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Perceptions of Digital Fabrication in Design Education: Skills, Confidence, Motivation, and Enjoyment

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Abstract

Education in digital fabrication design is characterized by a dynamic project-based learning environment, where ideas are materialized into prototypes. This environment affects the way design activities are conducted, the content that is learned, and the types of outcomes. However, existing research into digital fabrication curricula focuses on the outcomes produced by students. Not much is known about students' thoughts and beliefs regarding their learning. To gain insight into this learning experience, we investigated the self-perceptions of students in a digital fabrication course. The course targets first-year university students and was delivered in a hybrid online and in-person mode. It is designed to prepare students to create simple interactive physical prototypes using mechanical, electrical, and software components. In this study we delivered two surveys, one at the beginning of the course and the other at the end of the course. Four psychological measures were investigated, including self-perceived skills, confidence, motivation, and enjoyment, each represented by five technological dimensions. These five dimensions were 2D and 3D design, electronics, programming, and the use of tools and devices in digital fabrication. We found that while students' skills and confidence in performing a variety of digital fabrication activities significantly increased, motivation and enjoyment were unchanged or, in some cases decreased. Moreover, a positive correlation was observed between perceived skills and performance in the course. Self-reported skills and confidence were related at the end of the course, as were enjoyment and motivation. The results also showed that enjoyment and motivation were not associated with course performance. Intervention programs in higher education aimed at digital fabrication courses in design may benefit from considering the findings of the study. Important aspects to consider in future learning interventions are various ways to increase course motivation without sacrificing skill development.

Keywords: design education, design cognition, prototyping, FabLab, digital fabrication

1 Introduction

Design education in the context of digital fabrication is characterized by a project-based learning environment (Blikstein, 2013). Because the idea of digital fabrication laboratories (i.e., FabLabs) is to engage participants in the concretization of ideas into tangible products (Pitkänen et al., 2019), education in the digital fabrication context involves a number of learning by doing (Milara et al., 2019) and constructionist approaches (Blikstein, 2013; Iwata et al., 2020).

Such an environment requires an exploratory and non-directed process of materializing ideas into products, and every case might have specific characteristics. Given the wide range of methods employed in digital fabrication, pedagogical attempts must extensively cover many of the digital fabrication approaches (e.g., Fab Academy, see Soomro & Georgiev, 2020; Ylioja et al., 2019) or rely on an elective curriculum. The latter can be aided by an instructor case-by-case feedback on single projects with the goal of developing appropriate knowledge and skills for particular ideas and materializing them in a product. Digital fabrication and FabLabs as a platform for it are well established (Lin et al., 2020; Schad & Jones, 2020). Typical tools employed in digital fabrication are 2D fabrication tools (e.g., laser engravers and cutters, and vinyl cutters), 3D fabrication tools (e.g., 3D printers), electronics design tools (e.g., electronics workbenches), programming tools (e.g., computer workstations and microcontrollers), and others (Ylioja et al., 2019).

Most related studies have focused on the activities carried out in FabLabs (e.g., Blikstein, 2013; Togou et al., 2019). However, only a few of them have followed up with students on their experiences and perceptions, reflecting what they have learned in a course. Therefore, there is a need to understand this issue further in order to propose intervention programs to improve design education in the digital fabrication context. Although digital fabrication courses share some similarities with the design studio (Celani, 2012; Casakin & Georgiev, 2021), due to its specificity (Mostert-van der Sar et al., 2013; Soomro et al., 2021b), the development of curriculum-based digital fabrication has remained a great challenge.

While this might not be considered unique compared to the traditional design studio or workshop approaches, FabLabs offer advanced tools through a unique and well organized space that is accessible to a variety of stakeholders, independently of their design background (Lin et al., 2020; Schad & Jones, 2020; Soomro et al., 2021b; Soomro et al., 2022). FabLabs are open environments where students might meet people from multiple backgrounds working in the same space (Soomro et al., 2022), and be exposed to different ideas and knowledge fields, further opening the possibility of creating unexpected synergies and creativity. In addition, sharing knowledge is essential in the FabLab network (Soomro et al., 2021a).

This relatively new educational environment has not been explored, especially from the perspective of design studio. In this regard, a common need in studios is the production of design mockups as a representation of reality.

Some of the main contributions of FabLabs in terms of learning are regarding (1) aids to the learning process and workflow, (2) feasibility testing and understanding, (3) a practical orientation to learning, (4) the combination and synergy of multiple technologies, (5) aid for multiple iterations of prototypes, (6) aid for moving from idea to implementation, and (7) exposure to knowledge and processes from other different fields (see Katterfeldt et al., 2015; Soomro et al., 2021b). Moreover, maker-based pedagogy is theoretically and technologically oriented (Cohen et al., 2016). Therefore, FabLab is viewed as an educational space in which - different learning activities incorporate various technological aspects. In contrast to information technology, such approach requires the know-how of instructors for applying a broad range of technological tools (Ku et al., 2021). Currently, educational environments are not very technologically oriented, which also affects the learning process. For example, students suffer from problems to materialize their design ideas, especially when they need to combine multiple technologies.

In this study, we examined a pedagogical approach employed in a higher education digital fabrication course. The approach involves learning-by-doing using a design studio method. Students develop their projects by working in teams, and they receive regular feedback from their tutors during the sessions. They are free to select a project topic, considering basic requirements compatible with digital fabrication, and incorporating at least one sensor and one actuator. Moreover, students work at their own pace, which requires some self-organization compared to other approaches in digital fabrication contexts, such as STEM education (Togou et al., 2019) or youth education (Hartikainen et al., 2021). Based on this approach, the aim of this study was to explore the factors that may contribute to enhancing achievement in digital fabrication by considering psychological factors and technological aspects of digital fabrication.

2 Previous work

2.1 Digital fabrication pedagogy

Digital fabrication pedagogy can vary depending on the time of the educational activity, educational context, and target audience. The time utilized in the framework of curriculum-based and non-curriculum-based activities in digital fabrication ranges from short thematic workshops (Georgiev, 2019; Hielscher & Smith, 2014) to structured programs spanning from six months to two years (e.g., Ylioja et al., 2019). Consequently, curriculum-based courses are typically conducted for several weeks or months (Mostert-van der Sar et al., 2013; Soomro et al., 2021b). In terms of motivation, participation in curriculum-based and non-curriculum-based digital fabrication courses can fluctuate significantly. Short-term activities attract students who are motivated by intrinsic elements, such as curiosity and specific needs. In contrast, long-term activities, which are typically part of formal education (Georgiev & Milara, 2018; Hjorth et al., 2016; Ylioja et al., 2019), are characterized by extrinsic motivational factors, such as graduation or a promotion.

Moreover, the target audience of digital fabrication education can range from pre to high school levels (Iivari et al., 2016; Iwata et al., 2020), including educational experts (Milara et al., 2020) and up to the university level (Mostert-van der Sar et al., 2013; Soomro et al., 2021b). Independent of these are activities targeting non-formal education (Hartikainen et al., 2021). Considering the broad spectrum of tools and activities involved in digital fabrication, the level of prior experience with regard to specific tools and techniques can vary considerably. Taking into account issues such as the period of time dedicated to the activity and the audience involved, the content of a digital fabrication curriculum is a matter of balance between the variety of techniques taught and how well they are learned (Mostert-van der Sar et al., 2013; Smith et al., 2015).

2.2 Digital fabrication as design education

Digital fabrication can have an impact on the way design is taught in higher education (Mostert-van der Sar et al., 2013; Page et al., 2016). This environment affects the way design activities are conducted (e.g., Blikstein, 2013), the content that is learned (e.g., Smith et al., 2015), and the types of outcomes (e.g., Soomro & Georgiev, 2020). As a result, both process and outcome are affected by this tool in design education. We elaborate on these issues in the following.

2.2.1 *Aspects for consideration*

There are key parameters for understanding and evaluating the performance of students in curriculum-based digital fabrication teaching. The educational model based on the use of digital fabrication in design can focus on intrinsic and extrinsic factors. Extrinsic factors are concerned with the environment and social issues. Intrinsic factors deal with psychological aspects experienced during the design activity, such as skills, motivation, confidence, and enjoyment.

Digital fabrication knowledge involves learning different production methods, exploring the specific capabilities of digital fabrication tools or devices, searching for new concepts, and using interdisciplinary knowledge (Celani, 2012). In this context, digital fabrication technological skills are interrelated with different technologies or design approaches employed in FabLab environments (also known as makerspaces).

Confidence is essential in the overall aspirations of digital fabrication activity and its long-term effects, and digital fabrication is instrumental for building the confidence necessary to use the tools and approaches in FabLabs (Moore et al., 2021).

Motivation is another vital driver that predominantly affects non-curriculum digital fabrication education contexts (Iivari et al., 2016; Smith et al., 2015). Another core element in digital fabrication is the anticipation of what the participants want and how they are going to achieve it. In this regard, enjoyment and fun are essential factors contributing to the process and the outcome produced in a digital fabrication environment (Iivari et al., 2016).

2.2.2 *Psychological dimensions*

A positive psychological attitude toward making and creating is essential for the success of digital fabrication (Andersen & Pitkänen, 2019; Smith et al., 2015). Differences before and after the digital fabrication activity (which were considered in this study in a course context) are helpful for evaluating changes in the self-perception of students, including psychological dimensions. Our study explored students' perceptions of four different psychological dimensions, as proposed by Milara and colleagues (2017), that should be considered when working in environments using digital fabrication. These dimensions are acquired skills, confidence, motivation, and enjoyment, all of which are considered within the realization of a digital fabrication activity as perceived by the students.

2.2.3 *Technological dimensions*

The digital fabrication curriculum covers standard technologies supported by FabLabs and makerspaces (Blikstein & Krannich, 2013; Hielscher & Smith, 2014). The technological dimensions analyzed in this study are partly grounded in the study by Milara and colleagues (2017), which includes 2D design, 3D design, electronics, programming, and operation of the tools and devices supporting digital fabrication. These dimensions generally map with the content and learning outcomes of a standard digital fabrication curriculum (Iwata et al., 2020; Mostert-van der Sar et al., 2013).

2.2.4 *Research goals*

Most research on digital fabrication curricula focuses on the outcomes produced by students. However, little is known about the thoughts and beliefs of students regarding their learning. A research gap exists in the literature about design education in FabLab environments, particularly regarding different fabrication processes and also considering the psychological and technological dimensions and students' self-perception of these factors. Therefore, this study aimed to (1) explore how factors such as skills, confidence, motivation, and enjoyment are perceived by students before and after completing a FabLab course, and (2) examine the relationships between students' self-perceptions and their achievements in a FabLab course. In the next sections, we present the context in which the empirical study was carried out, followed by the results, discussion of findings, conclusions, and implications for FabLab design education.

3 Research methodology

This section offers a description of the educational context, participants, and data collection tools used in this study. A mixed-methods approach was chosen to triangulate the data.

3.1 Context of the study

The target population for this study was first-year students who enrolled in a 5-ECTS (1 ECTS equals 27 hours of effective work) digital fabrication course offered at a university in Europe and delivered via a hybrid mode. With such characteristics, the course is typical of the curriculum in terms of requirements, intensity, duration, and load. The language of instruction was English.

3.2 Course and student population

The study took place in the spring of 2021. The BSc course was aimed at helping develop design knowledge and skills and lasted seven weeks. Although it is part of the computer science bachelor's degree program, it was open to all students at the university. As such, it generally attracts students from a wide range of backgrounds and disciplines. It is designed to prepare students to create interactive physical prototypes using mechanical, electrical, and software components. The primary activities are designing and building mechanical parts and electronics and implementing software in a microcontroller.

The course is divided into two parts: a set of six direct-instruction lectures followed by guided project work. During the first two weeks, the course uses six lectures to present an introduction to the main aspects of design and digital fabrication, including the presentation of FabLab, physical object design, electronics design, embedded programming, 3D modeling and printing, and 2D design. The lectures were taught entirely online. During the following five weeks, students worked in teams composed of three to four class members, who were encouraged to generate and materialize their own ideas by designing and building a physical device (gadget) that interacts with its surroundings.

The design task given to the students was to prototype a functioning device. The device must meet the following requirements: (1) it must be composed primarily of parts (mechanical and electronic) that have been designed and manufactured in FabLab; (2) it must have moving parts that can be controlled by software; and (3) it must include at least one sensor and one actuator, and the software must react in some way to the sensor's readings. In contrast to the online delivery, the actual making of the projects was done in the large FabLab of the university on a dedicated schedule.

During the seven weeks of the course, teachers met with teams for weekly feedback sessions. Instructors provided input on design and technical problems with implementing the teams' ideas within the course time constraints (Soomro et al., 2021a). There was no schedule set for the development of the project, so students could work at their own pace. The course included mid-term presentations in which all teams presented their progress to teachers and other students taking part in the course. The class ended with a team project presentation about the prototype of the interactive device and the documentation concerned with the design and construction of the device. The documentation included detailed information about the idea generation process and the selected concept, a weekly diary, and a summary of the primary outcomes of the project, including a reflection on their own learnings. Figure 1 shows examples of the outcomes produced in the course.

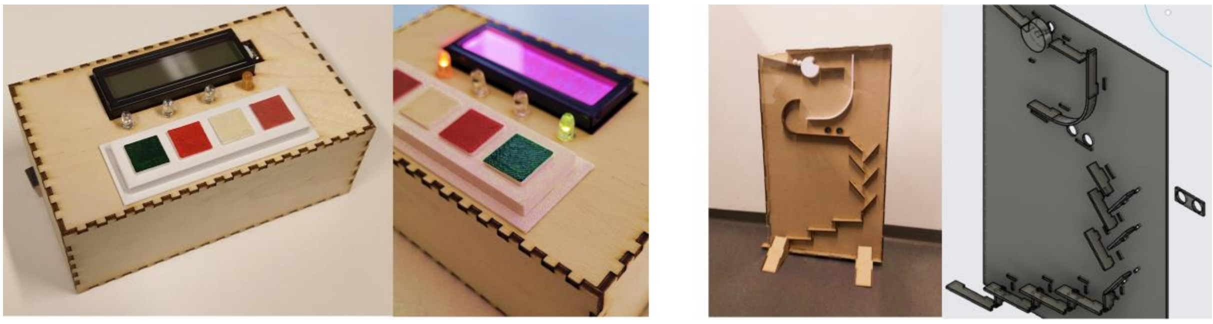

Figure 1. Two example outcomes of the course. Left: A memory game project where a randomly generated sequence displayed by the LEDs must be repeated using the buttons on the bottom. Right: A marble run project where marbles roll down the track until they reach the finish line.

3.3 Data collection instruments

3.3.1 Survey

Two surveys were used to collect the data. The first was delivered during the first week of the course. Students' demographic information and four psychological measures were collected, including perceived skills, confidence, motivation, and enjoyment, all as represented by five technological dimensions (2D and 3D design, electronics, programming, and use of tools and devices in digital fabrication). The second survey was delivered at the end of the course, after the students had presented the prototypes they produced as a team. In this survey, information was collected about how students experienced the course, particularly with regard to the extent to which they learned 2D and 3D design instruments, electronics, programming, and digital fabrication tools, in relation to the four previously mentioned psychological measures. The surveys were completed using a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). For example, the items regarding the students' confidence after the course included the following: "After the course, you feel confident utilizing 2D modelling software"; "After the course, you feel confident utilizing 3D modelling tools"; "After the course, you feel confident prototyping with electronics"; "After the course, you feel confident programming"; and "After the course, you feel confident utilizing the tools and machines at the FabLab." The questions about the perception of skills, motivation, and enjoyment were formulated to correspond with the questions about confidence. The formulation of the questions in the two questionnaires differed only in the use of the words "before" and "after." Students were informed that the completion of the surveys was not compulsory and their answers would not affect their grades in any manner.

3.3.2 Performance in the course

In addition to the survey, student performance in the course was assessed at the course's end using a scale ranging from 1 (low) to 5 (high). Student performance was evaluated individually by the teacher based on the quality of the final project and each student's contribution to the team during the course. The assessment was based on the functionality, complexity, and integration of the prototype and the quality of its related documentation, including the different stages of the ideation process. Performance was evaluated as high when all requirements for functionality of the prototype and content of the documentation were met.

4 Results

Survey scales were validated by computing Cronbach's alpha, and the data were analyzed using Wilcoxon signed-rank tests and Pearson's correlation. All statistical analyses were performed using SPSS 26 (IBM Corp., Armonk, NYork, USA). The findings are reported in this section.

4.1 Student backgrounds and demographics

We used two questionnaires to collect the data. They consisted of 20 items, and were administered in short, designated timeframes at the beginning and end of the course. Students were informed that the completion of the survey questionnaires was not compulsory and their responses would not affect their grades in any manner. Of the 74 students participating in the course, only 39% gave their consent to take part in the study, and completed the two questionnaires. Of these, 21 (72%) were males and 8 (28%) females. The average course performance of the group that completed both questionnaires and the group that did not was approximately equal. Therefore, it is reasonable to say that the study sample collectively represents the whole class.

4.2 Validity of the questionnaires

We validated our survey questions by computing Cronbach's alpha (α) for the two questionnaires (0.734 [before] $< \alpha <$ 0.841 [after]), which indicated a high level of reliability in the metric (Tavakol & Dennick, 2011).

4.3 Usefulness of the digital fabrication course

The difference scores were approximately symmetrically distributed, as assessed by histograms with superimposed normal curves. Wilcoxon signed-rank tests showed that a 7-week course on digital fabrication in which a concrete prototype was completed elicited a statistically significant improvement in students' perceived skills and confidence levels in all five technological dimensions, except for motivation and enjoyment. Table 1 shows a summary of these results.

Table 1. Differences in self-reported psychological and technological dimensions before and after the course (Notes: ** $p < .01$, results denoted with 'p' are positive ranks, the remaining are negative ranks, Z standardized test statistic, A. Sig. Asymptotic Significance).

Dimensions		2D design	3D design	Electronics	Programming	Utilizing tools/devices
Perceived skills	Z	-4.10**	-4.39**	-4.30**	-3.77**	-4.51**
	A. Sig.	.000	.000	.000	.000	.000
Confidence	Z	-3.32**	-3.82**	-4.20**	-3.50**	-3.95**
	A. Sig.	.000	.000	.000	.000	.000
Motivation	Z	-.27	-.74p	-.48	-.94p	-.89
	A. Sig.	.790	.457	.632	.346	.376
Enjoyment	Z	-.96	-.44	-.22p	-1.51	-.50
	A. Sig.	.335	.660	.830	.132	.617

4.4 Self-assessment of psychological dimensions and course performance

We performed Pearson's correlation to understand the relationship between all four psychological measures and the final grades obtained for a student's performance in the digital fabrication course. In this analysis, the individual technological dimensions of perceived skills, confidence, motivation, and enjoyment were taken together as overall levels of each psychological dimension. The results (see Table 2) showed that there was a marginally significant correlation between the students' confidence levels and perceived skill levels ($r = .361$; $p < .1$), as well as their motivation and enjoyment levels ($r = .366$; $p < .1$), at the beginning of the course.

However, after completing the course, a highly significant correlation was found between students' perceived skills levels and confidence levels ($r = .658$; $p < .001$), as well as between motivation levels and enjoyment levels ($r = .793$; $p < .001$). Significant correlation was also found for perceived skills and the grade received ($r = .394$; $p < .05$). After the course, the perceived skill levels were highly correlated with confidence levels ($r = .658$; $p < .001$) and enjoyment levels ($r = .490$; $p < .05$). Perceived skill levels correlated with the grade received ($r = .394$; $p < .05$) and also showed a tendency toward correlation with motivation ($r = .347$; $p < .1$). At that time, enjoyment highly correlated with motivation levels and with confidence levels and showed a tendency toward correlation with grade ($r = .338$; $p < .1$). Table 3 shows the correlation analysis for perceived skills, confidence, motivation, and enjoyment experienced after the course.

Table 2. Correlation analysis of overall self-reported psychological dimensions before the course with the final grade received (Notes: # p < .1).

Dimensions		Grade	Perceived skill levels	Confidence levels	Motivation levels	Enjoyment levels
Grade	Pearson	1	.162	.042	-.002	.093
	Sig.		.400	.827	.990	.631
Perceived skills levels	Pearson	.162	1	.361	.143	-.056
	Sig.	.400		.054#	.458	.775
Confidence levels	Pearson	.042	.361	1	-.046	.028
	Sig.	.827	.054#		.814	.887
Motivation levels	Pearson	-.002	.143	-.046	1	.366
	Sig.	.990	.458	.814		.051#
Enjoyment levels	Pearson	.093	-.056	.028	.366	1
	Sig.	.631	.775	.887	.051#	

Table 3. Correlation analysis of overall self-reported psychological dimensions after the course with the final grade received (Notes: ** p < .01, * p < .05, # p < .1).

Dimensions		Grade	Perceived skill levels	Confidence levels	Motivation levels	Enjoyment levels
Grade	Pearson	1	.394*	.215	.171	.338#
	Sig.		.035	.262	.376	.073
Perceived skills levels	Pearson	.394*	1	.658**	.347#	.490**
	Sig.	.035		.000	.065	.007
Confidence levels	Pearson	.215	.658**	1	.116	.454*
	Sig.	.262	.000		.548	.013
Motivation levels	Pearson	.171	.347#	.116	1	.793**
	Sig.	.376	.065	.548		.000
Enjoyment levels	Pearson	.338#	.490**	.454*	.793**	1
	Sig.	.073	.007	.013	.000	

5 Discussion

5.1 Development of psychological aspects: perceived skills, confidence, motivation and enjoyment

Significant differences were observed with regard to perceived skills and confidence, indicating that the course contributed to an increase in students' perceived skills (Table 1). It also aided with gaining confidence to successfully perform in all five technical categories of digital fabrication activities, including 2D design, 3D design, electronics, programming, and the use of tools and devices in digital fabrication. These suggest that on the basis of the digital fabrication curriculum, students perceived an improvement in their skills and gained the confidence needed to employ these skills within the framework of the course.

No significant differences were observed between motivation before and after the course (see Table 1). Similarly, no significant differences were observed for enjoyment when comparing students' views before and after the course (see Table 1). It should also be noted that, in a small number of individual cases, a decline in motivation and enjoyment was observed. This could be interpreted as the course content being challenging, which might not align with some students' initial expectations.

5.2 Self-reported effects and overall performance

Before the course, marginally significant relationships were found between perceived skills and confidence, as well as between enjoyment and motivation (Table 2). These might imply that students had to believe in their own skills if they wanted to enroll in a practically oriented course such as digital fabrication. Their self-confidence may decrease if they had not believed in their skills. Notably, motivation and enjoyment were marginally correlated before the course (see Table 2); however, they were highly correlated after the course (see Table 3). At the beginning of the course, the association between enjoyment and motivation to take the course suggested strong expectations for the course to be enjoyable. At the end of the course, the relationship between enjoyment and motivation suggested that intrinsically motivated students led to deeper engagement with the course and, therefore, learning.

At the end of the course, confidence was seen to correlate with perceived skills and motivation was correlated with enjoyment (Table 3). Furthermore, confidence contributed to increasing enjoyment. Notably, enjoyment correlated with perceived skills, but the connection between motivation and perceived skills was marginal. This might suggest that participants enjoyed the activities carried out during the course even if they were not highly motivated.

The strong correlation between grades and perceived skills indicated that performance, above all, was assessed as an outcome of the skills developed in the course (Table 3). The grade can be seen as one possible measure of knowledge that students generated during the course. The comparison between the grade and perceived skills level indicates differences of internal and external evaluation of knowledge. The perceived skills are in line with the expected outcome of the course. Hence, what the students perceived was similar to what teachers perceived. Although motivation correlated with enjoyment, neither contributed to the grade obtained. The results also showed that enjoyment and motivation were not strongly associated with grades. Possibly, students understood that these two factors were not critical for enhancing their learning, and if they want to succeed, they have to instead invest in the development of their skills.

5.3 Implications for a digital fabrication course

Intervention programs in higher education institutions aimed at digital fabrication courses in design may benefit from considering the above findings. If a goal is to deal with technical aspects, such programs should provide the necessary scaffolding to ensure that students will gain specific knowledge and expertise related to digital fabrication skills. This includes developing skills in different technological dimensions, 2D design, the use of tools, potentially challenging electronics, 3D design, and programming. Although the psychological dimensions explored in this study were not the primary goal of the course, they can potentially support technological aspects as well. For example, appropriate avenues had to be found to enhance course enjoyment, but not necessarily at the expense of skill development. How to enhance motivation is another important aspect to be considered in future interventions to enhance learning. It is possible that due to COVID-19 restrictions, student motivation could have been negatively affected by the online delivery of the lectures. Based on these findings, implications are foreseen for the interaction of psychological dimensions and digital fabrication prototyping, especially while dealing with product development in small teams and startups.

5.4 Limitations

One limitation of the study is that students worked in groups on their projects, and teamwork, team dynamics, and team management, which were not explicitly analyzed with regard to the potential lack of balance in the individual contribution to the team. Another limitation is that the results are not explicitly analyzed from the perspective of the actual prototypes, the outcome of the design activity. The study focused on only one instance of the course. Additionally, external factors such as the physical environment were not examined in detail, and it is therefore suggested to be considered in future work.

6 Conclusions

This study focused on a pedagogical approach proposed for a digital fabrication course in higher education. It was based on students' self-assessment of the psychological dimensions of skills, confidence, motivation, and enjoyment before and after the course. The main findings were that while perceived skills and confidence in performing the various digital fabrication activities increased, no significant differences were observed for motivation and enjoyment. Skill development largely contributed to the enhanced performance of the students during the course. It was related to confidence and enjoyment, but less related to motivation. Enjoyment, on the other hand, was also connected to skills, confidence, and motivation.

Design education intervention programs in such a context should provide the necessary scaffolding for students to learn specific digital fabrication skills. The psychological dimensions may help support technological aspects. Essential aspects to consider in future learning interventions are various ways to increase course motivation and enjoyment without sacrificing skill development. Based on the current findings, we plan to extend the current approach and implement it in the next delivery of the digital fabrication course.

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