to create prototypes, it becomes clear that there are far too many topics to cover in the span of a semester. The literature provides some guidance on which of the countless available methods are most likely to be useful for students: research has correlated simple prototypes composed of few parts with increased likelihood of successful outcomes [12]. But while prototypes that can be produced rapidly and inexpensively are shown to be beneficial for skill learning and creative ideation, some of the most effective prototyping tools can be challenging and burdensome to implement in an entry level context [12–14].

Research on cognitive load theory suggests that the way information is presented impacts not only how rapidly students can learn new concepts, but also how long students retain knowledge and how effectively they transfer it to practice [15–17]. Cognitive load theory proposes that above all, cognitive overload should be avoided. Cognitive overload can occur when learners try to process too much new information in a short time period, and it has detrimental effects on the absorption and transfer of knowledge. A typical method for preventing cognitive overload is to decrease extraneous cognitive load, which refers to any teaching or activity that does not directly contribute to overall learning objectives [18, 19]. This literature supports the notion of eliminating all parts of a curriculum that are not strictly necessary for the desired learning outcomes.

With this in mind, design instructors face an ongoing challenge of deciding which elements to include or omit in their curriculum. This problem is magnified in a first-year engineering design course, where, as well as teaching the engineering design process, an additional goal is often to provide students with fundamental skills that may be useful in their academic and professional careers. Therefore, first-year design teachers must be highly judicious in allocating their limited course time and resources.

At the OEDK we have an engineering design curriculum that introduces first-year students to a selection of prototyping tools and skills as they work in teams on semester-long design projects. A creative tension has existed for the life of the course centered around this philosophical question: How can we most effectively teach students about the engineering design process in one semester? Our approach has shifted from one of teaching breadth to one of selectively providing depth in areas that we feel are the most impactful. Thus, the question for us is not *how much* we can teach students about engineering in one semester, but *how little*.

In this study of students in an introductory engineering design course, we measured students' level of experience with a set of prototyping tools and then evaluated how those skills were utilized in the class. By interpreting these measurements and examining individual cases where skills had a notable impact on performance, we can explore the research question of whether using tools/skills supported by the class lead to more successful projects, improved team performance, and more effective prototyping.

2. Methods

This study was conducted on an Introduction to Engineering Design course consisting primarily of first-year students that has been the focus of intense research and constant reinvention to successfully achieve its learning outcomes [20, 21]. In the first half of the course, students work in teams to tackle real-world design problems with a focus on gathering information and developing an initial solution. During the latter portion of the course, teams transition to building and testing physical prototypes of their designs. Classroom instruction furnishes students with methods to assess and refine their prototypes, and the professors also provide direct feedback on the students' work during scheduled prototype evaluation sessions. Direct surveys were administered to a cohort of students from Fall 2019. Coded evaluation of prototypes was conducted from two full years' (four semesters) worth of teams, from Spring 2018 through Fall 2019.

2.1 Survey Data Collection and Analysis

Before embarking on the prototyping phase of the curriculum, students completed a survey asking them to report their level of experience with several tools and techniques frequently used in prototyping. Students were also asked to provide an example of how they had used each tool in the past, if applicable. The survey was administered again at the end of the semester, after teams had finished the teaming and prototyping units. An additional survey was given to students asking for personal identification information (gender, ethnicity, GPA) and project selection criteria. Survey data was de-identified while preserving team makeup.

To determine the proper family of hypothesis tests to run in order to compare student pre- and post-course experience survey scores, we ran a chi-squared test for the normality of the distribution of the two sets of survey scores. We found that the distributions were not statistically significantly distinguishable from a normal distribution, so we proceeded with an ordinary paired t-test in order to test for the differences between the students' pre- and post-course experience scores.

2.2 Construction of Statistical Models

We used a variety of regression models to analyze how different course factors correlate with students' experience scores for the tools and skills used in the course. We first applied a linear mixed effects model to investigate the relationship between the changes in student pre- and post-course experience scores for each individual tool and the various characteristics of the tools with respect to the course. Random effects in the model control for possible unmeasured differences between experience changes at the student level and for the individual tools. We included several potential fixed effects in the model: whether the tool is supported or required for the course, the relative difficulty of learning the skill, the time investment required for learning and applying the skill, and the potential quality, complexity, customizability, and repeatability of the parts produced with the tool. We built the mixed effects models using a forward stepwise procedure with likelihood ratio tests; the final model includes only random and fixed effects which are statistically significant. We also used ANOVA models in order to explore the relationship between the average student's pre- and post-course experience scores for a tool and the categorical instructor rating for how well the student's team used a tool as part of their prototype project. The instructor rating was tested whether overall it was statistically significant for predicting the experience score and where appropriate, hypothesis tests on the pairwise differences between the experience scores for each of the instructor rating groups were conducted using Tukey's HSD.

Team collective prototyping skill was evaluated by averaging skill experience for the team; only complete pairs of pre- and post-course surveys were included in the data. Situations in which two or more team members reported a decrease in skill experience between the pre- and post-course surveys are denoted by a Dunning-Kruger (D-K) effect label.

2.3 Evaluation of Skill Application and Functionality of Final Prototypes

Documentation from each team was collected: the final presentation, photos and/or videos of their final prototype. Using this media, prototypes were categorized and evaluated based on a number of parameters: level of fidelity (low, medium, high), materials used, and skills applied to build the final prototype. For each of the skills that was used to construct the prototype, a score was assigned based on how well that tool/skill was applied and it was recorded whether or not the prototype met the overall core or secondary project goals. Core functionality was defined as the prototype demonstrating or doing the most important thing for the project successfully, at any level of fidelity, even as a proof-of-concept. Secondary functionality referenced the prototype's demonstration of secondary functions needed for the project to be a success, at realistic levels of fidelity, more than proof-of-concept. Examples of secondary function include: was the prototype light-weight, safe, easy-to-use? Scoring was completed by two of the authors, by inspecting the prototype using the final presentation and available media. Based on discussion about the prototype and a written rubric a score was arrived at for each metric.

We used logistic regression models to analyze the effects of a team's tool usage on the probability of achieving core and secondary functionality for their prototype project. Below we describe several models that use separate types of explanatory variables to characterize team tool usage. In the first model, we analyzed measurements of overall team tool usage for each prototype – namely, the total number of tools used, the number of tools used adequately, the proportion of tools used which are supported by the course, and the proportion of tools used which are considered easy and hard to learn by the standards of the course. In the second model, we analyzed the effect of adequate individual tool usage, as rated by the course instructors for each of the 14 tools, on achieving core and secondary functionality. Specifically, for each tool we created a binary variable which indicates whether a team used a tool adequately or well, or if they used a tool poorly or not at all for their prototype; these were then used as explanatory variables for the model. For each of the modeling scenarios, we also fit two separate independent models for core and secondary functionality.

2.4 Evaluation of Prototyping Process

In addition to the 14 prototyping skills that were included in the survey, and the quality of the final prototype, we also scored each team in "prototyping process." This metric evaluated their entire process, independent of the ultimate quality of their final prototype and included the team's efforts to iteration, testing/evaluation, and consistent progress.

This research is IRB exempt because it considers data collected via direct observation in class on materials that were required for course completion. Students signed a waiver giving clearance to use coursework materials for course improvement and research inquiry.

3. Results

3.1 Student Population of Fall 2019 Cohort

The cohort which completed surveys (Fall 2019) consisted of 56% male and 44% female students (n = 81). 46.9% of the students were Caucasian, 21.0% were Asian American, 12.3% were Hispanic, 6.2% were African-American, and 13.6% were international. The students' majors are not reported since freshmen at Rice do not declare their major in their freshman year. A final sample size of n = 70 students completed the skills survey both before and after the prototyping unit, allowing for the comparison of paired responses.

3.2 Final Prototypes of Fall 2019 Cohort

Photos of final prototypes were collected from each team in the Fall 2019 cohort and identifying information was removed. All of the final prototypes from Fall 2019 are presented in Fig. 1. Appendix A includes a one-sentence description of each project's goals and resulting prototype; this is included to allow readers to connect a mental model of the project goal and resulting prototype.

Teams used a variety of materials and processes to create final prototypes which ranged in fidelity, size, and refinement[1]. These prototypes fulfilled an assortment of roles, from augmenting or automating existing objects to serving as standalone products and devices. Prototypes varied in size, with the majority of prototypes being between 1′ to 3′ on a side. Three prototypes were large, (BB, EE, PP) with at least one side greater than 3′ in a dimension. EE and PP in particular were very large, with all three dimensions being at or greater than 6′. Five of the final prototypes were classified as "small," with all dimensions under 1′. CC had many small design blocks that were interchangeable but all fit into a holder of >1′ side length. Team II had a very small prototype, less than 4″ on a side.

Teams used a range of materials to produce their final prototypes. The materials varied from those that were readily available at the prototyping facility, to materials that needed to be special ordered, to objects that were designed and built to specifications. Examples of materials that were used frequently were plywood, PVC pipe, foam, and synthetic polymers/plastics (3D printed parts). Materials that were special ordered included electronic components, motors and gears, and specialty fabrics (as seen in teams JJ, AA & QQ, LL & RR). Some materials were specific to the machine/tool and were custom made such as the 3D printed components, laser cut wood/acrylic, and CNC machined foam.

Many different tools and techniques were used to construct the final prototypes. Simple hand and power tools were applied whenever wood or larger materials were used, such as in prototypes for Teams AA, EE, and PP. Several projects were post-processed to improve the aesthetics of the final prototype including painting or staining like teams CC and QQ. Other teams' post-processing was simply to sand or make the device safe for human hands, like teams BB and PP.

The function of prototypes varied across projects. Some prototypes were constructed as standalone devices while others were built to be attached to or augment existing objects. For example, KK fit inside the body tube of a rocket and LL fit onto an existing shoe. Some incorporated automation like electronics (SS, DD) while others required a high amount of user interaction to operate, like CC and GG. Some were intended to produce other products (FF, SS, MM), several were "end products" for consumers, and others were novel ways of delivering existing objects (AA, HH, OO).

3.3 Team Population from Four Semesters

We sought to expand our measurement of prototyping beyond simply the Fall 2019 cohort by considering the final prototypes of teams from three additional cohorts. Considering team tool usage ratings, survey scores, and knowledge of each project's outcomes in terms of core and secondary functionality, we analyzed team performance through several parameters. Final prototypes were evaluated from four semesters of Introduction to Engineering Design (Spring 2018, Fall 2018, Spring 2019 and Fall 2019) comprising 48 total teams (6, 16, 7, and 19, respectively). Each team had the same two instructors as well as a dedicated teaching assistant, writing mentor, and faculty mentor. These conditions were the same for all teams, regardless of the semester in which they took the course.

We evaluated the levels of functionality that teams achieved each semester (Fig. 2). Each semester, more than half of teams achieved some degree of functionality – either core functionality, secondary functions, or both. Between one quarter to two thirds of teams achieved core functionality, and around half of teams achieved secondary functionality. The fraction of teams that achieved no functionality at all each semester ranged from just below one half to just below a quarter of teams.

3.4 Prototyping Tools/Skills Experience

The tools and skills included in the survey were

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[1] *fidelity* reflects the appropriateness of the materials (simple, analogical vs. correct intended materials); *refinement* means how many revisions towards achieving functionality are reflected in the prototype (at any fidelity).

Fig. 1. Matrix of prototype photos from end of semester, Fall 2019. This figure depicts the final prototypes each team finished with at the end of the semester. Prototype photos are taken as closeups of each photo, supplied by students in their final presentations. The letter in each photo represents the blinded designation of the teams. Scale of the prototypes is unequal thus scale annotations have been used to help the reader understand the relative size.

chosen based on the experience of the course over time and the types of tools student teams were predicted to use. Some tools are directly taught as part of the curriculum, while others can be learned with the aid of lab assistants, facility-specific training modules, public workshops, or step-by-step instructions posted by machines. Yet another subset of these skills lack appropriate training materials in the prototyping space but are documented by many online resources.

From the mixed effects model, we find that the fixed effects for the time to learn and the maximum

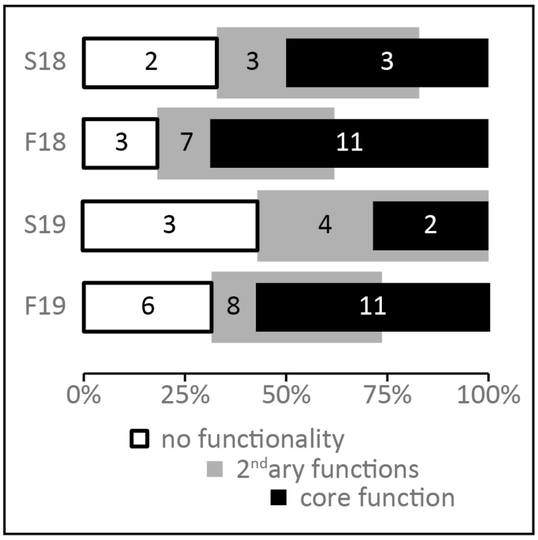

Fig. 2. Team functionality achieved by semester. Each semester's final prototypes are organized in a stacked graph based on the level of functionality achieved, as evaluated by the instructor. Teams could either achieve no functionality, secondary functionality, core functionality, or both secondary and core functionality. Each shaded bar represents the percentage of the total teams that semester achieving a level of functionality, and the numbers report the actual number of teams in that category.

potential quality of the part created by a given tool were statistically significant, along with the random effect for both tool and student. In particular, we see that a longer time required to learn a tool is negatively correlated with the change between pre- and post-course experience score, while higher maximum potential quality is positively correlated. The former result intuitively makes sense, as we would expect students to report smaller experience changes for tools which take a long time to learn compared to for those which can be learned in a shorter period of time, given the same amount of time on task.

Table 1 reports the statistical significance of increases in skill experience based on the survey results. The table also indicates whether each skill was required to be used in the course and describes the instructional methods and resources available for students.

Statistically significant gains were observed for skills that were directly supported by the course, such as hand tools, physical prototyping, power tools, post-processing, and CAD. Most teams lacked experience with advanced manufacturing tools, although some had prior knowledge of 3D

Table 1. Prototyping tools or skills used in the course and surveyed

Tool or skill	Supported by course?	Needed for course?	p-value of experience gains**	Tool/Skill specific educational materials available
Hand Tools	YES	YES	$p < 0.01$	In course: 3 hour guided workshop, required.
Physical Prototyping	YES	YES	$p < 0.01$	In course: dedicated lecture and exercise; corresponding videos, required.
Power Tools	YES	YES	$p < 0.01$	In course: 3 hour guided workshop, required.
3D Pen Drawing	NO*	NO	–	In course: 1 hour guided workshop, optional for select students participating in related study.
Post-Processing	YES	NO	$p < 0.05$	In course: 3 hour guided workshop, required.
Hand Drawing/ Sketching	NO	NO	–	NONE
Computer Aided Design	YES	NO	$p < 0.01$	In course: one hour guided workshop, optional but suggested for course.
Electronics	YES	SOME PROJECTS	–	In course: two hour guided workshop, required.
Laser Cutter	NO	NO - NOTE: other techniques can always be used	$p < 0.01$	In course: NONE In makerspace: lab assistants on staff to cut for teams; online training module; optional public workshops; step-by-step instructions posted at machine.
3D Printer	NO	NO - NOTE: other techniques can always be used	$p < 0.05$	In course: NONE In makerspace: lab assistants on staff to 3D print for teams; optional public workshops; online training module.
Plasma Cutter	NO	NO	–	In course: NONE In makerspace: lab assistants on staff to operate equipment for teams.
CNC Machining	NO	NO	–	NONE
Molding/Casting	NO	NO	–	NONE
Mill/Lathe	NO	NO	–	NONE

* A 3D Pen (3Doodler) was supported for an experimental group of students participating in a related study. It is not considered a core component of the curriculum and is not usually taught.
** Survey results and stats originally reported in Wettergreen, 2020 [22].

printing and plasma cutting. No teams demonstrated experience gains in 3Doodler unless they were part of a separate experimental study. Electronics, while supported by the class, did not result in statistically significant gains measured at the end of the course.

In addition to statistically significant gains in survey scores, we can also consider the numerical values of the survey scores as displayed in Fig. 3. The greatest overall gains were in physical prototyping, which reflected almost a full one-point gain from medium to high experience, and the laser cutter, which jumped from low/no to medium experience. Students reported very high average starting experience with hand tools, power tools, and drawing/sketching. This trend may be a good indicator of when the D-K effect occurs, as many skill decreases were observed in these tools. Conversely, few students reported prior experience with the advanced manufacturing techniques, in particular plasma cutting, CNC machining, and the mill/lathe. The low starting score makes it less likely for students to report a decrease in experience, and we believe the aggregate skill gains for these tools may be more accurate.

3.5 *Attrition in Skills due to the Dunning-Kruger Effect*

In many instances, individuals reported a higher level of experience with a skill at the start of the course and a lower score in the post survey. This phenomenon is described by the D-K effect, where novice learners report a decrease in understanding of a topic during early stages of learning [23]. We explored in detail the prevalence of the D-K effect in the individual student pre- and post-course experience surveys from the Fall 2019 semester. The effect was prevalent: 56 out of 70 students (80%) exhibited at least one instance of D-K effect in their survey results. Overall, there were a total of 139 instances of D-K effect across the 14 tools; of these, only 40 instances (28.7%) occurred for tools required by the student's prototype project. We also see that the D-K effect is prevalent amongst most of the individual tools, ranging from 8 to 27%. The exceptions to this are the laser cutter and plasma cutter, for which few students report prior experience. There is a fairly consistent rate of about 10–15% of students who exhibit the D-K effect for tools that they used in their prototypes. On the other hand, the proportion of students who exhibit the D-K effect for tools that they did not use varies more widely. In particular, electronics stands out as a tool where students tend to overestimate their pre-course experience level, with over one-third of all students who did not use electronics showing a D-K effect for said tool.

3.6 *Team Collective Prototyping Experience*

Aggregate prototyping experience for each team was derived from the surveys, allowing analysis of group collective skill and contribution to the project. To achieve the purpose of visualizing many teams skills growth over time, we developed the use of a radar graph as a dashboard snapshot, shown in Fig. 4. Represented by a clock face, or wheel and spoke, each spoke of the wheel represents one discrete skill with the starting and finishing skill level reflected. The right side of this map shows

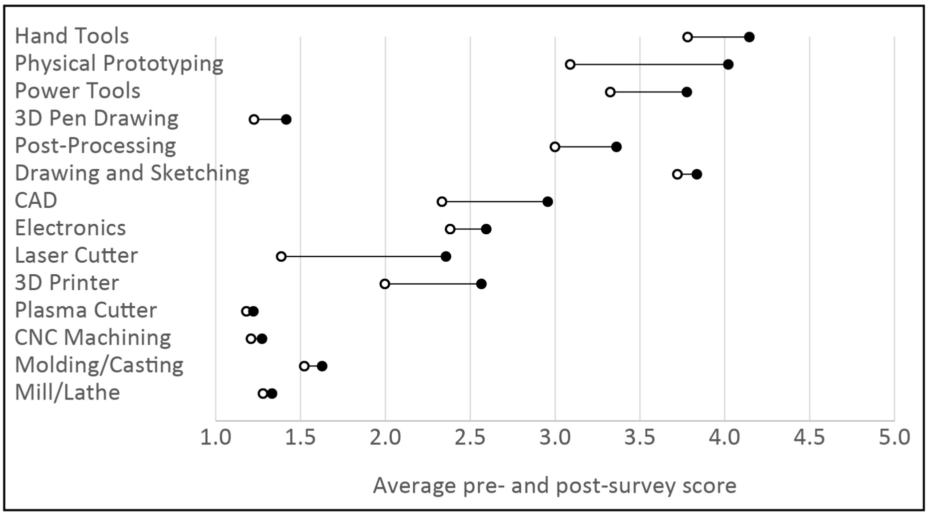

Fig. 3. Average individual experience gains for each tool or skill for the Fall 2019 cohort. Sample size reflected in this graph represents only the students who completed both the pre- and the post-survey (n = 70 of a potential 81). Organized from top to bottom, tools/skills are oriented with the quickest-to-learn at the top and (generally) the longest-to-learn at the bottom. On each row, the circles (white and black) reflect the average starting and finishing value, respectively, for the survey respondents.

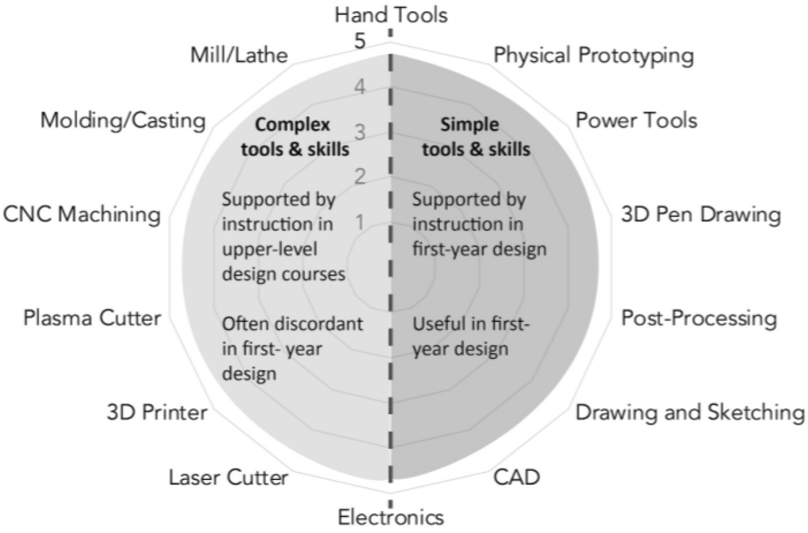

Fig. 4. Detailed team aggregate skill mapped to a radar graph. Skills increase in complexity and difficulty-to-learn clockwise starting from twelve o'clock. The right half of the clock face includes skills that have been shown to be useful in first-year design and the left half of the clock face are skills that are much higher in complexity and difficulty to use. A skill value is reported from the center of the circle (low/no skill) to a radial point at the exterior of the circle for a particular category (high skill).

simple-to-learn skills that are supported by the course and are favorable for prototyping in first-year design. On the left side of the map are skills that are not supported by the first-year course but are taught in higher level design courses. The pre-course scores are shaded in orange and the post-test scores are shaded in blue. Instances of the D-K effect are indicated with green dots on the radar graphs. Fig. 5 reflects this in greater detail for all of the teams. We found this radar graph representation an effective method to plot a team's aggregate skill set, and later, growth.

As reflected from the radar graph overlay of pre-vs post-skills, some groups, such as Teams BB, JJ, LL, and OO, started out with limited experience using most tools and then showed significant growth in several key skills. Others, such as Teams HH and RR, reported high initial levels of experience with many skills but saw minimal gains in the post-survey. Team FF began with significant experience in some skills, and they were able to make significant gains with the usage of additional tools. Most teams did not report experience in skills that were unsupported by the course and experience gains were also not observed in these skills. Exceptions to this are in the laser cutter and the 3D printer; many teams used these tools and experience gains can be observed.

3.7 Correlation Matrix of Improvement Between Tools

Many relationships exist between tools as reflected in Fig. 6. Some tools have a positive correlation, meaning that when students report gains in one of these tools, they are more likely to report gains in the other tool; other tools have a negative correlation, meaning that students who report gains in one tool are less likely to report gains in another tool. Positively correlated tools are often those that complement each other, such as 3D printing and CAD. An example of a pair of tools with a negative correlation are 3D printing and power tools. Positive correlations are found between holistic prototyping process scores and several of the tools that are quicker-to-learn, including hand tools, power tools, drawing/sketching, and post-processing/finishing.

3.8 Agreement between Instructor and Student Perception

The teams' usage of each tool in creating their final prototype was evaluated on a three-point scale, where a score of 1 corresponds with *poor* application of the skill, 2 indicates *adequate* usage, and 3 means the team implemented the skill *well.*

In the ANOVA models, we found that there are statistically significant differences in both average student pre- and post-course experience scores for teams whose tool usage was rated as good or poor by the instructor. Based on the Tukey HSD test, students whose teams are judged to have used a tool well or adequately by the course instructors also score themselves higher for pre- and post-course experience score on average compared to students who did not use that tool as part of their prototyping. Thus, it seems that students and instructors can recognize good tool usage in a similar manner.

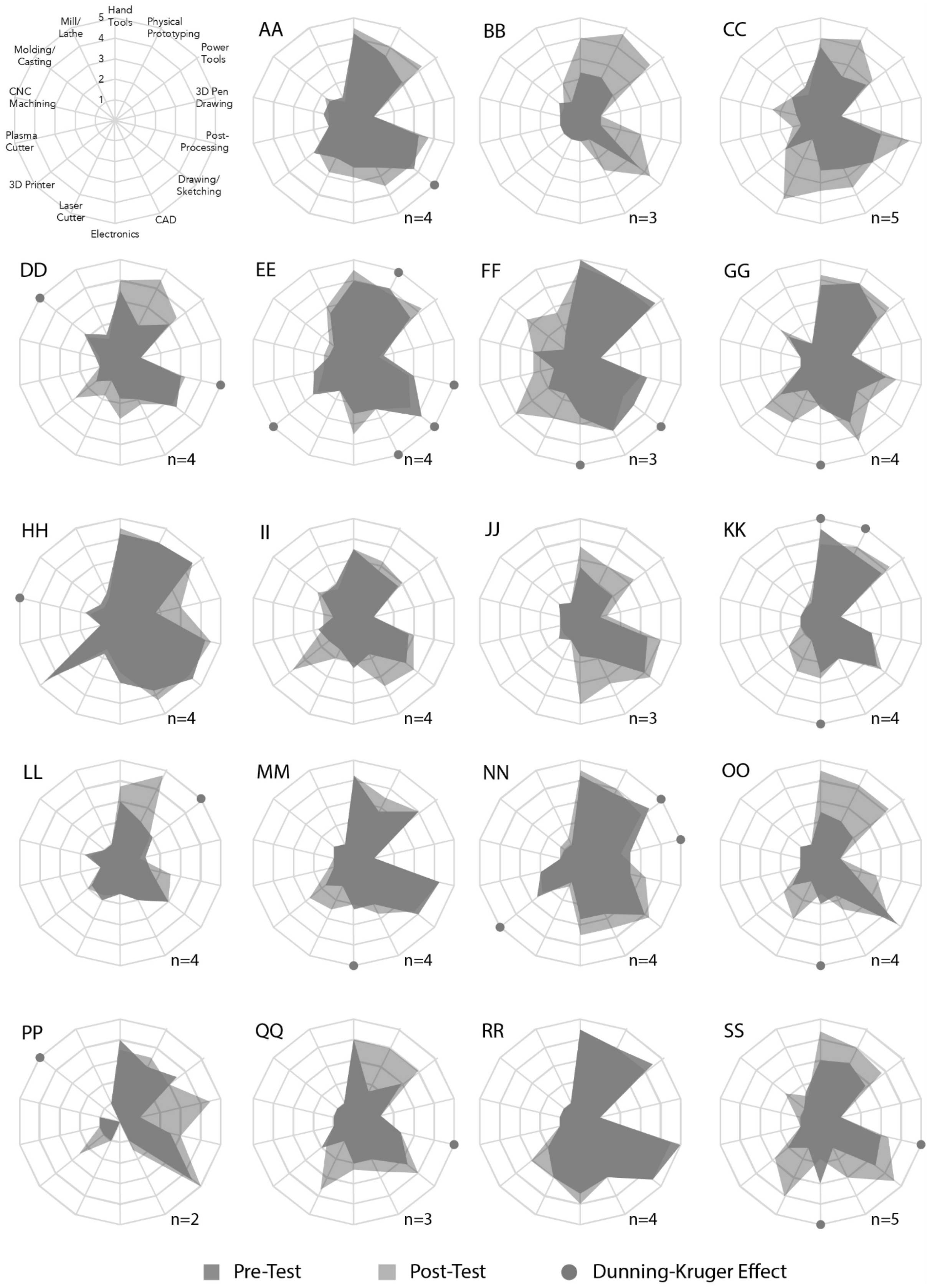

Fig. 5. Collective team aggregate skills per team for the Fall 2019 cohort. Reflected in this collection of radar graphs is the starting and finishing skill levels for the teams, overlaid on each other to reflect areas of collective skill growth, or attrition. Green dots represent the Dunning-Kruger effect for the entire team for a particular skill.

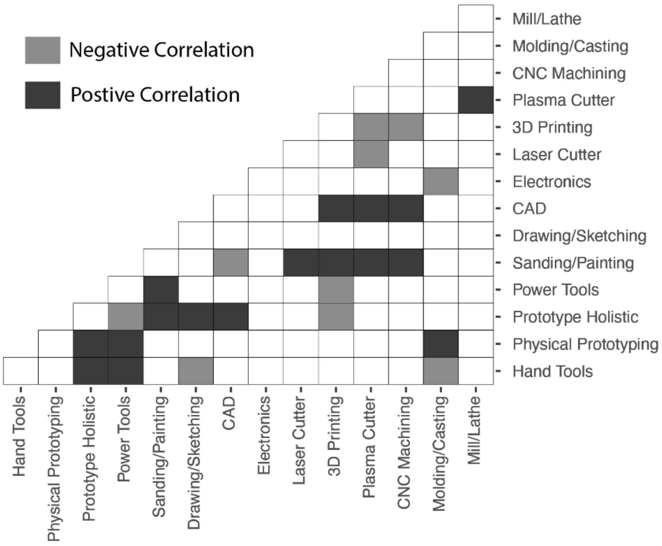

Fig. 6. Correlation between prototyping tools for all tools available to individuals. This matrix can be read by crossing two tools to discover if there is a positive correlation (blue highlighting), or a negative correlation (red highlighting). White areas represent a low or indistinguishable correlation between the tools, or a self-intersection.

A final instructor rating of 2 tends to be associated with higher student self-rating for post-course experience, while individuals that did not use a particular tool in their project tended to have a much lower post-course experience rating for that tool. In many cases, instructor rating of tool usage in the final prototypes agreed with students' post-score value for the same tool. For example, students whose teams were rated to have used electronics well had an average post-course experience score of 2.917, while students whose teams were were poorly rated only had an average post-course experience score of 1.800.

3.9 Predicting Core Functionality Bbased on Tool Usage and Prototyping Process

The proportion of teams that were able to achieve core functionality in their final prototypes correlates with the number of tools teams used effectively (Table 2). On average, *adequate* or *good* usage (2 or a 3) of a greater number of tools led to improved outcomes ($p < 0.01$). However, the total number of tools used by a team also has a statistically significant negative effect on the probability of achieving both core and secondary functionality ($p < 0.01$). Teams that failed to use at least two prototyping tools adequately were unable to create functional prototypes.

Table 2. Functionality vs # tools, mixed effects model

Variable	Estimate	Std. Err.
(Intercept)	-1.180	4.563
Number of Tools Used		
Total	-0.950*	0.439
Adequately	1.017*	0.355
Proportion of Tools Used		
Supported by course	6.610	4.731
Categorized as low difficulty	-7.107	5.231
Categorized as high difficulty	-0.234	5.787

The final metric that was evaluated for all teams was the "prototyping process" score. Almost all teams that struggled with the prototyping process (as indicated by a score of 1) failed to achieve core or secondary functionality while the majority of teams that demonstrated excellent process skills (a score of 3) created functional final prototypes (Fig. 7).

Thus, using the prototyping process adequately or well has a strong positive impact on both core functionality ($p < 0.01$) and secondary functionality ($p < 0.05$). Teams that used the prototyping process poorly were less likely to achieve core functionality ($p < 0.05$). Thus, it appears that strong application of the holistic prototyping process is by far the most important factor for achieving core and secondary functionality.

4. Discussion

This paper seeks to pierce the veil of the often messy process of prototyping in engineering design courses by breaking down the tools and skills teams use to produce prototypes and then compare those to the reported experience gains. Skills with a shorter time-to-learn were easier for students to gain meaningful experience that contributed to achieving prototype functionality. Tools that can create higher-quality work products, such as the 3D

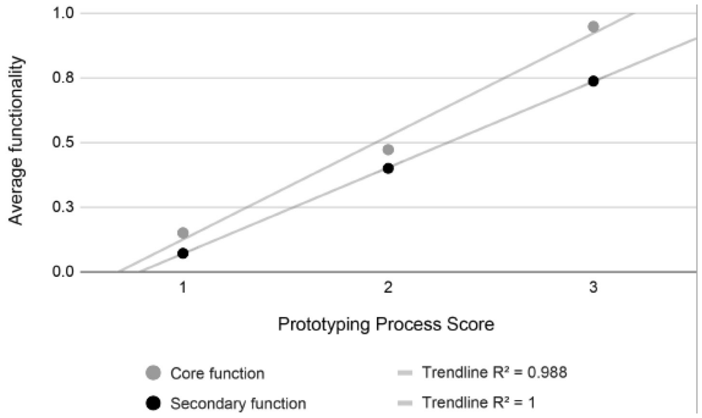

Fig. 7. Core and secondary functionality vs. prototyping process. Prototyping process scores (1–3) assigned to teams are strongly correlated to final core or secondary functionality.

printer and laser cutter, were also more effectively applied by students. Statistically significant gains were observed for skills that were directly supported by the course, including a selection of quick-to-learn and high-output tools. The number of tools that were effectively applied by a team positively impacted project outcomes; This result makes sense, as it naturally follows that using tools correctly will lead to the production of a better prototype. However, using more tools overall had a negative effect on teams' likelihood of creating a functional prototype. A likely reason for this relationship is due the limited time in which students must complete their prototyping project. Teams that use a greater total number of tools have less time to dedicate to learning and correctly applying each individual tool, leading them to use a substantial proportion of the tools poorly. This can have a deleterious effect on the overall quality of the final prototype. Finally, effective application of the prototyping process was shown to be a critical factor associated with achieving functional final prototypes.

The results of this study reflect that the selection of prototyping methods should be carefully considered when running project-based design courses, emphasizing specific skills that students can gain proficiency quickly and then use effectively. Preferentially selecting prototyping tools that can be adopted quickly and implemented appropriately in the prototyping process optimizes the FYD course for student learning and project success.

4.1 Student Experience Gains for tools with Varying Complexity

Students started FYD with a range of skill levels; their usage and learning of each prototyping skill is presented in Fig. 3. This figure demonstrates that students did gain experience in all of the tools that were surveyed, some more than others. The most growth was seen in the tools that were quick-to-learn and had the potential to create high-quality products. But students had the option to choose to use whatever tools they wanted in the prototyping section of the course.

The starting level of experience with each skill is reflective of how likely students are to encounter these tools before college: for example, most students are familiar with hand tools and drawing at the start of the year, while few have experience with a laser cutter. The magnitude of experience gained is explained by how the course places emphasis on different skills as well as the complexity of the different tools and the time required to learn them. We expect that most students would have some sort of starting experience with the simplest tools used in FYD, and average starting experience close to 2 for rapid manufacturing technologies such as 3D printers is reflective of the growing presence of 3D printing in high schools and even homes. The greatest gains were seen in physical prototyping, which is the most central skill taught in the class; and the laser cutter, which can be adopted rapidly with the facility's resources.

Despite being more complex, some rapid manufacturing machines, such as the laser cutter and 3D printer, actually have a low barrier to entry and often produce better-looking objects than their traditional counterparts. Additionally, these sophisticated technologies are appealing to many students. In some cases, the operational difficulty relies only upon following a written set of instructions to operate the machine. This explains how the laser cutter, an advanced tool, was reported by students to have one of the highest experience gains of all the tools used in the class, with an average increase from 1.37 to 2.36 on a 5-point scale. In the FYD class, lab assistants and teaching assistants managed the majority of the high cognitive load steps (file prep, cleanup, troubleshooting, technique) for the laser cutter, leaving the step-by-step machine operation steps to the students. Especially for the laser cutter, parts can be rapidly produced, even errors can be recovered from rather quickly. This is not the case for the 3D printer, where even the simplest execution still involves properly sizing a part for the prototype. This was the major failing for Team II, who downloaded files from a CAD repository and were unable to correctly size or print a dimensionally reduced version of their device.

In contrast to complex advanced manufacturing tools, hand-operated tools require a spectrum of declarative and procedural knowledge in the forms of design intention, tool selection and technique, and hand-eye coordination [7]. Many advanced manufacturing tools, including the 3D printer, plasma cutter, and CNC milling machine, can pose a trap to inexperienced makers. Students are allured by customizable, high-fidelity parts, but they do not consider the cost of time investment to develop starting proficiency, and they lack the expert knowledge to recognize that they are not actually learning much from these tools. When something goes wrong, the effort and time required to rectify the issue – for example, troubleshooting a malfunctioning 3D printer – is unproductive at best, and a significant obstacle at worst. Conversely, any issues that arise with hand and power tools tend to help students learn how to build and prototype more effectively.

4.2 Team Aggregate Prototyping Skill Experience Provides Insight into Prototyping Efforts

The previous section reflected on how individual students grew through the instruction, the use of tools, and the course itself. A useful direction is to investigate how individual teams used specific skills/tools to achieve functionality in their projects. The team-based skill metric and associated radar graph was a useful tool to compare these efforts; this type of visualization is more appropriate because it is only due to a team effort, not the actions of only one team member, that projects achieve functionality.

Insight making appropriate prototyping choices can be gained by reviewing the journey of Team II. This team worked on a customized, very small attention distraction device for pediatric operative patients being administered anesthesia. This team had a baseline of starting experience in simpler tools, including hand tools, physical prototyping, and power tools, and by the end of the semester had maintained or slightly increased their experience in these areas. They had no baseline experience in CAD, and showed a large increase from 1.75 (low/no experience) to a 3.75 (high experience) at the end of the semester; they also had no baseline experience in the 3D printer, and the team's experience increased from 1.5 (low/no experience) to 3.75 (high experience). While CAD and 3D printing can be simple-to-use for stock parts, they are much harder to apply when designing and creating custom parts. Despite having little-to-no experience in these areas, the team elected to rely on both of these tools to produce their iterative prototypes. These choices made Team II's prototyping efforts more difficult, and ultimately this team failed to achieve either core or secondary functionality in their final prototype.

Further exploration into appropriate tool choice is possible by directly comparing Teams BB and LL. Teams BB and LL both started with *low* experience in quick-to-learn skills and *no* experience in the more complex skills. Both teams stuck to using simpler skills: at the end of the semester Team BB posted large gains in most of these while LL's experience gains were highly variable. In the case of Team BB, we see that the skills taught in the class were used effectively in their prototyping work (Fig. 5). Their experience gains using simpler skills resulted in the team achieving both core and secondary functionality. Team LL's starting experience and skills growth mirrors Team BB's, but the outcome was dramatically different. Team LL's prototype required the skill of sewing, which was neither supported by the course, nor represented in our skills' dashboard. This is a clear gap in the model that was uncovered during the scoring phase of the study. An additional instance of a gap in the model was for Team JJ, whose prototype required use of a Raspberry Pi and programming of python. While electronics was supported by the course, no support was available for the Pi or python programming language. Despite this, the students on team JJ team were able to teach themselves enough to achieve primary functionality in their project.

In many cases, teams reflected that their experience with particular tools stayed the same or even went down. We have reflected this on the radar graphs with an asterisk signifying the D-K effect. This effect is when a novice lacks an understanding of how little they know about a tool in early stages of learning. We believe that this effect is showcased by a reduction reported in the end state of using the tool, even when the tool was clearly used. For example, Team KK reported a decrease in experience with hand tools despite using this skill to create their prototypes. Similarly, Team PP reported a decrease in experience using power tools, even though they used electric saws and drills to construct a wooden frame.

4.3 Student Self-Perception of Tool Proficiency

Students overestimate their experience with a tool before they have had the opportunity to learn more about it. This explains the prevalence of cases where a decrease is reported: most students are probably not actually losing skill, but learning how little they knew to begin with. Students who self-reported a higher level of experience at the start of the semester on the tools relevant to their project ultimately were less likely to create a prototype with secondary functionality.

We speculate that students who report low pre-course survey scores actually benefit from their lack of prior experience. They do not report decreases in the surveys, so the survey gains are a more accurate reflection of their learning. These students may also be less influenced by individual tool preferences, allowing them to better implement advice from instructors. Students with low pre-course survey scores seem to be more likely to achieve secondary functionality in their prototypes.

4.4 Critical Evaluation of Final Prototypes Reported whether Skill Application was Effective

The success of a team's prototyping efforts is ultimately measured by whether the team achieved their core and/or secondary functionality. A detailed analysis of this variable provides insight into a team's prototyping process and allows us to identify relationships between the usage of various prototyping tools and project outcomes. Fig. 3 demonstrates that the course effectively helps students gain experience in a range of skills and provides sufficient resources for students to explore some advanced skills; Fig. 2 shows that this experience translates into producing functioning prototypes. When students finish the course, their perception of experience is more accurate than at the start and more closely aligns with the faculty's perception, as evidenced by the agreement with post-course surveys and instructor evaluations of tool usage quality.

4.5 Classifying Tools To Improve Team Functionality Outcomes

Clearly the ways in which students learn and use tools have bearing on the results of the course. Hence it is critical for first-year design to teach an appropriate selection of tools. The myriad characteristics of the simple and complex tools allow for a further classification that can assist instructors in selecting appropriate tools to support in their classes. Classifying tools/skills by the time required to learn a tool, the versatility and customization available, and the quality of the parts produced can be helpful. In Table 3 we rate each tool/skill accordingly with the hope that this will allow other instructors and makerspace managers to select appropriate tools.

Many hand-operated tools, such as 3D pens, power tools, and post-processing, have a low barrier to entry, meaning that they can be learned and applied quickly. These are favorable traits for tools to be used by novice makers, allowing students to make early progress and develop confidence through creating low-fidelity prototypes. Visual design skills such as drawing/sketching and basic CAD are also accessible tools that students can apply right away to conceptualize their designs and envision their ideas. In a first-year class, a limited number of advanced tools such as the 3D printer and laser cutter can be introduced superficially, with later engineering courses providing more in-depth instruction. Some tools are negatively correlated in learning outcomes, such as 3D printing and power tools. It is possible that the time spent learning one of these tools takes time away from the other, or that attempting to learn too many complex tools at once leads to cognitive overload and poorer learning outcomes. When picking tools to teach, it is best to select ones that are complementary. Some tools pair well together, such as power tools and sanding/finishing. Other sets of tools fit well together as parts of the same toolchain, such as CAD being used to model a part that is then manufactured with a 3D printer. Teaching these tools together can potentially result in better gains in each skill.

The results and trends identified in this study lead to some central themes. Clearly first-year design can be an effective arena for increasing student proficiency in a variety of areas, including professional, tool-based, and teamwork skills. This is evidenced by the statistically significant gains reported in Table 1. However, there is a limit to how many skills can be taught, guiding design teachers to deliberately focus on skills that students should use in the course and support those through instruction and assignments. It is important to use training best practices for the selected skills; if training is conducted improperly, students are unlikely to see any improvement and at worst may experience cognitive overload. For example, cognitive overload was witnessed in one team that attempted to learn both CAD and 3D printing without understanding the fundamentals of either process. It would be appropriate to encourage such a team to prioritize using more basic prototyping tools or machines with which they had more prior experience.

Table 3. Table of prototyping skills map.

Tool/Skill	**Relative Difficulty (low/ medium/ high)**	**Time investment to learn**	**Part complexity**	**Part Customiza-tion**	**Variety of workable materials**	**Minimum time to apply technique**	**Part repeat-ability**	**2D vs. 3D**	**Quality of Final Shape**
Hand Tools	LOW	LOW	LOW - MEDIUM	LOW - MED	HIGH	LOW	LOW - MED	EITHER	LOW - MED
Physical Prototyping	LOW	LOW	LOW - MED	LOW - HIGH	HIGH	LOW	LOW - HIGH	EITHER	LOW - HIGH
Power Tools	LOW - MED	LOW - MED	LOW - HIGH	LOW - HIGH	HIGH	LOW	LOW - HIGH	EITHER	LOW - MED
3D Pen Drawing	LOW	LOW	LOW - MED	HIGH	MED	LOW	LOW - MED	EITHER	LOW
Post-Processing	LOW	LOW	LOW	HIGH	HIGH	LOW	LOW - HIGH	EITHER	MED - HIGH
Drawing/Sketching	LOW	LOW	LOW	HIGH	LOW	LOW	LOW - MED	2D	LOW - MED
Computer Aided Design (TinkerCAD)	LOW	LOW	LOW - MED	HIGH	HIGH	LOW	HIGH	3D	N/A
Computer Aided Design (SolidWorks or other industry standard)	MED - HIGH	MED - HIGH	LOW - HIGH	HIGH	HIGH	MED	HIGH	3D	N/A
Electronics	MED	MED - HIGH	MED - HIGH	MED - HIGH	N/A	MED	HIGH	3D	MED - HIGH
Laser Cutter	MED	MED	LOW - HIGH	LOW - HIGH	LOW - MED	MED	HIGH	2D	MED - HIGH
3D Printer - downloaded parts	MED	LOW	LOW - HIGH	LOW	LOW (PLA)	MED	HIGH	3D	LOW - MED
3D Printer - custom parts	MED - HIGH	MED - HIGH	LOW - HIGH	HIGH	MED	MED	HIGH	3D	LOW - HIGH
Plasma Cutter	MED	MED	MED - HIGH	LOW - HIGH	LOW	MED	HIGH	2D	MED - HIGH
CNC Machine	HIGH	HIGH	MED - HIGH	HIGH	MED	HIGH	HIGH	3D	MED - HIGH
Molding/Casting	HIGH	HIGH	MED - HIGH	HIGH	MED	HIGH	HIGH	3D	MED - HIGH
Mill/Lathe	HIGH	HIGH	MED - HIGH	HIGH	MED	HIGH	HIGH	3D	MED - HIGH

5. Discussion

Based on the findings of this study and established literature in the fields of education and skill training, we can recommend some best practices governing effective tool usage in early engineering classes. First, the scope of a project should include a mental model set by the instructors of what level of prototype should be achievable at the end of the process. With this in mind, a range of tools and techniques can be identified to most effectively achieve the project goals. Second, instructors should adjust project deliverables to include only prototypes that can be built using tools and techniques that are either fully instructed in a course or have sufficient support for students to learn quickly. Instructors should not envision or assign prototypes that require techniques that the classroom (optimally, makerspace) environment does not have, that the course does not support, or that require a large time investment to produce even rudimentary prototypes. Instructors should also limit the number of tools that students need to learn – we have found three to be an acceptable number for students to successfully apply with adequate scaffolding. In first-year design, instruction should be centered around tools with a short-time-to-learn, such as hand tools and power tools; complex techniques such as laser cutting and 3D printing should be used only if operation and technique is sufficiently supported to allow students to apply them quickly. Students who have a positive experience in first year design surely will seek more experiences later that will give them the opportunity to successfully learn more advanced techniques.

Ideally, design instructors would like to furnish their teams with as much information and experience as possible. However, when learners try to acquire too many skills at once, there can be a negative impact on both learning and performance.

We support the practice of teaching only skills that students absolutely need and which they can immediately put into practice. In a first-year engineering design course, these may include hand tools, power tools, basic electronics, and 3D printing with only minor modifications to parts. Teaching additional supplementary skills to first-year students requires them to devote time and mental effort that they cannot afford.

The nature of this study leads to several questions on how to process the data and interpret results. One of the most significant limitations is that skill experience surveys were only administered to one semester's cohort of students. For the other three semesters, instructor knowledge of the teams' progress was relied upon to supplement this missing information. When evaluating the teams' usage of prototyping skills, only the final prototype was taken into account, which in some cases might neglect tools that teams applied in intermediate stages of the iterative prototyping phases. Restricting these evaluations to the final prototypes may undermine the robustness of the prototyping process scores.

Assumptions about the tools teams might use led to an oversight of two tools that were unused in the Fall 2019 semester. One team used Raspberry Pi programming which was originally lumped in with electronics, and sewing was not considered at all. When reflecting how these two skills were used, these tools have a high difficulty to use effectively, even for beginners (Raspberry pi requires knowledge of coding; sewing requires much machine troubleshooting and presents a high operational knowledge barrier) and these factors caused difficulty in two teams' forward progress.

Several teams or individuals on teams demonstrated a decrease in their reported experience with certain tools. This may be accounted for by the Dunning-Kruger effect. Additionally, skill proficiency can decline over time with disuse, and decreasing survey scores may reflect where students feel less familiar with a tool after not interacting with it for a long time. An unexplored question is how a decrease in reported experience ultimately impacts students' prototyping process and outcomes.

This study presents a nascent model for the mapping of student/team prototyping skills. This model needs further data and analysis to develop it into a validated instrument for measuring performance. Future research could investigate the relationship between the decreased survey score phenomenon and team output. A future longitudinal study could administer surveys over multiple semesters to record a larger set of data and enable more detailed comparison and analysis. These surveys could include more prototyping tools or be otherwise augmented to increase the robustness and accuracy of results. Data collection could further be expanded to include recordings of routine in-class feedback sessions, making it possible to track team progress throughout the semester in addition to end-of-year outcomes.

6. Conclusion

This study makes unique contributions toward understanding how novice teams progress through the prototyping phase of a project as the result of the instruction, selection, and application of various tools. It demonstrates that while students are able to gain experience with a range of prototyping tools, identifying the appropriate tools to support in a course and matching them with the project demands can promote successful outcomes. As this study shows, even teams composed of individuals with no prior tool experience can still finish design projects if there is adequate support in the course for them to gain experience in relevant tools. In fact, our study shows that students who lack prior experience are often more effective in solving prototyping problems due to their fresh perspectives and low expectations of success.

There are a number of interesting conclusions from this paper that are worth repeating. First, student teams' ability to successfully produce functional design prototypes was shown to be dependent on appropriate tool selection in terms of both quantity and type of tool, how well teams applied each of those tools, and proper implementation of the prototyping design process. The tools and techniques that were quick-to-learn made it easier for students to gain operational proficiency and achieve prototype functionality. Second, teams who used a smaller set of tools to create their prototype but who used all of these tools well were the most likely to achieve core and secondary functionality. Third, tool proficiency alone did not guarantee success; even when teams reported experience gains with tools, they sometimes failed to create functional prototypes, especially when using complex tools. Finally, independent of individual tool usage, we found a direct relationship between consistent prototyping progress over the life of the project and the likelihood of achieving success in the project.

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Appendices

Appendix A: Description of Project Goals and Prototypes

Team (Blinded)	Project Goal (Brief)	Description of prototype (Brief) - independent of achieved function
AA	Enrichment device for the bears at the Houston Zoo.	Electronically controlled catapult-based device to launch food pellets to specific locations in the bear enclosure.
BB	Design for disabilities device to allow pediatric disabled individuals to shoot a bow and arrow.	Rigid, weighted stand to firmly hold a bow horizontally (ot vertically) at a variable height.
CC	Physical therapy device to rehab spinal injury patients to re-develop motor skills.	Tray with various activities that require physical motor skill interaction, like button pushing, Operation-like game (shown), credit card swiping.
DD	Patient specific design for disabilities device that allows an individual with CP to swing a tennis racket that is attached to his wheelchair.	Hydraulic system mounted to the side of a wheelchair holds a tennis racket and swings at the push of an electrical button.
EE	Build a system capable moving a chicken coop short distances on level ground.	Battery powered, remote controlled system with motor driven wheels attached to the chicken coop frame; includes wood flaps to protect and cover wheels.
FF	Build a mold capable of repeatedly producing a concrete flame collection device for rocket testing.	Custom built 3D printed mold to be filled with poured concrete.
GG	Build a device that allows for defibrillation of obese patients quickly in the OR.	Human-sized clamp with cantilever to compress defibrillation pads against patient's chest.
HH	Enrichment device for the red river hogs at the houston zoo.	A 2' clear globe with specific sized holes and a custom designed attachment system to add food pellets to the inside of the globe.

II	Distraction device for pediatric cases who are being administered anesthesia.	Complex 3D printed tube that spins a collar with fins when air is blown through it.
JJ	Device designed to measure and report water leaks in deep municipal tunnels inaccessible to humans.	Project box containing a microprocessor board with a microphone, processing algorithm, and wireless communication module, suspended by a chain.
KK	Device/method to release payload mid flight on a test rocket.	Laser cut box suspended in a rocket body tube and released with an elastic band; breakaway mechanism with rings and string.
LL	Slip on/slip off device that can protect cleats from floors and vice versa.	Contoured fabric sleeve that is pulled onto shoes, fitted with elastic bands and a foam bottom.
MM	Device to recycle plastic from water bottles.	Box with a high friction roll that feeds plastic bottles into spinning blades to shred plastic bottles.
NN	Device for timing irrigation for crops.	Arduino-based device that controls the release of water based on time.
OO	Design for disabilities device to allow pediatric disabled individuals to cast a fishing rod.	Fishing rod fixed to a stationary base with a trigger-based release mechanism to cast bait into water.
PP	Interactive device for drawing a hypochotroid design in a museum setting.	Large wooden frame with a horizontal platform in the center, able to swing back-and-forth based on user manipulation; an arm holds marking instruments against the platform as it swings.
QQ	Interactive museum exhibit that demonstrates concepts of robotic surgery.	Three separate hands-on activities that require user manipulation: one requires ping pong balls to be moved from Point A to B; one requires precise placement of cubes on force sensors (shown); one requires turning a rod a set number of degrees.
RR	Device capable of shielding the lead screw in a 3D printer to prevent plastic buildup.	Fabric sheath that covers the 3D printer's lead screw and is able to compress and move with the lead screw.
SS	Device capable of sifting 3D printed regrind.	Gravity-driven filtration system with a funnel feeding into a rotating tumbler with specific hole sizes and a collection system to separate the particles.

Appendix B. Definitions of prototyping skills

The tools/skills are described as follows:

- Hand Tools: use of basic tools including hammer, screwdriver, pliers, wire crimper.
- Physical Prototyping: putting things together, fixing or modifying machines around the house.
- Power Tools: use of power tools including drills, electric saws to cut, shape, or join material.
- 3D Pen Drawing (3Doodler or others): making representations of objects, creating functional structures.
- Post-Processing: how to sand/file/prepare a surface and then coat the surface with paint/stain/etc.
- Drawing and Sketching by hand: making representations of objects with pen and paper.
- Computer Aided Design: digitally design an object for fabrication or 3D printing.
- Electronics: ability to create circuits or use a microcontroller to make things responsive.
- Laser Cutter: operating a laser cutter to cut or etch planar objects.
- 3D Printing: design or download parts / operate a 3D printer to produce objects.
- Plasma Cutter: operating a plasma cutter to cut planar metal sheets.
- CNC Machining: Modify or create a 3D file to be fabricated on a CNC machine.
- Molding/Casting: using molding techniques to copy a material and reproduce it in another material, like plaster.
- Mill/Lathe: usage of professional machine shop tools.

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