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COLLABORATIVE TEAMWORK PROTOTYPING AND CREATIVITY IN DIGITAL FABRICATION DESIGN EDUCATION

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ABSTRACT

Digital fabrication laboratories play a role as an educational environment in which different learning activities incorporate advanced technological developments. Digital fabrication design education often involves exploratory and scaffolded processes of materialising ideas into products. However, FabLabs poses multiple challenges for pedagogy and design learning. Based on a large-scale digital fabrication course in a higher education institution, we examine whether teamwork carried out in a digital fabrication environment improves creativity. Furthermore, we analyse if teamwork affects self-assessment of learning activities involving building tangible artefacts. Finally, we examine whether the type of produced prototype affects the team's overall performance. The results allow for digital fabrication design education recommendations, including interventions intended for improving the creativity of the outcomes, team performance, and learning of different digital fabrication issues.

Keywords: Creativity, Design education, Teamwork, Digital fabrication, Prototyping

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1 INTRODUCTION

The concept of digital fabrication laboratories (e.g., FabLabs, makerspaces) is to enable the transformation of ideas into physical objects. Design education employing digital fabrication is characterised by a project-based learning environment (Iwata et al., 2020; Milara et al., 2019). As an educational space (including both physical and social environments), digital fabrication laboratories have a fundamental role with regard to the development of different learning activities (Mostert-van der Sar et al., 2013) that incorporate cutting-edge technological tools (Milara et al., 2017; Shi et al., 2019). Often, this involves an exploratory and non-directed process of materialising ideas into products (Barhoush et al., 2019; Pitkänen et al., 2020), often scalable to research activities, such as makerspace-driven user research (Jensen and Steinert, 2020). These characteristics pose various challenges to design pedagogy and learning (Iwata et al., 2019; Pitkänen et al., 2019).

Digital fabrication design education targets a variety of technical and prototyping skills; therefore, a balance between the time span of the educational activity and a range of domain-specific skills is needed. This represents a challenge, provided that typical design education courses delivered in this context involve one period (Georgiev et al., 2022; Georgiev and Nanjappan, 2023) or one semester (Chan and Blikstein, 2018; Erichsen et al., 2021).

2 PREVIOUS WORK

2.1 Digital fabrication skills

Digital fabrication offers an opportunity to introduce technology-related skills to a broader audience (Unterfrauner et al., 2020). Such fabrication spaces promote the development of skills and practices essential to engineering and design (Bouwma-Gearhart et al., 2021).

A typical application of digital fabrication is the learning of various skills to match individual needs and abilities. Such is the personal fabrication phenomenon, which involves gaining knowledge of a specific technical skill or knowing how to use particular tools and equipment (Bouwma-Gearhart et al., 2021).

Formal design education targets a particular range of skills that match the standard digital fabrication processes in courses (Soomro et al., 2021) or programmes (Ylioja et al., 2019). This is particularly relevant for digital fabrication spaces or makerspaces that are part of the FabLab network (Ylioja et al., 2019), which require the availability of specific equipment. Digital fabrication knowledge entails understanding various production processes, investigating the unique capabilities of digital fabrication equipment or devices, seeking new ideas, and using interdisciplinary knowledge (Celani, 2012). Commonly technological processes and activities carried out in these environments are 2D design, 3D design, electronics fabrication, programming, and utilisation of dedicated tools and equipment for prototyping (Milara et al., 2017).

Educational programs based on digital fabrication rely on most of these technological processes (Milara et al., 2017). Depending on the type of audience or learning requirements, the learning activity can be set on different technological processes. However, the coverage of skills and techniques to be learned is similar across other education application cases, such as thematic workshops (Iwata et al., 2019, 2020; Milara et al., 2019; Pitkänen et al., 2020) and courses (Georgiev et al., 2022; Georgiev and Nanjappan, 2023; Soomro et al., 2021).

2.2 Teamwork, skills and digital fabrication

Teamwork in the context of digital fabrication design education is generally an underexplored topic. A few exceptions are the works of Georgiev et al. (2022), Nagel et al. (2017), and Zhan et al. (2022). As a difference to the exploration of teamwork in the design studio, teamwork in the context of digital fabrication is influenced by the wide range of technological tools and related skills targeted. In the digital fabrication context, teamwork has been explored as interdisciplinary skills that foster individual strengths and improves student engagement (Nagel et al., 2017). The multidisciplinary experience and utilisation of digital fabrication technologies enhanced student learning and engagement, fostered teamwork and interdisciplinary skills, and increased innovation ability.

Digital fabrication skills are often understood as crucial 21st-century digital skills (Unterfrauner et al., 2020) or as a way to promote 21st-century skills such as effective communication and problemsolving (Morado et al., 2021). These fabrication skills can be seen as instrumental in developing computational and design creativity skills and competencies (Nagai et al., 2019) and tackling a variety of aspects in the focus of design creativity research (Cascini et al., 2022).

Interpersonal skills are a common objective in specific digital fabrication education contexts. Often interpersonal skills are targeted to a similar degree to the professional or technical skills that are the primary target of such education (Veldhuis et al., 2021). Furthermore, cultural knowledge and skills were seen as a way to navigate and understand the digital fabrication (FabLab, makerspace) community (Tomko et al., 2020). Additionally, learning through others, namely, observing the actions of others or interacting with them as a means of learning, has been pointed out as a type of learning in digital fabrication spaces (Tomko et al., 2020).

2.3 Creativity and digital fabrication

Makerspaces and digital fabrication are ideal environments to encourage and develop substantial aspects of creativity. These include person, product (design outcome), environment (physical and social), as well as process aspects of creativity (Soomro et al., 2022, 2023). Furthermore, digital fabrication spaces also contribute to fostering creative competence (Taheri et al., 2020) and creativity in co-design activities (Choi et al., 2022).

Moreover, assigning open-ended design tasks can help promote creativity in the digital fabrication context (see Georgiev et al., 2016; Luis Saorin et al., 2017). Regardless of its importance for design, creativity is not always an explicitly targeted skill to be nurtured in digital fabrication environments in higher education. Although creativity is naturally occurring in this context (Georgiev et al., 2016), in general, it is not part of the criteria of assessment for the course grade. This is in contrast to early education digital fabrication activities, where creativity is explicitly targeted along with a range of related skills (Veldhuis et al., 2021). Creativity in digital fabrication design education is dependent on the scope of the design task. For open-ended design tasks, few or no constraints related to creativity are generally given. On the other hand, giving example solutions or guidance supported by prior cases used as examples might limit the creativity of the outcomes (Georgiev et al., 2016).

In this study, we aim to gain insight into how teamwork in the context of digital fabrication design education may affect creativity and self-assessment of learning activities, with a focus on prior experience, gender, performance, design outcomes, and creativity. Moreover, we investigate teamwork contribution to the type of technology employed to develop the design prototype. We address these aims by exploring a higher education digital fabrication design course.

3 METHODOLOGY

3.1 Digital fabrication course context

This research targeted BSc students engaged in a 5 ECTS (1 ECTS is equivalent to 27 hours of effective work) digital fabrication course provided by an European institution. The course lasted seven weeks, was delivered in English and an in-person format and little feedback was provided online. In this context, classes were given at the end period of the first-year BSc programme. Prerequisites, intensity, length, and load of the course are typical of the curriculum. Although it was part of the degree program in computer science, classes were available to all university students. As a result, it attracted students from diverse backgrounds and academic disciplines.

3.2 Content and projects

The course is intended to teach students to develop interactive physical prototypes with mechanical, electrical, and software components. Designing and fabricating mechanical and electrical components and integrating software in a microcontroller are the major activities and operations.

The course is organised into two sections: a series of six lectures followed by supervised project work. During the first two weeks, six lectures introduce the fundamental aspects of design and digital fabrication that include an overview of the topic, the design of physical objects, electronics design, embedded programming, 3D modelling and printing, and 2D design. During the five subsequent weeks, students are encouraged to generate and develop their own ideas by constructing a physical prototype that should interact with its environment. They worked in teams that were created based on equal distribution of prior knowledge, which typically comprised four members. In order to produce the physical prototype, a component kit is given; however, if requested, teams are provided with additional alternative components. The produced device has to meet the following requirements: (1) be primarily composed of mechanical and electronic components designed and manufactured in the FabLab; (2) have moving parts that can be controlled by software; and (3) include at least one sensor and one actuator, with the software responding to the sensor's readings.

Throughout the seven-week course, instructors held weekly feedback meetings with the team members. They advised on design and technical issues related to implementing the ideas generated by the different teams. No strict timeline was pre-established for the development of the projects so that students could be able to work at their own pace. The course included a series of design presentations, where all teams reported their work to the course instructors and the other students. The course concluded with a presentation of a prototype of the produced device and documentation related to the design and fabrication of the device. The documentation contains key design goals, detailed information about the idea generation process and the selected design concept, as well as a weekly diary, and a summary of the student's self-perceived learning. Iterative prototyping is explicitly encouraged, along with sustainability considerations for the digital fabrication context.

Figure 1 shows two prototypes produced by the teams. These involve various technological aspects targeted as a consequence of the skills developed through the digital fabrication design course.

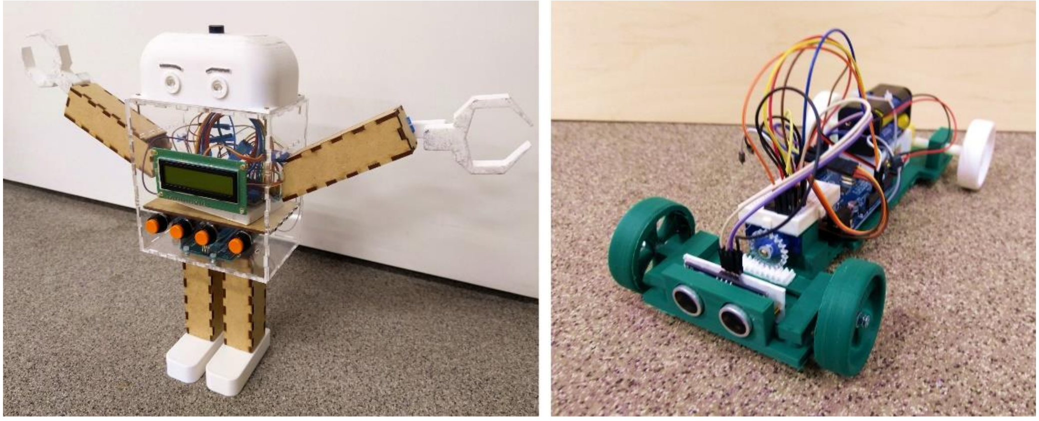

Figure 1. Two examples of teamwork outcomes as prototypes:
Robot alarm clock (left) and Smart car (right)

3.3 Data collection: teams, self-assessment questionnaires and creativity tests

We utilised the data of 18 teams (out of 23) for which all team members completed the questionnaires delivered before and after the course. The selected data comprises 65 students working in teams, typically of four members. Since a few students abandoned the course after the first two weeks, five teams were left with three members and another one with two members. The data of individual responses from the 65 students was organised based on the teams.

The teams were formed on the basis of the responses by the students to the questionnaire administered during the first week of the course. The aim was to classify team members according to their prior experience. In regard to gender, there were two types of team composition that included male only and mixed gender (in all cases, two males and two females).

We used two additional pre- and post-course questionnaires to explore students' self-assessment of learning activities in the course (see Figure 2). In particular, we inquired about issues related to practices of learning by generating and constructing tangible artefacts and working together as a design team. The questionnaire at the beginning of the course included queries about each student's prior experience in each of the main digital fabrication technical dimensions, namely, 2D design, 3D design, electronics, programming and use of FabLab tools and machines (Georgiev et al., 2022; Milara et al., 2017). The questionnaire and the end of the course included inquiries into the actual roles taken by the team members during their work on the prototype in the course. The inquired roles match the technical dimensions, 2D design, 3D design, electronics, programming and use of FabLab tools and machines. Moreover, we inquired about the students' self-perceived skills in all the technical dimensions after the course.

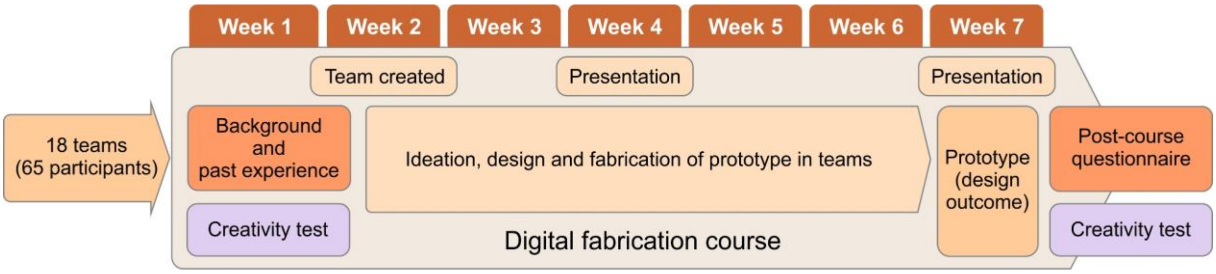

Figure 2. Data collection during the digital fabrication course

In addition, a pre and post-course online test was used to measure the individual level of creativity (http://www.testmycreativity.com). The test includes 40 questions focusing on different creativity metrics that resulted in a numeric score with a precision of two decimal points (e.g., 54,04). This is a multifaceted creativity test involving a variety of questions, for example, visual, textual, scale ratings and others. The test is based on basic concepts of creativity and is similar to various known assessments of individual creativity (Berger et al., 2014). The global average of this creativity test is 62.76.

Informed consent was obtained from all students to participate in the data collection and all the questionnaires administered in the course. All questionaries are administered individually, not as a team. The questionnaire and the creativity test before the course was inquired during the first week of the course, while the questionnaire and the test after the course were administered after the final presentations.

3.4 Course assessment

Assessment criteria employed in the course to establish the final grade were presented to the students at the beginning of the course, and included the following aspects: design, electronics, programming complexity, function as intended, quality of the final prototype and the corresponding weekly documentation and presentations. The quality of the final prototype and the corresponding documentation and presentations were the criteria with the highest impact on the final grade. Each of these aspects was assessed independently to establish the global grade. The assessment was made by the course instructors. The final grade was assigned per team, using a value between 1 and 100.

4 RESULTS

In the next subsections, we present the results of the analysis carried out for the self-performed creativity test and the self-assessment survey of students, and the assessment of the final design prototype by instructors. Data per team are used in further analyses. The statistical analyses were performed using SPSS 28 (IBM Corp., Armonk, NewYork, USA).

4.1 Teams: Gender ratio, prior experience and design outcomes

Table 1 lists all the teams with gender ratio, self-reported prior experience, the name of the design outcome (prototype), and average creativity levels. Each prototype was labelled as originally named by the team. The teams decided on the idea of the prototype on their own as long as it satisfied the requirements for the prototypes produced in the course.

Three of the teams were mixed in terms of gender ratio, while the remaining 15 teams were composed of males only. Eight of the teams had no prior experience with any of the digital fabrication technological dimensions. Seven of the teams reported prior experience with 3D design, and the remaining three teams had experience with programming in the context related to digital fabrication.

4.2 Learning by building tangible artefacts

A series of non-parametric Wilcoxon Signed-rank tests examined the median difference of interest of students pre and post-course. Results revealed that using FabLab machines and tools to build tangible artefacts significantly increased the interest of students in learning by generating, and constructing tangible artefacts (Z = -3.243, p <.001). In particular, the course significantly increased their appeal to working as a team for the sake of building objects together (Z = -1.994, p = .046). Moreover, they claimed that learning by building artefacts as a team was beneficial for them (Z = -3.081, p = .002).

Table 1. Teams, gender ratio, prior experience, design outcomes, and creativity levels.

Team ID	Gender Ratio	Prior Experience	Prototype Name	Average creativity levels	
				Pre-course	Post-course
1	Mixed	None	Mouse Trap	58.62	66.26
2	Male	None	Smart cup holder	50.35	57.73
3	Male	None	Talking Toy	58.01	58.74
4	Male	None	Beeralyzer	56.53	62.07
5	Male	None	The Drink Passer	58.01	56.48
6	Male	None	Face spot	60.07	52.07
7	Male	None	Caroline the Coin Sorter	58.29	60.74
8	Mixed	None	Robot alarm clock	49.08	53.46
9	Mixed	3D design	Robot Arm	63.19	63.11
10	Male	3D design	Alarm Clock car	54.53	56.96
11	Male	3D design	Companion Car	55.56	58.49
12	Male	3D design	Voice activated lock	52.18	56.13
13	Male	3D design	Remote controled car	61.10	67.04
14	Male	Programming	Alarm robot	56.54	62.68
15	Male	Programming	Refresher gadget	56.55	62.11
16	Male	3D design	Smart Car	54.48	58.74
17	Male	3D design	Automated scale	59.64	61.41
18	Male	Programming	Self-orientating solar panel	47.48	51.81

4.3 Contribution of FabLab activities in improving creativity levels

An additional Wilcoxon Signed-rank test was performed to explore the effect of FabLab activities on the improvement of the creativity of the teams. Results showed that a seven-week digital fabrication course that used FabLab facilities and resources to jointly develop tangible artefacts showed statistically significant improvements in team creativity ($Z = -2.765$, $p = .006$).

4.4 Impact of prior experience, design, and gender on grades

A series of non-parametric Kruskal-Wallis H tests were run to analyse the extent to which prior experience in teams (significant differences between three experience groups, none, 3D design and programming) has an influence on their final grades. Results showed that only in electronics grade among the groups with prior experience there was a significant difference ($H(2) = 8.016$, $p = .018$). The mean rank electronics grade was 13.33 for teams with programming experience, 11.88 for groups with no prior experience, and 7.93 for teams with 3D modelling experience. Pairwise tests were carried out for the three pairs of groups. A statistically significant difference was found between the teams with no prior experience and those with 3D modelling experience ($p < 0.05$). Additional Mann-Whitney test results showed that mixed teams (male and female) performed equally to their counterpart (male only) as no significant difference was observed between them in all grades ($p > 0.05$).

4.5 Impact of gender, prior experience, roles in team performance

A series of non-parametric Mann-Whitney tests were used to determine if there are differences between groups. Results revealed that the gender ratio did not affect team member performance, overall team performance, and communication with the team during the course ($p > .05$). Similarly, a series of Kruskal-Wallis revealed similar results for prior experience and the number of roles played by members to build the tangible artefacts ($p > .05$).

4.6 Usefulness of collaborative learning in developing FabLab skills

Students enjoyed working collaboratively using the FabLab machines and tools ($Z = -2.778$, $p < .005$). Students also reported that collaborative learning helped them to significantly improve their 2D modelling skills more than other FabLab skills ($Z = -2.092$, $p = .036$). However, a significant marginal improvement was reported for 3D modelling skills ($Z = -1.825$, $p = .068$) and computer programming ($Z = -1.718$, $p = .086$) after constructing the prototypes.

5 DISCUSSION

5.1 The effect of learning by building tangible artefacts

Working in a team improved the self-assessment of learning activities by building tangible artefacts. That is to say, the digital fabrication activity, with all its characteristics in terms of environment, technology, and specifics, increased the overall acceptance on the level of the team of the learning by building tangible artefacts practices compared to the state before the course. Building tangible artefacts and constructionist learning are recognised as outlining features of digital fabrication education (Milara et al., 2019; Morado et al., 2021; Tomko et al., 2020). Self-recognition of own work and learning by building artefacts as a team was beneficial and can be seen as critical for digital fabrication.

5.2 Creativity

The work in a team in the digital fabrication course improved the creativity of the individual participants. Creativity was not the primary target of the course; however, the students were encouraged to be creative, especially with regard to their ideas for prototypes. Notably, these results are based on objective creativity tests, not on external evaluation of prototype creativity, external evaluation of personal creativity, or self-evaluations of creativity levels. The significant increase in creativity levels can be interpreted in the context of self-recognition with regard to own work and learning. This interpretation might be in terms of fostering creative competence, in line with previous research (Taheri et al., 2020), and creative confidence. Previous studies also employ digital fabrication activities explicitly designed to stimulate creative competence and test creativity with specific visual tests, such as the abreaction test of creativity (Saorín et al., 2017). The current study employs regularly delivered large-scale digital fabrication design course and multifaceted creativity test. Furthermore, the prototyping process and the physical prototype itself might influenced creativity skills. This might be realised through iterations and interactions with the physical prototype (Georgiev and Taura, 2015).

5.3 Prior experience, gender and performance in the course

The prior experience partially affected the overall performance of the teams. Only the electronics prior experience, out of five technical dimensions, 2D design, 3D design, electronics, programming, and use of FabLab tools and machines, influenced the grade, hence, performance in the course. Previous studies pointed out that electronics are among the most challenging digital fabrication processes (Milara et al., 2017). In our case, the previous electronic experience probably contributed to a more elaborate or better-executed electronics design, reducing the challenge of electronics fabrication.

Notably, the different gender compositions of teams do not affect their performance. Existing studies point to gender inequalities in terms of digital fabrication (Campreguer França et al., 2021). However, in our case, the course, delivered as a core part of the computer science bachelor programme, did not exhibit gender differences, possibly due to the fact that students have similar fundamental training.

5.4 Developing FabLab skills

Collaborative learning helped team members to improve their skills in using FabLab machines and tools, 2D modelling skills, and to a lesser extent, 3D modelling and computer programming skills. This indicates that actual work in FabLab is based on teamwork and is essential in the overall context of digital fabrication design education. Collaborative learning of skills for using FabLab machines and tools, along with 2D design is probably easier to execute compared to 3D modelling and programming. The former two skills can be seen as more dependent on the physical and social environments offered by the digital publication space.

5.5 Implications

The results allow for presenting digital fabrication design education recommendations, including interventions and successful practices towards improving the creativity of the outcomes, team performance, and learning of digital fabrication topics. This scaffolding in digital fabrication should emphasise specific needs for design teams with regard to the development of specific skills from the vast array of abilities targeted by digital fabrication. When successful practices of open-ended idea generation and prototyping are targeted, this scaffolding should be tailored per prototyping instance while pursuing the course's learning objectives and learning outcomes.

In addition to recognizing the significance of teamwork in digital fabrication, the larger implications for design education and design practice that emphasize design creativity and innovation include recognizing the significance of teamwork in digital fabrication.

5.6 Limitations and future work

The study used a sample of a single digital fabrication design education course. Furthermore, results might vary depending on the location where the study is conducted. Future studies should examine teamwork activity in FabLabs on a larger scale and in longer time periods. Team dynamics also warrants further research in this educational environment. Similar intervention programs should be tested using different initial design conditions and requirements.

6 CONCLUSION

A case study based on a formal digital fabrication design course was used to examine the effects of teamwork on self-perceived creativity, self-assessment of learning activities, and the skills for the production of design prototypes. The main findings at the team level suggest that digital fabrication design education increases creativity and self-assessment of learning activities by building tangible artefacts. Prototypes that involve 3D design contribute to a higher performance of the teams and their produced outcomes.

Intervention programs in design education were found to support the development of creativity and self-assessment of learning activities, provided by these interventions built upon the generally accepted scaffolding in the context of digital fabrication education. This scaffolding should focus on specific requirements for design teams to develop particular skills among the wide range of skills targeted in digital fabrication. Specifically, those skills needed to deal with the design and digital fabrication of 3D objects, such as spatial abilities required for the use of 3D software. Should the digital fabrication context of design education allow for open-ended idea generation and prototyping, this scaffolding should be customised per prototyping case while pursuing the course learning goals and learning outcomes. The broader implications for design education and design practice targeting design creativity and innovation include the recognition of the importance of teamwork in digital fabrication. Collaboratively working in teams to build tangible artefacts contributes to creativity and the development of specific digital fabrication skills irrespective of gender and actual roles.

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