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Individual Design Experiences Improve Students' Self-Efficacy on Team-Based Engineering Design Projects

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INDIVIDUAL DESIGN EXPERIENCE IMPROVES STUDENT SELF-EFFICACY ON TEAM-BASED ENGINEERING DESIGN PROJECTS

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Introduction

Team-based projects are widely used in engineering courses, particularly product or process design courses in disciplines such as mechanical, chemical, civil, and biomedical engineering [1]-[6]. While the intention of team-based design projects is to provide all students with a diversity of technical and non-technical mastery experiences, students enter into these experiences with differences, whether real or perceived, in relevant technical skills that undermine individuals' learning objectives on team-based work [6]-[9]. Prior research indicates male engineering students are more confident than females in their math and science abilities, as well as their abilities to solve open-ended problems [9], [10]. Chachra and Kilgore [7] found the 'confidence gap' between males and females was more profound for open-ended problem solving than for math or science. They posited this gap was attributable to the team-based nature of design-oriented projects where feedback is more subjective and diffuse. Lower confidence in women often translates into lower likelihood that they will take an active role in technical tasks and instead relegate themselves to administrative or people-oriented tasks on design projects [3], [11], [17].

Prior research by our research group and others [7]-[16] indicate majority (white) male engineering students are more confident than females and traditionally under-represented minorities (URMs) in their math and science abilities, open-ended problem solving, and hands-on prototyping skills. These disparities lead to behavioral differences on team-based projects that in turn reinforce students' beliefs about their own skill set and those of others often along gender or racial lines. It has been suggested that lower self-efficacy among females negatively affects performance on course assignments and exams, even when they have the same academic aptitude as their male counterparts [17], [41].

This study focuses on one of the four moderators of self-efficacy, namely, mastery experiences. Positive mastery experiences, which are task-related experiences that culminate in a performance accomplishment, are an established mechanism to bolster students' self-efficacy [18]-[22]. Self-efficacy is positively correlated with self-regulated learning in which learners can potentially monitor, control, and regulate certain aspects of their own cognition, motivation, and behavior as well as some features of their environments [20], [23]. Theories of self-regulated learning assume that students who are task-oriented (cf. performance oriented) can set goals to strive for in their own learning, monitor their progress towards those goals, and adapt and self-regulate their cognition, behaviors, and motivation in order to reach those goals. Students who believe they can learn (personal efficacy) and perceive their efforts to learn will result in desired outcomes (outcome expectancy) [18], [19] are more likely to report the use of self-regulatory strategies associated with task orientation [23], [24].

Self-regulatory strategies are important because they can be used by learners to manage their academic time on projects or tasks, prioritize and reflect on their progress towards learning goals, and seek help when experiencing difficulty [20]. By contrast, students with low self-efficacy may perceive that they aren't capable of learning the knowledge and skills necessary to be successful and/or will fail even if they work hard on a task. Research on self-efficacy [25]-[29] indicates that task orientation plays an important role in academic motivation and persistence. Hirshfield and Chachra [30], for instance, suggested that students with low engineering self-efficacy may not take on more technical tasks in design projects.

Although several studies have indicated improvement in student self-efficacy as a result of mastery experiences (e.g., hands-on design tasks) [21], [31], others have shown that simply providing mastery experiences will not necessarily result in enhanced, sustained student self-efficacy. For instance, more time spent on design projects does not necessarily lead to monotonic increases in self-efficacy for all students [32] and student self-efficacy can change over time with subsequent learning experiences [25]. Although logical, not all prior research supports the idea that more time spent by students on building prototypes has a direct positive correlation with engineering self-efficacy [31],[32]; in fact, Hirshfield and Chachra [33] found that fourth-year students do not have significantly high self-efficacy than first-year students. In other studies, first year engineering students' GPA [31] and individual course grades [25] were more predictive of self-efficacy than time spent prototyping or engaged in design tasks. Overall, previous research indicates student self-efficacy in engineering is malleable and multifarious psychological construct, influenced by multiple factors including course context, student demographics, types of learning opportunities, experiences with failure, relevant prior knowledge, and the emotions students experience during learning [32]-[34].

Study Purpose and Hypotheses. Although mastery experiences have been studied previously in undergraduate engineering settings [33], [35], [36], the purpose of prior studies has been mainly to boost student performance on team-based tasks. The purpose of our study is subtly but critically different in that mastery experiences used with our students, which we term Individual Design Experiences (IDEs), were embedded within higher stakes, team-based design exercises in engineering coursework at our institution.

At the beginning of our study, we hypothesized that IDEs would be an effective instructional strategy for mitigating disparities in students' opportunities to learn basic engineering prototyping skills prior to entering their engineering undergraduate programs of study, and by extension, improve students' self-efficacy for prototyping. In particular, we anticipated that IDEs would promote the growth of prototyping skills and positive self-efficacy among all students, but especially women and underrepresented minorities (URMs) [37-41].

Below, we explain our approach with using IDEs, and then we present the results of our mixed methods study on the influence of IDEs on student self-efficacy.

Individualized Design Experiences (IDEs)

For this study, an Individual Design Experience (IDE) was developed to mitigate pre-existing disparities in hands-on prototyping tasks in introductory engineering design courses. The IDE project required students to create a child's pull toy manufactured primarily out of wood and complied with ASTM toy safety standards. IDE learning objectives were: (1) to develop and execute a manufacturing plan to create complex shapes from common stock materials, e.g., stock lumber, dowels, and rounds; (2) to identify and use common hardware like screws and springs to create a multi-part assembly; and (3) to confidently use hand tools and low precision power tools, e.g., power drill, band saw, and sanders. Evaluation of the IDE was consistent with these learning objectives and stressed demonstration of competence over master craftsmanship.

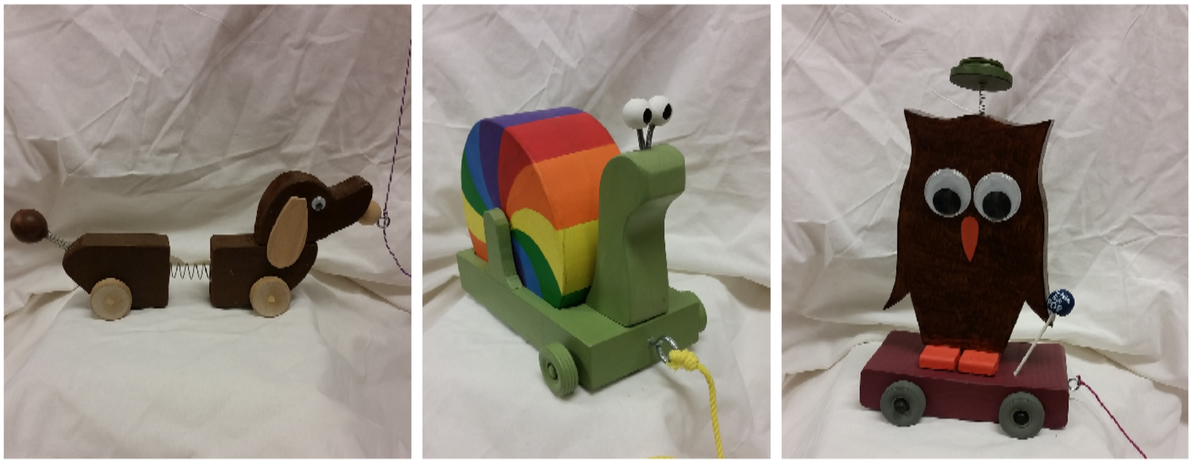

Figure 1: Images of children's pull toys that were designed and manufactured by students during a two-week Individual Design Experience (IDE) in an introductory engineering design course.

The IDE was thoughtfully administered in two ways to maximize the likelihood for an individual students' growth in prototyping self-efficacy. First, the IDE was sequenced in the course such that it preceded similar hands-on prototyping tasks for the semester-long team-based project. The semester-long project was completed in randomly assigned teams of four students and involved new product design of a children's toy for an external industry client. A second key administrative decision was to modestly weight the IDE assignment such that it was taken seriously by the students while not being overly penalizing or rewarding for students with drastically different a priori skills. To maintain this balance, the IDE was administered as one of nine individual assignments in a 14-week term that were worth a total of 40% of the final course grade. The IDE assignment itself was equally weighted with all other assignments and thus constituted approximately approximately 4.4% of the final course grade.

There were other logistical elements that similarly facilitate successful implementation of the IDE. The 3-credit course consisted of two weekly lecture periods (75 minutes each) and one laboratory session (75 minutes). All lectures were single-session (ca. 160 students), and there were six to eight identical laboratory sections (ca. 20-40 students). A single instructor taught all lectures, and a common undergraduate teaching assistant workforce (10-12 individuals) shared coaching responsibilities across all lab sections. All IDE-related laboratory periods were held in the program's undergraduate makerspace [29]. Prior to the start of the IDE, in-class time was dedicated to safety and tool competency training. In the weeks preceding the IDE, all students watched a video-based safety orientation, took an online safety quiz, and completed a self-paced laboratory experience that involved them demonstrating competencies in-person to a teaching assistant. All students viewed the same demonstrations and received similar coaching to successfully complete their in-person tool competencies. After completing all training, students were given two weeks to complete the IDE project. Two consecutive laboratory sections were dedicated to the project, and teaching assistants supervised additional open laboratory hours to provide students with more time to complete the IDE project.

Methods

Study Context. The setting for this study was the first mechanical engineering design course taken by all mechanical engineering majors at a mid-sized (ca. 160 students/year), ABET-accredited program at a land grant university in the mid-Atlantic United States. The timing of this study was such that it coincided with a pre-planned change in the undergraduate program's curricular structure that resulted in two identical sections of the course being offered concurrently by the same instructor: one for second-semester sophomores (n=125) and the other for first-semester freshmen (n=151). For both groups of students, the course was the first in the undergraduate design sequence and involved their earliest exposure to hands-on prototyping. Course logistics were purposefully separated for the two sections to minimize confounders, like overlapping laboratory sections or class announcements, that could confound the study of the IDE intervention. The IDE was administered as described previously to the freshmen section of the course, while the sophomore section was held as the control group. For the control, students completed the same hands-on prototyping exercise as the IDE treatment group, but this exercise was completed in teams rather than individually. The teams were the same composition as the semester-long design project.

Study Design. A cohort-based, sequential exploratory mixed methods study design was used to determine whether the IDE experience improved student self-efficacy for hands-on prototyping tasks. Self-efficacy was assessed pre- and post-course with a validated instrument developed and previously reported by our team [12]. We created this instrument by combining items from APPLES [51] and a previously unvalidated tinkering instrument [52], and then checked the validity of the instrument using confirmatory factor analysis based on student responses from a larger data set (n=602). The instrument was administered online (Qualtrics XM) during the first and last laboratory sections of the semester, and completion and consent were voluntary. The self-efficacy instrument included five factors that encompass most skills necessary for team-based engineering design, namely: (1) math and science skills; (2) engineering application; (3) professional and interpersonal skills; (4) hands-on prototyping ("tinkering"); and (5) open-ended problem solving. General linear modeling procedures were used to develop regression models for each of the five factors to predict post-scores based on treatment group while controlling for pre-scores. Similarly, ANOVA procedures were used to determine if self-efficacy gains within the IDE treatment group differed by gender (male, female) or race (majority, URM). All statistical analyses were performed using SAS.

Focus group interviews were conducted post-course. We chose a small subset of students (n = 44) using maximum variation sampling [42]. Students were purposely chosen from among the participant pool because they represented the range of responses to the survey. Focus group interviews included two to five students and questions were asked about: (1) their interactions with team members on previous design tasks, (2) their experience with completing the toy project with team members (control group) or alone (IDE group), and (3) to what extent, if at all, the toy design project influenced their confidence with hands-on prototyping. Focus group interviews were recorded and then transcribed into text verbatim. Transcripts were analyzed using the five factors measured by the survey instrument as a priori themes [43]. The results of thematic analysis of interview transcripts were used to triangulate survey results.

Results

Study participation was fairly robust, with 40% of the total class (n=81 students) in the IDE treatment group and 54% in the control group (n=50 students) completing both pre and post-course surveys. The regression model for the hands-on prototyping factor [$F(2,122) = 31.51$, $p<.001$, $R^2 = .34$] showed greater gains in the IDE treatment group than the control group as evidenced by a statistically significant treatment group coefficient ($p=.01$). Statistically significant differences were isolated to this one factor. However, the regression model for math and science abilities [$F(2,122) = 48.22$, $p<.001$, $R^2 = .44$] showed a nearly statistically significant treatment group coefficient ($p=.06$). Estimates of the control vs. treatment Cohen's *d* effect sizes were .44 and .33 for the hands-on prototyping and math and science abilities factors, respectively. Among the students in the IDE treatment group, gains in hands-on prototyping self-efficacy were more pronounced for students with lower pre-course self-efficacy (see Figure 2), and some students with high pre-course self-efficacy actually demonstrated negative gains (i.e., losses) in prototyping self-efficacy post-course.

Neither gender nor race were found to be predictive of effectiveness of the IDE treatment across all factors studied, including hands-on prototyping self-efficacy. A G*Power post hoc power analysis revealed that the study was underpowered to disaggregate treatment effects. For example, the estimated gender difference within the treatment group ($d=.44$) was not statistically significant. Given the sample size and male to female balance, a gender difference effect size of .93 would have been necessary to detect an effect.

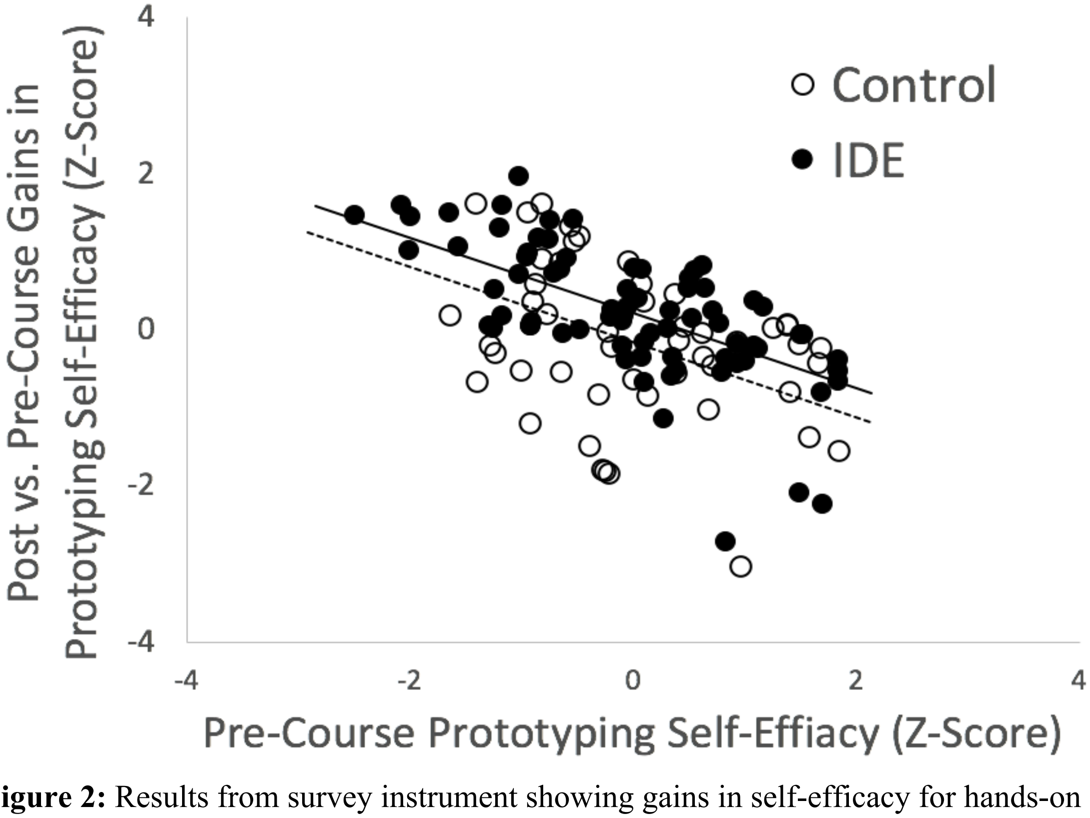

Figure 2: Results from survey instrument showing gains in self-efficacy for hands-on prototyping skills as a function of pre-course self-efficacy. Data points reflect individual students, and both axes reflect z-normalized values across the survey population. The solid line

represents the best-fit model for the IDE Treatment group, and the dotted line for the control group.

Results of the focus group interviews suggested that students who had little prototyping experience appreciated the individual design experience where they could learn basic carpentry skills in a supportive environment with experienced peers serving as teaching assistants (TAs). Table 1 provides interview excerpts related to students' experiences with their IDE projects. All participant names are pseudonyms. Students such as Karla and Adam (see Table 1), who began the course with lower than average tinkering scores, gained confidence for building prototypes with basic carpentry supplies and tools.

There was no indication from focus group interviews that those students with prior prototyping experiences were adversely affected. Rather, even those students with prior experiences often intimated that the IDE project reinforced prior technical skills or extended those skills and made evident how such skills were useful in design projects. Students such as William and Eddie, who had higher than average tinkering scores at the onset of the course, indicated that the IDE project helped extend their prototyping skills. Interestingly, students who began the course with a tinkering score that was, on average, similar to those of their peers, indicated a wide range in their confidence and skill level as a result of their experience with the IDE project. Krista, for example, had a significant amount of making and building experience during high school and was able to produce a fairly sophisticated prototype for her IDE project, but had a tinkering score that was similar to the average amongst her peers. Samantha, on the other hand, indicated that she had no prior experience with power tools, CAD, or making; however, her tinkering score was also average in relation to her peers. Based on her comments during the focus group interview, Samantha did not seem bothered by the notion that she would make mistakes during the IDE project. To her this was part of the learning process. Candice, on the other hand, had some limited personal experience prior to the course, but seemed extremely anxious about working independently with power tools. For her, being fully competent with each tool was a prerequisite for using them to produce her prototype for her IDE project.

Table 1. Focus group interview data on students' experiences with prototyping during their Individual Design Experience (IDE) projects.

Krista, female took engineering in high school, average score on tinkering	"Well I hadn't used a band saw before, like using it as in depth as I needed to. I cut out a succulent or cactus... I had to cut out two of them on three quarter inch plywood. I had to do a lot of relief cuts. I'm used to using hand tools like hand jigsaws and stuff from my stage crew experience during junior and senior years of high school to cut out pretty precise, like lettering in plywood, but not for the craftsmanship of a child's toy."
Karla, female no prior prototyping experience, lower than average tinkering score	"I had actually no experience at all coming into this… I mean I feel a lot more comfortable now. Before I was like, scared to even go in the [maker space], but now I feel totally fine, yeah, that was definitely a good experience."

Kimberly, female no prior prototyping experience, higher than average tinkering score	"It was the first kind of like experience with tools and I never really thought that I could be good at stuff like that. I mean, not that my pull toy was good, but like it was a lot better than my expectations I have for myself. It was just cool to be able to make something."
Jessica, female no prototyping experience, higher than average tinkering score	"I had a handyman dad… I watched him but I don't think I had experience with like a drill that was unsupervised.... It's a lot of freedom that we have in the [maker space], and yes, definitely the pull toy project helped… I guess it just increased my confidence knowing like, 'okay, like I can do this like now by myself. I don't need anybody.' I can do it. But if I need help, the TA is always there."
Samantha, female no prototyping experience, average score on tinkering	"...I've never had woodshop in my entire life… I learned a lot but it was only because I wasn't afraid to learn. So, there's someone who wasn't as outgoing or extrovert[ed] as I was, like, I don't know how they'd be able to because it was really difficult. I had to go up to the TA and not be embarrassed to be like, 'how do you screw this?' I [learned] simple things but I didn't know how to do other things… Now, I like tools. I learned what not to do. Such as like don't put your fingers near things when they're moving… Yeah, and uh, you have to make sure it's clamped when you try to screw something in or else the piece moves with the drill. But, yeah, just like things that you would learn in basic wood shop in high school. To me it was like super cool."
Candice, female used Autodesk during high school, average score on tinkering	I felt stupid because I used to help my dad with all this stuff. I should have taken the time then to learn then when I was watching him… So I was familiar with most of the stuff anyone does. I know not to put my fingers near it, you know, like the essentials but I didn't really know a lot… And it was kind of hard because even in our [power tools] training it was kind of rushed because it was like, 'hurry up, let's go.' And one TA scared me because he didn't do something and then the thing started smoking and then he yelled at me. Another TA came up to me after that; I asked her about it. She was like, 'that wasn't even you, that was all him.' And I was like, 'well great, it scared me.' Because it's scary, you don't want to mess up. You don't want to hurt anyone, hurt yourself, or get in trouble, at least I feel that way…. Personally, I didn't feel comfortable just trying something because it could be dangerous so I would always ask five million questions before. I don't really care if it annoys [the TAs]. But it was hard to learn.
William, male extensive prototyping experience,	"I was on [theater] stage crew in high school all four years and I also make furniture with my dad in my garage at home…"

higher than average tinkering score	“...I took engineering in high school and learned Autodesk Inventor so CAD modeling isn’t a big deal for me…” “Yeah, I built a train for my toy project. I had slight experience using power tools before this course, but not much. So again, to use them as extensively as we did with this project was very helpful and I guess I learned a lot.”
Adam, male no prior prototyping experience, lower than average tinkering score	“I learned how to use all the machines in the [maker space]. Because I haven’t used anything with those machines before pretty much so cutting the shapes out was a learning process. I had never used anything more than a drill or a hammer. I think I know what I’m doing now.”
Eddie, male three years of high school engineering, SolidWorks certified, higher than average tinkering score	“I already had skills with hand tools and sanding. So, learning some of the power tools was something that I slowly picked up on but then it became easy. I learned tricks for making relief cuts so I could actually cut the curves on the band saw and use the belt sander which was helpful.”

Discussion

Our goal was to design individual mastery experiences that would lead to gains in self-efficacy that persisted during team-based activity. The results of our study indicate that Individual Design Experiences (IDEs) are useful mastery experiences that can benefit students with a broad range of prior educational experiences and self-efficacy. Given that our IDE intervention was focused almost exclusively on hands-on prototyping, it is not surprising that significant effects were seen for this factor alone. Interestingly, IDE may also help students to develop a more accurate view of their prototyping skillset. From our quantitative analyses, there was an observed trend for some students with high pre-course self-efficacy in prototyping to demonstrate a loss in self-efficacy post-course (see Figure 2). This is not to suggest that students with a loss in self-efficacy experienced a setback in their actual hands-on prototyping skills. Rather, in conjunction with the qualitative evidence, these data suggest that a negative gain in hands-on prototyping may actually be positive from a developmental perspective. For example, through IDE, students like William (see Table 1) with fairly extensive pre-course prototyping experiences develop an appreciation for the range and complexity of skills needed in engineering design and are able to recalibrate their initial estimate of their skills in this area. This finding is consistent with prior studies, which have indicated student self-efficacy is higher at the beginning rather than at the end of an engineering design course [17], [20], [32] and, in some cases, may not improve significantly over the course of a four-year program of study in engineering [33].

Our findings add to the body of knowledge concerning self-efficacy and team-based learning in engineering education [31-35], [44]. Chachra et al. [38] found that tinkering and technical self-efficacy did not appear to change over the duration of a team-based engineering course, which they attributed to students taking on tasks that played to pre-existing strengths, which in some cases, reinforce gender stereotypes about performance – i.e., females took on writing tasks, males took on technical “building” tasks. Gendered task orientation may be a possible explanation for results; this finding coheres with a study by Masi [25] who found that hands-on prototyping during team-based engineering design projects had a significant impact on the self-efficacy of first-year male engineering but not female engineering students. However, other explanations for why students engage (or not) in different tasks on team-based design projects may exist [30], [33], [34]. For instance, team dynamics [13], academic orientation towards learning [31], [45-48], fixed- or growth-mindset about intelligence [49], [50] may also factor into how and when individual students engage in particular design tasks.

Our study adds to what is known about how the structure of design tasks might influence student self-efficacy in engineering. The findings from our study suggest that IDE may be an effective intervention in “leveling the playing field” prior to initiating team-based engineering design projects. Mastery experiences such as IDE may be particularly important for skills like hands-on prototyping where gender and racial stereotypes may be at play in team-based settings. Moreover, findings from student interviews reinforces earlier studies on students’ academic orientation towards learning. Student likes Samantha and Adam indicate that being task-oriented fosters the development of new skills, and problem-solving and self-improvement become motivators [38], [46], [47]. Task-oriented students are more likely to engage in various cognitive and behavioral activities that improve personal educational outcomes – establishing a productive work environment, using resources effectively, monitoring performance, viewing problems or challenges as opportunities to learn, managing time effectively, and seeking assistance when needed [20], [26], [35], [50].

There are strengths and limitations to consider in interpreting the results of this study. The strengths are in the study design itself, which was well controlled to isolate the effect of the IDE. The instructor, assignments, and rubrics were identical between IDE and control groups, and the only curricular difference between groups was whether the IDE activity (children’s pull toy) was assigned individually (IDE) or in groups (control). It should be noted that the control group was two semesters further advanced in the undergraduate program (2nd semester sophomores) than the IDE group (2nd semester freshmen). This maturity difference would only serve to mitigate our observed finding that IDE results in greater self-efficacy gains, and the true effect of IDE may be even greater with students in the same year of the program. Lastly, the quantitative portion of the study was unfortunately underpowered to disaggregate effects by gender or race. Our focus group results do suggest that gender may be a factor in approaching early prototyping experiences, e.g., the comments by Candace about observing her dad and interacting with teaching assistants. However, because IDE was designed to benefit all students, we assert that there is no reason to believe that IDE would preferentially affect women or historically under-represented students any more than their majority peers with similar pre-course experiences.

In conclusion, our study indicates that IDEs, which we define to be individual mastery experiences embedded within team-based curricula, can lead to gains in self-efficacy that persist during team-based activity. Follow-up studies will focus on developing interventions, like self-reflection and team-based assessment of individual learning goals, that might reinforce self-efficacy for engineering design while also promoting growth in other engineering knowledge and skills. We are currently pursuing a study on self-reflection during team-based design projects as a way to prompt engineering students to think explicitly about how and when they engage in particular tasks in a team-based project. We anticipate this intervention will support students in being more aware of their roles on teams and how they participate.

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