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Analysis of the Factorial Structure of Graphic Creativity of Engineering Students through Digital Manufacturing Techniques*

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The development of creativity must be an axis in engineering training, and maker spaces are presented as ideal environment to achieve it. Specifically, in engineering degrees, creativity is considered among the generic competences included in the Tuning project and in the Engineering White Papers that regulate the university degrees of engineer in Spain. The measurement of creativity has been and is a focus of interest in literature, as well as to find out what factors it is divided into. Above all, graphic creativity is one of the factors of creativity, essential for engineers. The objective of this paper is to explore how digital manufacturing experiences influence the different variables of graphic creativity and to explore the factorial structure before and after them. For this, two maker workshops with different approach based on creativity theories have been carried out at the University of La Laguna during the academic year 2016/17. The sample consists of 100 engineering students from two different degrees. Wilcoxon signed-rank test, Kruskal-Wallis and exploratory factor analysis were carried out. Both maker workshops have increased graphic creativity with statistical significance in 36.96 ($p = 0.002$) and 37.68 ($p > 0.001$) points respectively, which were measured with TAEC test. Meanwhile, the creativity of students who did not attend to any workshop increased by less than two points without statistical significance ($p = 0.875$). The distribution of variables and the percentage of explanation of the tool has varied depending on the level of graphic creativity (pre-test and post-test). Moreover, relations between maker workshop design and the development of different variables of graphic creativity are discussed.

Keywords: maker space; creativity; engineering graphics

1. Introduction

Engineers face challenges that require to generate different design proposals in order to be addressed. Thus, companies have sought for creative and innovative professionals [1]. Therefore, the development of creativity should be an axis in engineering training [2], which seems to be related to project-based learning [3]. Moreover, maker space tasks such as creation, design and manufacture of three-dimensional scale models are presented as ideal elements to achieve this purpose [4].

At the University of La Laguna, Engineering Graphics professors launched an innovation project that implemented the use of low-cost 3D printers as a learning tool in 2012. This experience involved undergraduate students in the process of manufacturing their own design for their first time, which let them to test the project through digital manufactured scale models. This experience made available the first low cost 3D printer for the university community.

Advanced in 2014, the digital design and manufacturing laboratory (Fab Lab ULL) was created, which meant one step forward in the incorporation of maker spaces in educational processes. Consequently, Fab Lab ULL has supported both professional (i.e. the manufacture of a high-detail model of a spatial instrument belonging to the Solar Orbiter mission developed by the European Space Agency [5]) and educational works (bachelor final projects, master theses and doctoral theses) (see Fig. 1). Among these engineering projects, the design and prototyping of a filament extruder for 3D printers, the scale replica of the hotel project in the old lighthouse in Anaga (Tenerife), and the design of workshops to develop creativity stand out. Besides, some authors have previously related Fab Lab experiences with creativity [6–8].

This paper focuses on the workshops that have been conducted with engineering students in order to bring maker space benefits to the development of creativity. These maker experiences are discussed to deepen the factorial structure of engineer graphic creativity. The importance of this study lies in the need to know how the variables of graphic creativity are structured and thus be able to establish the basis for working on their training. Likewise, the experience of improvement through two maker space workshops with different approaches allows us to study whether the variables change in relation to the design of the maker experience. Relations between

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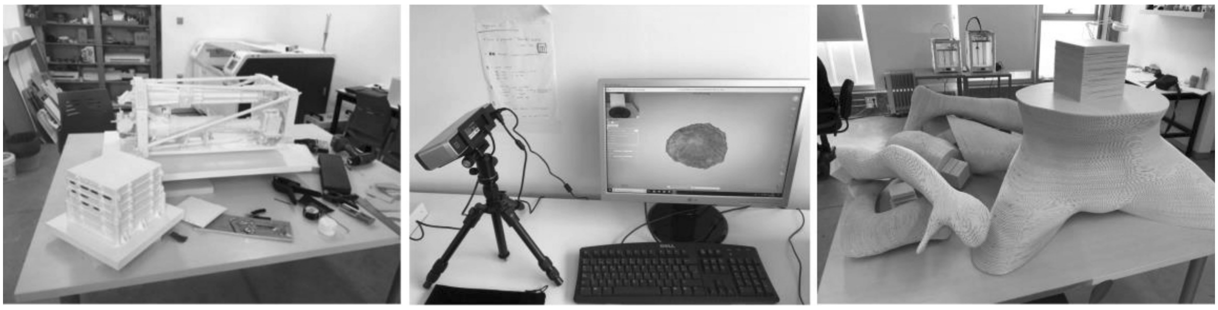

Fig. 1. Fab Lab ULL professional works: High-detail model of a spatial instrument. Photogrammetry applied for 3D modelling. Body-scan and creation of a full-scale sculpture.

workshop design approaches and the development of different variables of this competence are provided.

2. Background

Maker space nature of transversally turns them into a strategic educational factor in which science, technology and humanities operate in an interdisciplinary way. This context overcome the traditional separation between these areas [9], which design and engineering educators recognize as essential for their students [10]. Besides, Wilczynski [11] affirms that the arrival of maker spaces to university implies a great development in engineering degrees. This effect is related to the use of digitally controlled machines to build, which students use to meet demanded challenges [12] (i.e. cutting-edge technologies and 3D printers), a wide variety of products and where knowledge is exchanged among its members.

Activities performed in these environments are usually designed under project-based learning approaches [13] which allow the promotion of communication, creativity, empathy, time management or leadership. In addition, authors have revealed that when engineering students face real problems in makerspaces they propose creative solutions and develop viable prototypes [14]. These transversal abilities, also called soft skills, are increasingly demanded by large companies [15]. Therefore, in these environments, learning is more active, there is a greater relationship between teachers and students and they generate contact with the professional world [16]. This maker method is related to the design thinking method which has emerged as a key area where students develop creative [17].

Creativity is specifically considered among the generic competences included in the Tuning project and in the Engineering White Papers that regulate the university degrees of engineers in Spain. Therefore, it is consistent that the evaluation of creativity in engineering degrees has been pointed out as a must [18–21].

Thus, different strategies have demonstrated to improve creativity such as the use of CAD programs [22], to a greater extent when the software environment is three-dimensional [23] or through the use of digital manufacturing techniques and 3D printing [4]. However, they do not provide information on how training has altered creativity in relation to the design of the teaching method, nor on how the factorial structure of creativity behaves.

In recent decades, literature has focused on how to measure creativity, since it is essential to design methods that improve it. For this reason, traditional measurement tools have been questioned [24] and dynamic tools have been proposed [25]. Likewise, proposals have emerged to measure the level of creativity of the products, which has shown a direct correlation with the creative capacity of the creator [26]. Among others, this ability has already shown relation to other skills that engineers need such as spatial ability [27], critical thinking, innovation capacity, problem solving [28] and the generation of different solutions using visual and tangible tools [29].

The relationships of the variables that display creativity could be explored through the statistical technique factor analysis. Its purpose is to reduce the number of observed variables to a smaller number of non-observed variables called factors. Nogueira, Almeida and Lima [30] applied this technique on creativity, which resulted in a two-factor structure: Innovativeness and Adaptiveness. Their model suggested the need for conventional and non-conventional thinking for the creative processes. Furthermore, one of the factors of creativity is graphic creativity, which is essential for the teaching processes of engineering graphics, since traditionally, their teaching has focused on the universalization of drawings and the existence of a single solution, a concept contrary to creativity.

Despite the fact that engineering graphics professors have begun to adapt their traditional teaching methodologies to more active ones [31] and the inclusion of ICT methodologies [32, 33], it is essential to share didactic proposals for engineering training. Therefore, from a digital manufacturing environment in higher education, two maker workshop experiences are presented as source of information to explore the relationships of the variables of graphic creativity and its factorial structure.

3. Methods and Materials

This research was conducted under a quasi-experimental exploratory design in order to inquire whether engineering student graphic creativity (GC) could be improved through maker experiences, and whether the level of GC (before and after training) present factorial structure differences. For this purpose, two maker workshops were designed and performed with engineering undergraduate students.

Descriptive analyses of the mean are indicated on the global results and then individually for each variable. In addition, the mean values of the two groups that have made a workshop are compared. Kolmogorov-Smirnov test was applied in order to evaluate if the sample corresponds to a normal distribution. Consequently, the Wilcoxon test was conducted to find out if there are significant differences between the creativity before and after the workshops. Kruskal-Wallis test is applied to know if the results of creativity are statistically related with dependence to the participation or not in the workshops. Finally, factorial structure of creativity, for pre-test (all the students) and post-test results (students that have carried out any workshop) is analysed through the method of principal components of exploratory factor analysis.

Despite the use of a validated measuring instrument (TAEC), tests have been carried out to indicate the validity of its application in the context of this investigation. Reliability is calculated through Cronbach's alpha and validity through construct analysis with the Exploratory Factor Analysis test.

In addition, to mitigate the influence of external variables to the study, and to improve the validity of the results, the two experimental groups with different maker trainings have been compared with the group of students who have not done the experience, in order to isolate the possibility that the full-time training in the regular engineering subjects does not affect the graphic creativity improvement.

3.1 Sample

The workshops were held during the academic year 2016/17 with 100 students from two engineering degrees from the University of La Laguna. The first group consists of 31 first year students of the Degree in Agricultural Engineering, of which 19 made the workshop Stella 3D Tangible (Workshop I). The second group consists of 69 first year students of the Degree in Computer Science, of which 57 conducted a workshop on the manufacture of a terrain scale model (Workshop II). The sample consists of students with a similar profile. They are all first-year (same age) engineering students (in Spain, Computer Science is an engineering degree) and take the Engineering Graphics course as the only graphic subject. For this, the 24 students that have not attended to any workshop are considered as a control group in this research.

3.2 Measurement Tool & Variables

Many measurement instruments have focused in the field of creativity (Test Torrance, Test Guildford, Test CREA, etc.). However, most of these tools use questions to evaluate creativity [4]. For this study, the Test Abreaction for Evaluate Creativity [34] (TAEC) has been chosen, since it is an inductive graphic test of figure completion. Therefore, it is very suitable for the context of Engineering Graphics. The test has no specific instructions (no limits are described) and can be used by any teacher without previous knowledge of the subject, which does not generate difficulties in the student's behavior and, therefore, gives full freedom in the way it is used.

Graphic creativity was measured before and after conducting the workshop in each degree, both to the control experimental groups. TAEC consists of twelve figures of diversity of positions and forms. Once the student makes his drawings or global composition, the characteristics of abreaction, originality, elaboration, fantasy, connectivity, imaginative scope, figurative expansion, expressive richness and graphic ability are analysed. Following, a brief description of each variable is presented:

- Abreaction: the resistance of a person to the natural tendency to close the openings of a drawing.
- Originality: the ability to give solutions that do not follow a stereotype according to the shape of the figure, provides different solutions to the rest of the simple.
- Elaboration: the level of detail of the drawings.
- Fantasy: the representation of something that does not exist. People with little imagination tend to draw familiar objects, while individuals with more fantasy draw objects that do not exist in real life.
- Connectivity: the fact that a drawing connects several of the 12 figures that are arranged in the test. The tendency is to make a unique composition with each one of the figures.

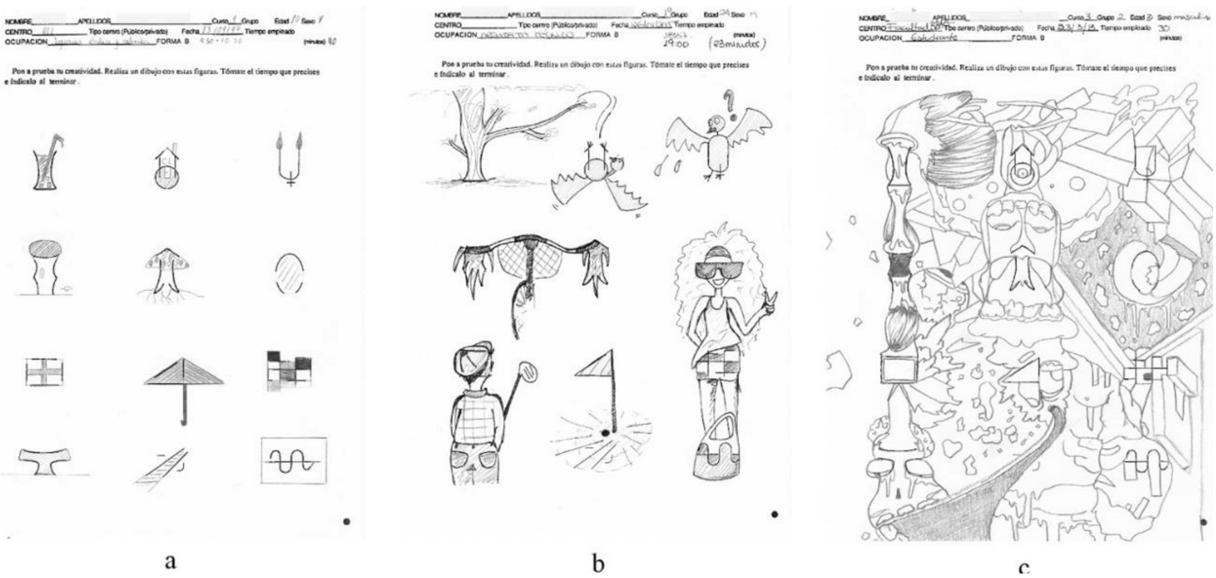

Fig. 2. TAEC examples of students from the University of La Laguna.

- Imaginative scope: the role of each given figure within the drawn object. If the figure is a main element of the composition, the person will have a less imaginative scope.
- Figurative expansion: the space occupied by the drawing. It is measured with a template in which each figure is bordered with given dimensions. The figurative expansion responds to the tendency of the person to face risks and exceed the limits of the initial figure.
- Expressive richness: the extent to which the drawing represents static or moving objects, or if they are made with perspective or colour.
- Graphic ability: the following elements of the drawing are valued: coordinated movements, firmness in the stroke, safety of movements, speed and precision, proportion and mastery of certain techniques such as perspective and shading.

TAEC can be evaluated by two criteria, one global and the other analytical. On the one hand, a global estimation of the test allows placing the subject at a low, medium or high level in each of the variables. For its part, the analytical assessment of each of the twelve figures allows to quantify the results obtained and carry out objective analyses. In this research, analytical evaluation has been used. To do this, each figure (nf = 12) is scored between 0 and 3 points for each of the variables (nv = 9), so the maximum score that could be obtained is 324 points (maximum score = 12*3*9).

Fig. 2 shows three examples of TAEC carried out by students of the University of La Laguna. Fig. 2(a) corresponds to a score of 70 points out of 324, in which drawings are limited to the space of each figure (low figurative expansion), they have no perspective or colour (low expressive richness), they do not present a relationship between them (low connectivity) and they lack of graphic quality (low graphic ability). However, in figures (b) and (c), with a score obtained of 267 and 284 on 324 respectively, students have related several figures to generate a drawing (high connectivity). In addition, it is difficult to distinguish the original figures within the drawing made (high imaginative range) and also, in the case of the image "c" it is shown how the drawing made does not represent real objects (High originality).

3.3 Procedure

The research was conducted in six sessions, three for each engineering degree. In both, the first and the third one-hour session, all the students (experimental group and control group) performed the TAEC Pre-test and post-test. In the second session each workshop was conducted (see Fig. 3).

3.3.1 Workshop I: Stella 3D Tangible

For this workshop, the educational material Stella 3D Tangible puzzle was designed and developed through digital manufacture. This tool allows students to make a three-dimensional composition from a two-dimensional pictorial work (in this case the work Irregular polygons by Frank Stella). The activity, based on one of the definitions of creativity, consists of generating different solutions based on the same proposal: create a 3D puzzle whose top view is similar to the proposed picture.

In this collaborative maker activity, students organize themselves in groups of four or five

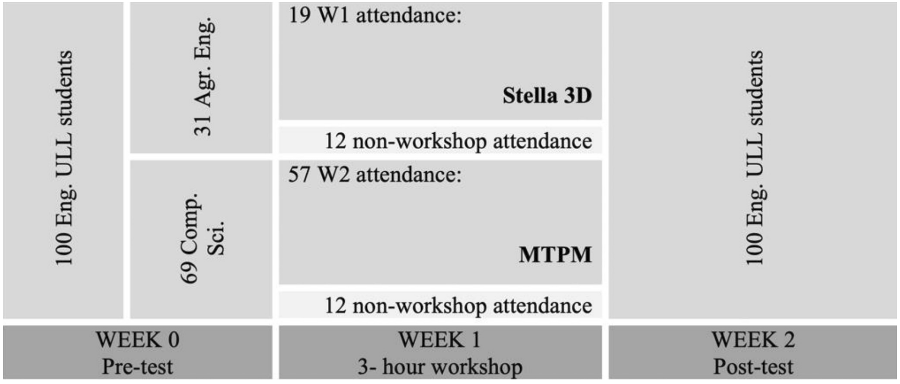

Fig. 3. Research procedure.

people and one Stella 3D tangible puzzle is distributed to each group. Each student chooses four pieces to create their three-dimensional composition with the original form as a reference. As all the pieces are different, as many different three-dimensional solutions will be created in each group as members have. Once the compositions are finished, a template is distributed in which each student individually performs the orthogonal views and the perspective of their creation (Fig. 4).

3.3.2 Workshop II: Manufacture of a physical terrain model

This workshop deals with the development of a tangible model of a plot of land. For this, 3D modelling and digital fabrication are used, through Sketch-up and Slicer software. The activity aims to promote creativity through: the modelling of three-dimensional elements in CAD systems, the procedure of dividing the model into horizontal layers and the subsequent manufacture of the physical 3D model.

First, students organize themselves in groups of four or five people. Each group chooses the plot of which they have to obtain their digital model and to determine the dimension and scale for the physical model. In addition, they had to create a platform in the digital model and build the volume of a building on it. Therefore, each group generated two files in STL format, one from the ground and another from the building. The physical model of the building was obtained with a 3D printer. While, for the construction of the terrain model, Slicer was used to divide the digital model into horizontal layers. Thus, each group can create the ground from the addition of pieces that cut into material such as cardboard (Fig. 5).

4. Presentation of Results

4.1 Normality Test of Residuals

The distribution of residuals was analysed through the Kolmogorov-Smirnov test. Table 1 shows non-normal distributions for the pre-test residuals ($p < 0.001$) and the post-test residuals ($p = 0.032$), as well as the post-test results of the students who have attended a workshop ($p = 0.002$), while the mean difference between pre and post-test follows a normal distribution ($p = 0.200$).

4.2 Description of Mean Values (Pre-Test and Post-Test) and Wilcoxon Test

The results of graphic creativity mean values are shown in Table 2. Students that have participated in the workshop I or II has significantly increased their graphic creativity in 36.96 ($p = 0.002$) and 37.68 ($p <$

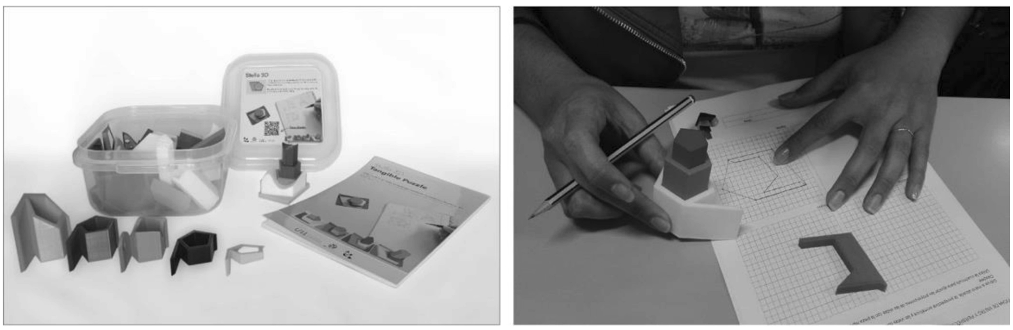

Fig. 4. Stella 3D Tangible Puzzle material and an exercise carried out by a student in the Stella 3D Tangible Workshop.

Fig. 5. Photographs of workshop II.

Table 1. Kolmogorov-Smirnov test results

	Statistic	n	p
Pre-test overall score	0.161	100	<0.001
Post-test overall score	0.122	100	0.032
Post-test Workshop groups score	0.133	76	0.002
Mean difference (pre-post)	0.087	76	0.200

0.001). Meanwhile, students who did not attend to any workshop increased by less than two points without statistical significance (p = 0.875).

Regarding students who have attended workshops (see Table 3), the variables that have increased the most are imaginative scope with a mean value of 6.22 points and figurative expression with 5.08. Conversely, the lowest difference is experienced in abreaction with .53 mean value, followed by expressive richness with 1.18.

Subsequently, Wilcoxon test was applied to find out if these differences are significant. Statistically significant differences were obtained between the previous values and those after the workshops, both the global score and individual variables (highest p value = 0.008), with the exception of graphic ability (p = 0.104).

4.3 Mean Comparative Analysis (Pre-Test and Post-Test)

The differences obtained between the two workshops for each variable are presented in Fig. 6. All the variables have increased their mean value. These changes can be categorized into three groups: those that have increased in a same proportion in both workshops (abreaction, originality, elaboration, fantasy and expressive richness), which increase between 4.3, and 5.9 more midpoints in Workshop I (imaginative scope and figurative expansion) and those that increase between 3 and 6 more midpoints in Workshop II (connectivity and graphic ability).

Afterwards, a Kruskal-Wallis test was carried out to find out if there is significance in the difference of means (pre-post) depending on the workshop carried out. In this way it is possible to find out if the improvement of graphic creativity is linked to engineering training (full-time event that student samples have in common), or if it has worked as an

Table 2. Mean values and Wilcoxon statistics categorized by workshop participation

Participant group	n	Pre-test mean	Post-test mean	Z	p
Non-workshop	24	90.37	92.00	–0.157	0.875
Workshop I	19	89.42	126.11	–3.099	0.002
Workshop II	57	79.82	117.50	–6.205	<0.001

Table 3. Mean TAEC item values (pre-test and post-test) and Wilcoxon test results (students that have attended to any workshop)

Graphic creativity variables	Pre-test mean	Post-test mean	Z	p
Abreaction	12.13	14.03	–2.659	0.008
Originality	11.03	15.58	–5.224	<0.001
Elaboration	6.87	11.42	–5.797	<0.001
Fantasy	4.25	8.22	–5.684	<0.001
Connectivity	4.50	8.72	–3.487	<0.001
Imaginative scope	11.28	19.42	–6.766	<0.001
Figurative Expression	18.92	25.78	–5.639	<0.001
Expressive richness	6.20	7.80	–2.692	0.007
Graphic ability	7.05	8.83	–1.627	0.104

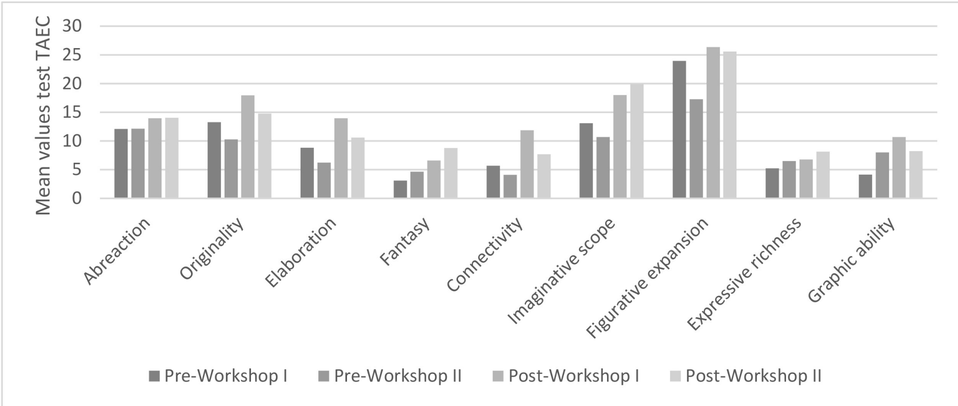

Fig. 6. Pre-test and post-test mean values of TAEC variables categorized by workshop.

Table 4. Kruskal-Wallis results by significant pairs

		n (total)	H	p
Non-workshop attendance (n = 24)	Workshop I (n = 19)	43	7.17	0.007
	Workshop II (n = 57)	81	16.15	<0.001

isolated event for only the groups participating in the workshops. The results indicate that there are significant differences ($p < 0.001$). Next, the same analysis was applied by selecting cases to know between which groups this relationship occurs (see Table 4). It is obtained that the significant differences exist in the difference of means (pre-post) between the students who did not have a workshop and those who attended workshop I ($p = 0.007$), and between those who did not have a workshop and those who attended the workshop II ($p < 0.001$).

4.4 Exploratory Factorial Analysis (TAEC Pre-Test)

Regarding pre-test graphic creativity results, sampling adequacy index was conducted through Kaiser-Meyer-Olkin (0.80), and Bartlett's test of sphericity was significant (Chi-square (36) = 455.63, $p < 0.001$), which indicates that it is appropriate to apply the Exploratory Factorial Analysis (EFA). Principal components analysis was performed on the 9 variables of TAEC. The structure is composed of three factors that explain a total of 72.71 percent of graphic creativity: traditional creativity (33.52%), graphic ability (25.03%) and abreaction (14.16%). Table 5 shows the matrix of components rotated through the analysis of principal components and the varimax rotation method, which has converged in 6 iterations. Communalities indicate at least 0.659 of variance in each variable.

4.5 Exploratory Factorial Analysis (TAEC Post-Test) – Workshops Sample

Regarding pre-test graphic creativity results, sampling adequacy index was conducted through Kaiser-Meyer-Olkin (0.82), and Bartlett's test of sphericity was significant (Chi-square (36) = 321.083, $p < 0.001$), which indicates that it is appropriate to apply the Exploratory Factorial Analysis (EFA). The structure is composed of two factors that explains a total variance of 62.93% of the graphic creativity: Traditional creativity

Table 5. EFA rotated component matrix (pre-test data)

	Variable	Communalities	% Variance explained
Traditional creativity	Figurative expansion	0.912	33.52
	Imaginative cope	0.804	
	Originality	0.724	
	Connectivity	0.676	
	Elaboration	0.659	
Graphic ability	Expressive richness	0.815	25.03
	Graphic ability	0.711	
	Fantasy	0.666	
Abreaction	Abreaction	0.870	14.16

Table 6. EFA rotated component matrix (post-test data – workshops sample)

	Variable	Communalities	% Variance explained
Traditional creativity	Imaginative scope	0.878	46.72
	Elaboration	0.876	
	Connectivity	0.822	
	Expressive richness	0.720	
	Figurative expansion	0.704	
	Fantasy	0.674	
	Originality	0.634	
Technical expressivity	Graphic ability	0.828	16.21
	Abreaction	–0.502	

(46.72%) and Technical expressivity (16.21%). Table 6 shows the matrix of components rotated through the analysis of principal components and the varimax rotation method, which has converged in 3 iterations. Communalities indicate at least 0.502 of variance in each variable. Abreaction communality results to influence graphic ability in the opposite direction ($c = -0.502$).

5. Discussion

Soft abilities provide engineers with skills beyond technical competencies, such as creativity. This research contributes with two proposals to improve graphic creativity in engineering students with statistically significant results ($p < 0.001$) through experiences in maker environments in the Design and Digital Fabrication Laboratory of the University of La Laguna.

Thus, normality Kolmogorov-Smirnov test has shown that the residuals of the growth of graphic creativity follows a normal distribution ($p < 0.200$), which supports that the maker experiences have worked for the global population and not for isolated cases that are raising the global average, what supports the results of previous research [4]. Furthermore, the comparative analyses of the means between pre-test and post-test, and Wilcoxon and Kruskal-Wallis tests have indicated that the improvement of the variables of graphic creativity was statistically significant (highest p value = 0.008), except for graphic ability ($p = 0.104$). And that they are related to the workshop in which the student has participated.

Stella 3D workshop has increased the imaginative scope and the figurative expansion. The resolution of a problem with different solutions supports other results that relate creativity with competencies such as critical thinking, innovation capacity, problem solving [28]. Also, manipulation of three-dimensional tangible elements agrees with research that correlates creativity with spatial capacity [29].

In the case of the manufacturing physical terrain model workshop, connectivity and graphic ability have increased more than the students attending the other workshop. These results agree that the use of three-dimensional CAD environments improve the development of creativity [23]. In particular, connectivity can be related to the subdivision made in digital models for subsequent physical manufacture. The process carried out with the Slicer tool is automatic, however, students carry out the assembly by connecting the horizontal layers.

Likewise, the factorial structure has been explored for the values prior to and after the completion of the workshops. This has shown different results both in the number of factors and in the percentage of variance explained. The inverse relationship between total variance explained reduction and graphic creativity may be an indication of the need to propose new variables to measure graphic creativity. This is defined by the generation of different solutions. Therefore, it is possible that the training of this competition generates a process of normalization of what we understand by creativity. In fact, the normality of the residues of graphic creativity has increased from pre-test ($p = 0.001$) to post-test ($p = 0.002$). These results support the need to rethink the way of measuring creativity through other methods [25, 26] or the inclusion of variables. However, TAEC has made it possible to obtain a high explanation portrayal of graphic creativity (close to 63%).

Although it is fundamental to propose more variables for the composition of each factor in both structures obtained, the second one seems more consistent and supports the results of Nogueira, Almeida and Lima [30] whose model of creativity was structured in two factors that suggested the need for conventional and non-conventional thinking for the creative processes. Likewise, the inverse relationship between abreaction and graphic ability (indicated by the communalities) deserve special interest, since training in engineering graphics has traditionally been focused on the existence of a single solution, as opposed to the definition of creativity.

6. Conclusions

It is possible to conclude that experiences developed in maker spaces at the University of La Laguna have improved creativity in engineering students. This global improvement has shown correspondence with variables of graphic creativity according to the design of the activity performed by each group. Therefore, three-dimensional problem-solving tasks can improve the imaginative scope and the figurative expansion. Meanwhile, the practice of computer aided design and the separation into parts of a 3D model can enhance the connectivity and the graphic ability.

In addition, these results give rise to the dialogue on the possible normalization of what is considered as graphic creativity and the need to establish new variables for its measurement at a higher level.

Some limitations should be considered such as the genre of students. In engineering courses in Spain, males are represented in a higher percentage. So, in order to analyse difference among male a female graphic creativity improvement, a wider sample should be needed. In addition, these maker experiences have been carried out by Engineering Graphics professors, which entails an additional workload. In some cultures, there is the figure of the mentor that seems to be key as support for teachers and bring new students closer to makerspaces. Likewise, the laboratory facilities are limited, so it is necessary a long time before preparing the material of the activities, in addition to the time of its design.

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