Moving from STEM to STEAM: The Effects of Informal STEM Learning on Students' Creativity and Problem Solving Skills with 3D Printing

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***Abstract*— Modeling with 3D computer-aided design (CAD) software to design and print 3D products can improve students' spatial visualization skills, creativity, and problem solving skills. 3D CAD software has been used as a teaching tool in secondary school classrooms since the early 2000s, but it becoming more ubiquitous due to increased affordability of an innovative concept: 3D printing. Yet research about the effect of 3D design and printing on students' academic achievement, problem solving skills, and creativity has been limited. For the present study, the effects of applying 3D CAD software and 3D printing were observed on students' perceptions of their need for creativity when solving problems that could be encountered across STEM careers. Participants (N = 95) were high school students who attended a two-week long STEM summer camp at a university located in central Texas in 2016. Results indicated that the students who participated in the 3D CAD and printing improved their perceptions about creativity and problem solving skills required for STEM disciplines ($p < .01$). The effect for the study was impressive with Cohen's d effect sizes for students' perceptions about creativity and problem solving skills in STEM disciplines at $d = 0.61$ and $d = 0.66$, respectively. Students who participated in the informal STEM learning and engaged with 3D project-based learning indicated that creativity was important for STEM fields and for engineering in particular. They also indicated that problem solving skills were essential for being successful in a STEM career. Teachers who desire to increase their students' creativity along with their STEM competencies should integrate classroom activities that promote creativity and problem solving while being actively engaged in the activity.**

Keywords—problem solving skills, creativity, informal learning, summer program

I. Introduction

A. Inclusive STEM Education

STEM education has been economically and politically gathering support in the last decade in the United States [1] and has been utilized to promote students' engagement in STEM fields [2]. There is an increased emphasis on the importance of creativity and abstract reasoning in STEM education [3]. The misnomer of inducting Arts into the STEM, or STEAM, may be partially responsible for common beliefs that STEM fields are not creative [4, 5], lack aesthetic goals, and fail to provide a satisfying outlet for right-brained inclined individuals. Those advocating for Arts in STEM most often referred to the need for creativity and that creativity needed to include divergent thinking [6]. What is important is that young people, during formative times in their lives, learn that STEM disciplines require (1) invention or discovery of unknown phenomena and observations; (2) non-traditional physical and mental tools, analogies and models; (3) communication; and (4) testing possible solutions for real-world situations [7]. The arts curriculum alone cannot accomplish this task, nor can adding artistic tasks on top of STEM activities without a meaningful integration of the two. What is paramount is that meaningful and purposefully selected STEM tasks be chosen that necessitate invention, non-traditional solutions, high level communication and vocabulary development, and iterative testing of those solutions. The integration of high quality STEM activities helps to stimulate both the right and left hemispheres of the brain, building connections that reinforce learning across hemispheres [8]. Therefore, high quality STEM tasks helped students build facility across both scientific and creative hemispheres [9].

B. Innovation Skill (Creativity and Problem Solving Skills)

Innovative STEM experiences positively affected middle and high school students' STEM-related learning and career goals [10]. While high school students typically benefitted more from high quality STEM experiences, it is often in middle school where students make the decisions that can destabilize their STEM career potential. In the design of innovative STEM-focused educational experiences, one purpose can be to increase students' innovation skill. Innovation skills are practical skills consisting of a combination of cognitive and behavioral capabilities expressed through actions that are often measurable.

Innovation skills enable an individual to think creatively and critically as well as to manage stress and solve problems. The ability to approach new situations creatively has been linked to possessing excellent problem solving skills. In addition, visual-spatial skills are important to innovation because acute visual-spatial skills allow people to succinctly and clearly share their ideas, thoughts, and opinions with others [11]. Therefore, it is important for students to participate in high quality STEM activities that integrate creation, encourage

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non-traditional solutions, use high level communication and vocabulary development, and make use of iterative testing of those solutions.

Experiences with Computer Aided Design (CAD) software and 3D printing, if properly structured, can develop students' creativity and visual-spatial skills [12]. CAD software and 3D printing have recently become popular and more widely available in secondary school classrooms as a medium where students could easily demonstrate their creativity [13].

Creativity was identified as one of the most desired skills by potential employers [14] and listed as a crucial 21st century skill [15]. CAD and 3D printing enable students to generate objects where both the process and the final product can be easily observed by teachers. The design and virtual object generation are connected to student behaviors that cognitive psychologists have associated with creativity [16]. In addition, integrating 3D CAD software enhanced students' creative dispositions [17]. Engaging with CAD software (e.g., Google Sketch-Up®) enabled students to be more fluent and flexible in their thoughts. Fluency and flexibility are the two most vital measures of creativity [18]. Enhancing students' creativity during middle and high school years is essential because these students are more likely to employ divergent thinking than elementary school students [19]. Being able to follow multiple paths and devise multiple solutions requires fluency, flexibility, and originality of thought processes [6].

While students engage with CAD software and 3D printing, they can test multiple views of the object, and this process helps them create quality 3D products. Research has shown that female students performed better than male students while they engaged with CAD software and 3D printing, though there was no meaningful difference between genders in problem solving skills [20, 21]. It is possible to reduce the load on students' working memory by using CAD software and 3D printing so they could devote more intellectual capacity to the creation of original ideas and products [22]. Teachers should understand the importance of implementing this type of technological tool into their classroom to foster creativity and to provide more time for students to actively design and build products [23]. Using CAD software and 3D printing provides students an environment where they can increase their problem solving skills. This is because increased creativity leads to more divergent thinking [7, 24] enabling students to create multiple solution strategies for a given problem. Some activities and projects that foster students' problem solving skills include bridge building, creating marketing materials for a product they develop and build, and 3-D software and printing [25].

C. Informal STEM Learning

Informal STEM learning programs support students' understanding and performance in mathematics and science in formal school settings [26]. When students learn about STEM fields in informal settings, they often increase their interest and develop deeper understandings of the content. Informal STEM learning can be instrumental in increasing student interest in STEM fields, especially those underrepresented in STEM careers. Informal STEM experiences provide experiences in real life oriented problems and require students to come up with various solutions to a problem that they may never encounter in formal educational settings. Several factors of impactful informal STEM programs have been identified: mentoring informally, having fun while learning, managing time effectively and efficiently, applying previous mathematics and science knowledge, feeling accomplishment through collaboration and competition, building self-confidence, and building mutual trust and friendship through collaborative and cooperative efforts [27]. Informal STEM experiences make mathematics and science learning meaningful by integrating learning across STEM subjects just as STEM professionals do in their jobs. Students typically enjoy the collaborative informal STEM learning opportunities that are rarely available in formal educational settings [28-30]. Informal STEM learning opportunities have been credited with increasing secondary school students' interest in pursuing STEM-related careers because they learned more about the tasks mathematician, scientist, doctors, and engineers perform [28, 31]. Unfortunately, although there has been an increased need for informal STEM learning programs, only 20% of households contain children who have been able to participate in informal STEM programs [32].

D. 3D Printing in Project-Based Learning Classrooms

Innovative STEM instructional practices such as project-based learning (PBL) have increased content knowledge, interest in STEM fields, and 21st century skill levels [33-36]. In PBL classrooms, students were more responsible for their own learning as teachers served as facilitators of that learning [37-39].

STEM PBL activities are arranged in a way that students have fun while they are learning. In addition, STEM PBL activities integrate real life situated complex problems, involve cutting-edge technology, and can engage a diverse student population. For example, creating useful objects such as cell phone covers, key chains, and knick-knacks by implementing CAD software and applying 3D printing is a cutting-edge technology [20]. In addition, 3D printing is becoming more and more useful for printing actual parts to be used in various contexts. 3D printing technology has found industrial applications in the automotive and aerospace industries for printing prototypes of car and airplane parts, in the architectural world for printing structural models, and in the consumer goods industry for prototype development. Experts have used 3D printers to create models of the heart, skull, and other body parts for teaching anatomy [40], building parts for unmanned aerial vehicles, and developing parts for small household applications.

The conception of 3D printing was developed by Charles Hull in the 1980's. The initial process had lengthy fabrication times and was highly prone to design imperfections requiring multiple iterations [41]. By 1993 the manufacturing issues were addressed and the integration with CAD software achieved, and so the first apparatus termed "3D printer" was patented. However, it was still extremely cost-prohibitive and cost more than $100,000. However, 3D printers have recently become more affordable and thus have become more popular with the general public. Fused deposition modeling (FDM) printers are the most commonly used in education because they are simple to operate. FDM uses a thermoplastic filament and objects are printed in layers.

II. Purpose and Research Questions

The purpose of this study was to determine influences of a summer STEM camp that engaged students in the use of CAD software and 3D printing within a PBL-focused classroom on their perceptions of the need for creativity in STEM disciplines. The research questions were:

1. How do students' perception about creativity in STEM disciplines change after they engage in a 3D printing project-based learning during a STEM summer camp?
2. How do students' perception about problem solving skills in STEM disciplines change after they engage in a 3D printing project-based learning during a STEM summer camp?

III. Methodology

High school students (32 female and 63 male) n = 95 enrolled a two-week long STEM summer camp in 2016. The camp was held on a university campus in central Texas. Students were accepted on a first come first served basis regardless of academic ability, STEM interest, ethnicity or gender. Unfortunately, not all students were accepted due to the logistic limitations, so the program only accepted students who registered before the enrollment limit was reached. A diverse student population was served in terms of their ethnic background (50 White, 3 African American, 24 Hispanic, 3 American Indian, and 15 chose not to identify).

The camp consisted of students entering grades 8 to 12 the next fall. A survey administered prior to the beginning of the camp revealed reasons students attended this two-week long STEM summer camp. The reasons included, but were not limited to, prior interest in STEM fields, parental requirement, and interest in a two-week camp.

A. *Intervention*

Students participated in 3D printing PBL activities, including theoretical concepts and applications, as one learning module during the two-week STEM summer camp. Students learned how to use the CAD applications Sketch-Up® and XYZ software to design their own 3D objects. They also learned how to use a 3D printer to build 3D objects. While students were working on the design portion, they worked on individual laptops. Two teachers were present in the classrooms at all times to scaffold student learning. While one teacher taught the necessary concepts and skills of the software and 3D printing, the other one helped students who needed additional support. As part of the STEM camp experience, the students were presented with a discussion of the engineering design process, and the model followed had the following seven steps: 1) Identify problems and constraints, 2) Research, 3) Ideate, 4) Analyze ideas, 5) Build, 6) Test and refine, 7) Communicate and reflect [42, 43].

The 3D printing learning module was centered around a PBL where students were given the well-defined outcome of creating and producing a physical object. The main project criteria was that the object needed to serve an educational purpose. The constraints were that: 1) the student must create the object in its entirety, 2) the object can be abstract must be explained by the student, and 3) the object must be able to be printed and within the size limitations of the 3D printer. The expected learning outcomes were 1) scaling, which included algebra, 2) spatial awareness, measurement- including volume, area, and linear dimensions, 3) engineering design principles, 4) science and mathematics vocabulary specific to the topic (e.g., extruded, planar, dimension, perspective, rotation etc. and 5) technology awareness and use to move between the CAD software and the printer software.

Depending on when students completed their design task, students would be able to iterate through their design and production efforts. They could attempt to print and if they encounted a problem they could go back make revisions and make another attempt. The iterative trials were to allow students to opportunity to succeed and to experience the iterative nature of the engineering design process. The two most common problems encountered by the students were that the object was not fully linked or that the object was not sitting on the build plate in the design.

Students were expected to print their 3D objects and be able to explain the mathematics and science underlying the item, and present strengths and weakness of their designs. They also had to explain the educational purpose for the object. Some students considered abstract art as the educational purpose. For those students ascribing to abstract art they developed the background, art history, and build information and the objects were placed on display at the Stark Galleries on campus.

B. *Assessment*

A pre-post survey was administered to the participants through Qualtrics. The survey questions consisted of Likert-scale items on a scale from 1 to 5 or from strongly disagree to strongly agree. Students took the pre-survey one week before the camp started and the post-survey on the last day of the camp. Two items were employed to measure differences in students' perceptions of the need for creativity and problem solving skills for STEM success.

The pre-post survey questions were: 1) I believe STEM (Science, Technology, Engineering, and Mathematics) courses and careers require a lot of creativity, and 2) I believe STEM courses and careers often involve solving problems that require artistic solutions.

SPSS 23, was used for statistical analyses. To determine pre-to-post differences on survey items, a paired-sample *t*-test was used. Cohen's *d* effect sizes and confidence intervals were reported.

IV. Results

Results from the study revealed that students' perceptions about the need for creativity in STEM fields were statistically significantly changed ($p < .05$, see Figure 1) after they engaged with a CAD software and 3D printing intervention. Students realized that they did need creativity when solving problems in STEM disciplines after the CAD software and 3D printing intervention. The Cohen's *d* effect size for this difference was

0.61, and the confidence interval associated with this effect size was (0.26, 0.71).

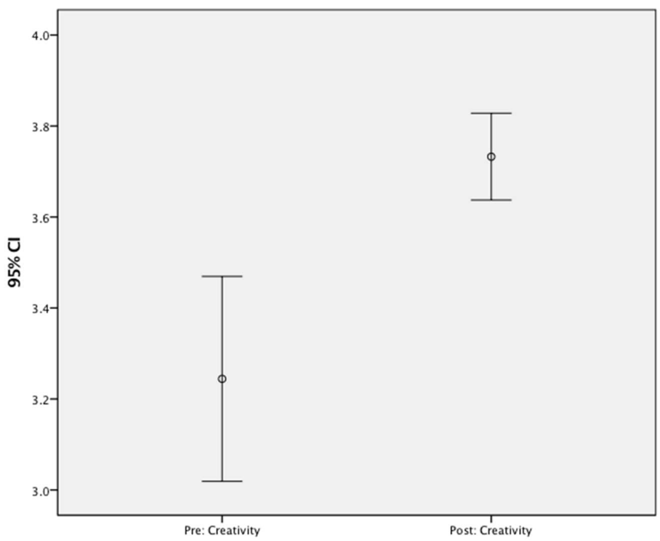

Fig. 1. Perceptions about the need for creativity in STEM fields

Results for students' perceptions about the need for problem solving skills in STEM fields were also statistically significantly changed ($p < 0.05$, see Figure 2) after the CAD software and 3D printing intervention. Students believed that they needed to be better problem solvers when solving problems in STEM disciplines. The Cohen's *d* effect size for this difference was 0.66, and the confidence interval associated with this effect size was (0.32, 0.75).

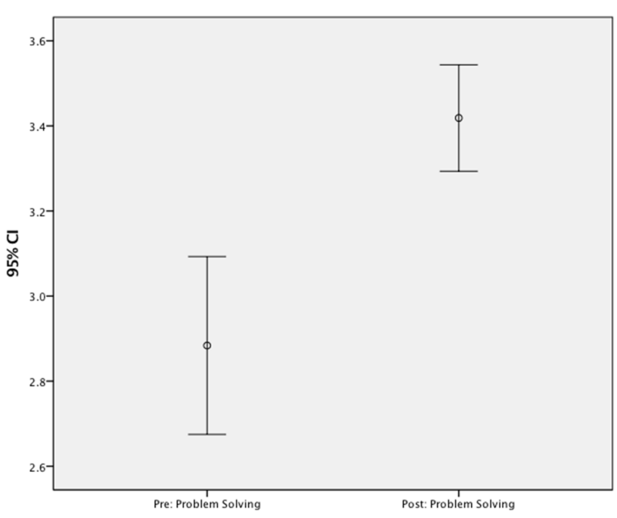

Fig. 2. Perceptions about the need for problem solving in STEM fields

Results were disaggregated by gender and ethnic background. Pre-to-post changes in students' perceptions of the need for creativity and problem-solving skills in STEM disciplines were not statistically significantly different ($p > 0.05$) among students from four ethnic backgrounds (Asian, African American, Hispanic, White, and Native American). Pre-to-post changes between male and female students were also not significantly different ($p > 0.05$, see Figure 3).

Female students more often indicated that they needed to be better problem solvers to be successful in STEM fields compared to male students; however, this difference on their perceptions was not statistically significant ($p > 0.05$) as illustrated in Figure 3. On the other hand, male students indicated that they need to be more creative to be successful in STEM fields compared to female students; however, this difference was not statistically significant.

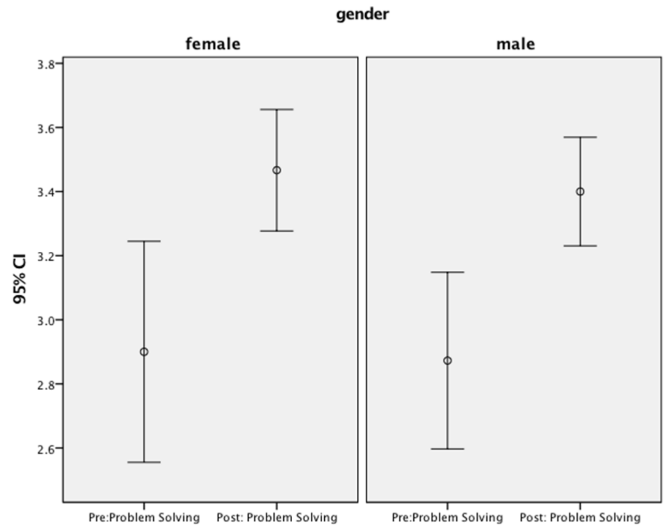

Fig. 3. Problem solving perceptions by gender

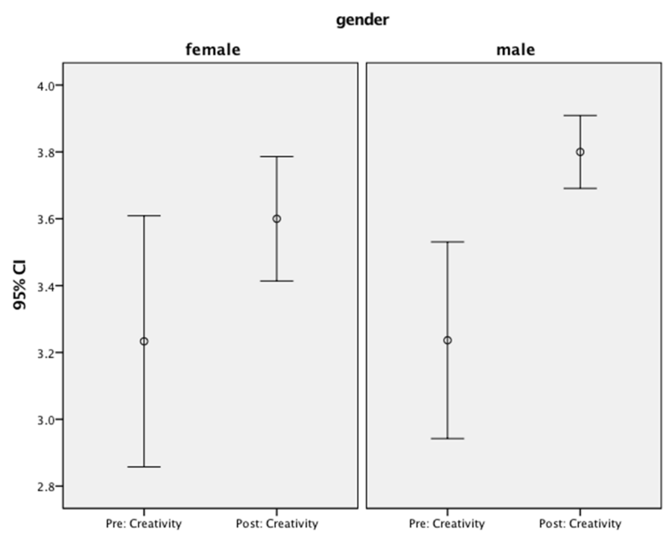

Fig. 4. Creativity perceptions by gender

V. Conclusions

The use of 3D CAD and 3D printing in an informal learning experience changed high school students' perceptions about the use of creativity and problem-solving skills in STEM disciplines. After engaging with CAD software and 3D printing, students acknowledged the importance of being creative problem solvers in STEM fields. The quality of the activity allowed students see how creativity and problem solving were resident in an engineering task. In this study, male students believed that they needed to be more creative to be successful in STEM fields as compared to female students. However, female students more often indicated that they needed to be better problem solvers to be successful in STEM fields as compared to male students. This dichotomy in beliefs could be rooted in long standing gender expectations that depict males as better problem solvers and females as being more creative. Therefore, each group may have initially held these beliefs about their own gendered strengths. However, by the end of the two weeks both groups had modified their beliefs and there were no statistically significant differences.

The most important finding is that students who used CAD software and 3D printing during a STEM summer camp increased their perception of the incorporation of creativity and problem solving skills in STEM fields regardless of their gender or ethnic background. They learned that STEM fields and engineering in particular are intrinsically creative, and success requires problem solving skills beyond rote calculations or rote application of scientific formulas. Typically, some have argued that inducting the arts was the sole way for students to experience creativity and problem solving in STEM disciplines. However, once the skills necessary for STEM fields are joined with tasks that mirror what STEM professional actually do, student realize that these fields require and foster creativity and problem solving. This realization was inevitable because students engaged in PBL, where ill-defined tasks are emphasized and multiple outcomes are possible that can meet the constraints of the task, are forced to use those skills to address the project challenges [44].

Emphasis on 3D printing enabled students to engage with cutting-edge technology. Pre-to-post differences in students' perceptions of the need for creativity and problem solving skills in STEM fields are noticeable. The study showed that students benefit from an instructional approach and technological emphases of the two-week summer camp.

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