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HOW TO CHARACTERISE PERFORMANCE IN ENGINEERING FRESHMEN'S MODELLLING TASKS?

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ABSTRACT

This paper presents a study aiming at characterising engineering freshmen's performance in modelling tasks, as well as the strategies they adopt to execute them, before and after taking a 3-D modelling course. 97 freshmen in a French engineering school were asked to produce 3-D models of a part, using three views and the product development platform Onshape. The accuracy of their models was assessed using geometrical, dimensional and functional criteria. The students' performance was also investigated with regards to their modelling strategies. We characterised more specifically the strategies they adopted to constrain the overall length of the part, and pierce the central key groove. We complemented this experiment with spatial visualisation and spatial orientation tests, to explore the potential relation between modelling performance and spatial ability. We identified two strategies for piercing the key groove and three for defining the total length of the part. We observed that the latter was linked to the students' spatial ability, unlike the key groove piercing strategy. We observed a significant increase in the number of students who adopted an efficient strategy to define the length of the part after the 3-D modelling course. This increase seems to indicate that more students were able to take into account visual information regarding size. We nevertheless observed a lack of progression in the ability to dimension this element accurately. This confirms the unchanging need for teaching students, as well as pupils, how to read and interpret 2-D information.

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1 INTRODUCTION

Product design aims at manufacturing great volumes of goods, in short lead time, at low costs (Geronimi et al. 2005, 118). Nowadays, designers use Computer Aided Design (CAD) tools to produce dynamic trustworthy complex representations of objects, making "manufacturing more time and cost-efficient" (Brown 2009, 54). This professional practice has greatly impacted the curricula of the schools where mechanical design is taught: descriptive geometry and engineering graphics have been replaced by 3-D modelling courses (Ault and John 2010, 13). In 2016, the French government decided to investigate the impact of the increasing role played by digital tools on learning, by sponsoring research programmes addressing this issue[2]. EXAPP_3D, an e-FRAN project, aimed at better understanding how multi-purpose 3-D modelling software was used by learners at different levels of schooling. This project provided the opportunity to investigate spatial ability and its possible inferences as a necessary ability in French engineering education. More specifically, this work aims at studying how engineering freshmen's modelling performance and strategies evolved following an introductory 3-D modelling course. A secondary objective is to explore whether the initial performance is linked to spatial scores.

2 RESEARCH CONTEXT

2.1 Teaching 3-D modelling

3-D modelling courses have a twofold aim: they must teach students how to use 3-D modellers, as well as how to best use them (Rynne and Gaughran 2007, 59): students need to learn not only how modellers work and the functions they offer, but also efficient strategies that enable them to make the most of parametric modelling (Chester 2007, 23; Rynne and Gaughran 2007, 57). Commands are specific to a modeller, whereas strategies can be used in any modeller (Hamade, Artail, and Jaber 2005, 306). Unlike learning software commands, learning efficient strategies is difficult as there are several ways of designing an object (Bertoline et al. 2009, 416). The difficulty lies in developing strategies which are time-efficient and limit the number of mistakes (Bhavnani, Reif, and John 2001, 230).

Creating an object in a 3-D modeller follows a procedure, which can be observed in professional practice (Hartman 2005, 11) and in modelling courses (Bertoline, Hartman, and Adamo-Villani 2009, 640):

- Choice of a sketch plane in a 3-D space,
- Sketching of a 2-D profile on the chosen plane,
- Dimensioning and constraint of the sketched profile,
- Application of a feature to the 2-D profile, or part of it.

The effective use of CAD tools therefore requires strategic knowledge (Bhavnani, Reif, and John 2001, 229), mathematical and computing knowledge (Ye et al. 2004, 1454), the ability to break down a solid into elementary geometrical parts (Rynne and Gaughran 2007, 55), and that to understand numerical representations relating to size, shape and orientation (Bertoline et al. 2009, 6).

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[2] Espace de formation, de recherche et d'animation numérique (e-FRAN) projects are supported by the Ministère de l'enseignement supérieur, de la recherche et de l'innovation.

Modelling performance can be measured by assessing the accuracy of the models, and the strategies used (Chester 2007, 30; Steinhauer 2012, 47): these can be observed for example in the feature tree, which shows the final order of the sketches and the features used to produce the model.

2.2 Spatial ability

The ability to understand, recognise, and manipulate 2-D and 3-D representations has been named spatial ability (Linn and Petersen 1985, 1482; Lohman 1993, 3). It is often subdivided into several factors; the most quoted factors are spatial visualisation and spatial orientation (McGee 1979, 889; Hegarty and Waller 2004, 175). Tartre (1984) bases her classification on this distinction, which separates skills requiring the mental manipulation of shapes, from those involving the perspective of the viewer (6). She subdivides the two factors depending on the portion of the shape is involved: regarding spatial visualisation, she refers to Kersh and Cook's distinction (1979, in Tartre 1984, 8) between mental rotation, where the whole shape is manipulated, and mental transformation, which involves part of an object. Similarly, spatial orientation can be divided into the reorganised whole category, which concerns the "organization and comprehension of an entire pictorial representation or a perceptual change from one representation to another" (Tartre 1984, 16). On the other hand, the part of field category describes "the relationship of part of a representation to the whole field, either presented visually or imagined" (20). Tartre's classification is illustrated in Figure 1.

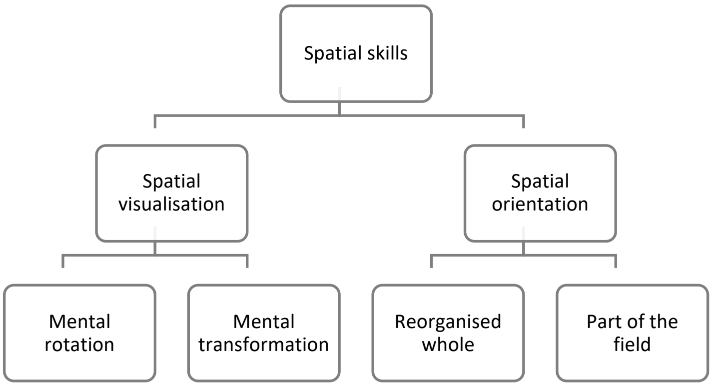

Fig. 1. Adapted from Tartre's spatial skills classification scheme (1984, 27)

These skills are often assessed through psychometric pen-and-paper tests (Eliot and Macfarlane Smith 1983). We will present here five tests, which aim at measuring one of the components of Tartre's classification.

The Mental Rotation Test (MRT) (Vandenberg and Kuse 1978) and the Revised Purdue Spatial Visualization Tests: Visualization of Rotations (R PSVT:R) (Yoon 2011) aim at measuring mental rotation. The Special Aptitude test in Spatial Relations, better known as the Mental Cutting Test (MCT) (College Entrance Examination Board 1939), seeks to evaluate mental transformation. These three tests involve mental manipulation of 3-D objects.

The Purdue Spatial Visualization Test: Visualization of Views (PSVT:V) (Guay 1976) aims at measuring the change of perspective. The Closure Flexibility Test (Concealed figures) Form A (CFT) (Thurstone and Jeffrey 1956) solicits the ability to isolate a shape embedded in a larger figure. These two tests come under spatial orientation, as they ask respondents to recognise and understand shapes.

Performance at spatial tests has been linked to academic success in Science, Technology, Engineering and Mathematics (STEM) (Wai, Lubinski, and Benbow 2009, 827): these disciplines require students to visualise, manipulate and understand 2-D and 3-D shapes. More specifically, several studies have demonstrated a relationship between spatial performance and 3-D modelling (Steinhauer 2012, 47; Branoff and Dobelis 2012, 40).

2.3 Research question

3-D modelling courses hold a two-fold objective: teaching students how to use 3-D modellers, and how to use them efficiently. The objective of this study is to characterise engineering freshmen's performance in modelling tasks, as well as the strategies they adopt, before and after taking a 3-D modelling course. As spatial ability has been described as a predictor of success in 3-D modelling, a secondary goal is to explore the potential relation between students' spatial ability and their modelling performance, before they undertake a modelling course.

3 METHODOLOGY

3.1 Participants

The experiments were scheduled at the beginning of the year, and at the end of the first term of the first-year course. The participation of the students varied according to the assessment. In this paper, we will describe the performance and strategies of the students who took part in all the experiments.

Our sample consisted of 97 freshmen in a French engineering school, aged between 18 and 21, mean 19.9. There were N_F = 20 [20.6%] women and N_H = 77 [79,4%] men. French engineering students join a school after taking competitive entry exams following two-year intensive preparatory courses, the first two years of a university degree, or obtaining a two-year vocational qualification. 54 [55.7%] students had been exposed to technological content prior to joining the school, whereas 43 [44.3%] came from courses deprived of technological content. 86 [88.7%] students had some experience with 3-D modellers, when 11 [11.3%] had none.

3.2 Instruments and procedure

3.2.1 Modelling experiment

In September 2019, the students were asked to produce 3-D models of a part, using three views, one of which included dimensions, as illustrated in Figure 2, and the online product development platform Onshape (Hirschtick et al. 2014). We decided not to use technical drawings, as some of the students lacked a technical background and might find the drawings difficult to interpret. The students were first asked to follow a tutorial to learn how to use the software. They completed the same modelling task in December 2019, that is to say at the end of the first term, during which they received a 10-hour 3-D modelling course using the CATIA software (Dassault Systèmes 2012).

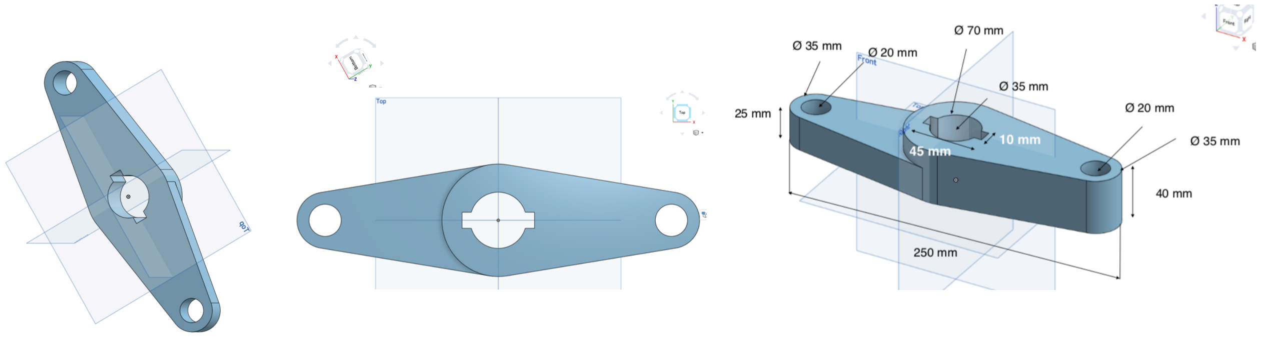

Fig. 2. Modelling assessment

Technical drawings were generated to assess the students' models, using geometrical, dimensional and functional criteria, the details of which are illustrated in Figure 3. We allocated a further point for the trimming of excessive elements. The total score was 35.

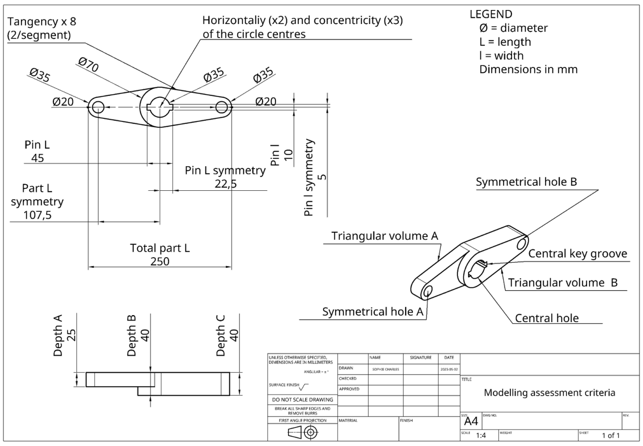

Fig. 3. Modelling assessment criteria

The students' performance was also investigated with regards to their modelling strategies. We observed 3 different procedures for constraining the total length of the part:

- Strategy 1: defining it as a combination of different elements, as illustrated in Figure 4;
- Strategy 2: defining it as a unique dimension, as illustrated in Figure 5;
- Strategy 3: not allocating it a dimension.

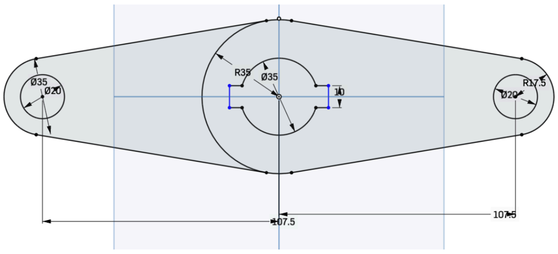

Fig. 4. Length defined as a combination

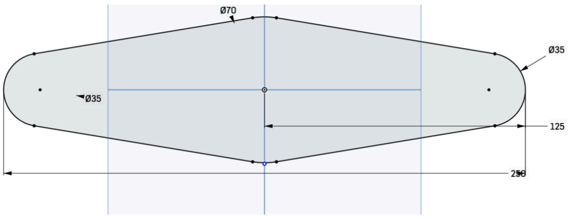

Fig. 5. Length defined as one dimension

We finally consulted the feature tree to observe the sequence of sketches and extrusions, to determine the strategy the students adopted to pierce the central key groove. Two behaviours were identified: some students pierced it in one or several extrusions without filling it, while others did it in several extrusions, some of which led to the obstruction of the key groove. The latter group pierced the central key groove, filled it with a further extrusion and pierced it a second time. This strategy is illustrated in Figures 6 and 7.

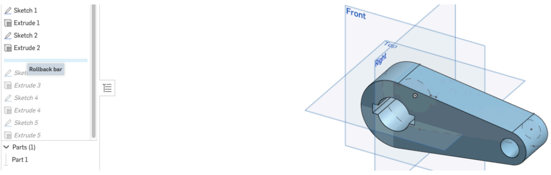

Fig. 6. Piercing of the central key groove

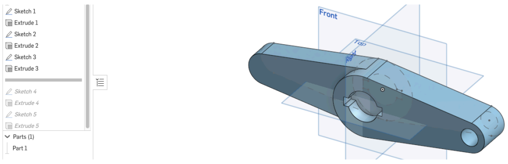

Fig. 7. Obstruction of the central key groove

Spatial tests

In September and December 2019, 97 freshmen took a battery of five spatial tests under the following testing times:

- PSVT:V: 20 minutes, according to the description in Eliot and Macfarlane Smith (1983).
- MRT: 3 minutes to complete each part. They were separated by a 3-minute break. Such timing was deemed appropriate for our sample by one of the authors (Allan R Kuse, e-mail to author, June 25, 2018).
- MCT: 20 minutes, as prescribed in the instructions.
- R PSVT:R: one hour for timetabling reasons. This aligned with the author’s indication that most students complete the test in 30 minutes (So Yoon Yoon, e-mail to author, May 16, 2018).
- CFT: 10 minutes, according to the instructions (Thurstone and Jeffrey 1965).

The instructions of the tests were translated in French, except for the MRT whose French version was available (Albaret and Aubert 1996), so that English ability would not affect student performance. We used the pen-and-paper versions of the tests. The students answered directly on separate answer sheets for the PSVT:V, the MCT and the R PSVT:R, but answered on the question papers and reported their answers on the answer sheets after the test, for the MRT and the CFT. The students were instructed to not guess the answers. The scores were calculated according to the instructions.

3.2.2 Data analysis

We first checked the normality of the distribution of the scores for the spatial tests and the modelling assessments by using the Shapiro-Wilk test (Shapiro and Wilk 1965) in SPSS (IBM Corp. 2021). Only the CFT scores followed a normal distribution. We consequently opted for parametric tests for the CFT and non-parametric tests for the other assessments:

- Spearman correlations were calculated to explore the link between modelling performance and spatial scores. They were completed with the study of scatter charts to check the validity of the correlations (Kinnear and Gray 2015, 290).
- The sign test was used to compare the evolution of the modelling scores and strategies, as it is deemed more robust than the Wilcoxon signed-rank test (Kinnear and Gray 2015, 174).
- The Kruskall-Wallis test (Kruskal and Wallis 1952) was used to compare the performance of groups of students according to their modelling strategies, for

the PSVT:V, the R PSVT:R, the MRT, and the MCT. One-way ANOVAs were performed to compare CFT scores between groups of students according to their modelling strategies. When a significant result was observed, box plots were generated to interpret the result.

4 RESULTS

We will first present the results for the initial performance, followed by those regarding the performance measured at the end of the first term, and finally the results concerning the evolution, or lack of, in performance and strategies between the two sets of experiments.

4.1 Initial modelling performance and strategies

4.1.1 Accuracy of the model

As mentioned in paragraph 2.2.2, most students obtained high and very high modelling scores when they first joined the school. The descriptive statistics are available in Table 1. This can be partly explained by the fact that most students had some prior experience with 3-D modellers.

Table 1. Descriptive statistics for the modelling assessments

Testing date	Mean	Median	Standard deviation	Minimum	Maximum
September	31.16	33.00	4.64	12	35
December	32.85	34	3.12	13	35

4.1.2 Dimensioning of the length of the part strategy

A majority of the students (*n* = 70; 72.2%) split the total length into several dimensions, some of them (*n* = 15; 15.5%) did it by dimensioning the length between the two ends of the part, while other students (*n* = 12; 12.4%) did not dimension enough elements to constitute the total length of the part. Furthermore, 51 [52.6%] students defined the total length of the part successfully, when 46 [47.4%] students did not. These results seem to indicate that a minority of the students did not fully exploit the information in the view with the dimensions. They also show that about half the students failed to determine the length successfully, whether they did not enter enough dimensions to define it, made a mistake in calculating it, or entered the wrong overall dimension. This suggests a lack of understanding and/or interpretation of the information given in the view with the dimensions.

4.1.3 Piercing of the central key groove strategy

A majority of the students (*n* = 88; 90.7%) pierced the central key groove without refilling it, whereas a small number did (*n* = 9; 9.3%). This indicates that the latter group failed at analysing the volumes which compose the part, and consequently at efficiently planning their modelling activity.

4.1.4 Relationship between the students' spatial ability and their modelling performance

Except for the CFT scores, our sample's spatial performance was fairly high. The details can be found in Table 2. This result can be explained by the fact that French engineering school students are recruited through highly selective processes and that they join the school after two-year courses with mathematics, physics, chemistry and/or technological courses (Charles et al. 2019, 240). The difference in the CFT scores may be due to skills developed outside of formal education.

Table 2. Descriptive statistics for the spatial tests

Spatial test	Highest possible score	Mean	Median	Standard deviation	Minimum	Maximum
PSVT:V	30	25.48	27.00	4.98	5	30
R PSVT:R	30	25.75	26.00	3.71	11	30
MRT	20	13.34	14.00	4.03	0	20
MCT	25	16.93	18.00	4.83	5	25
CFT	196	99.86	100.00	26.53	22	160

In Table 3, we observe significant positive relationships between modelling and spatial scores, except for the MRT.

Table 3. Spearman correlation for spatial scores in function of modelling scores

Dependant variable	Independent variable	r_S	*p*
Modelling scores	PSVT:V	0.34	0.001**
	R PSVT:R	0.31	0.002**
	MRT	0.16	NS
	MCT	0.31	0.002**
	CFT	0.24	0.017*

Note. r_S = Spearman's coefficient; *p* = p value.

On the scatter charts in Figures 8-11 , we observe that modelling scores starting from 25, that is about 95% of our sample, are more or less gathered around the correlation axis. This explains that the correlation coefficients are weak despite the significant result.

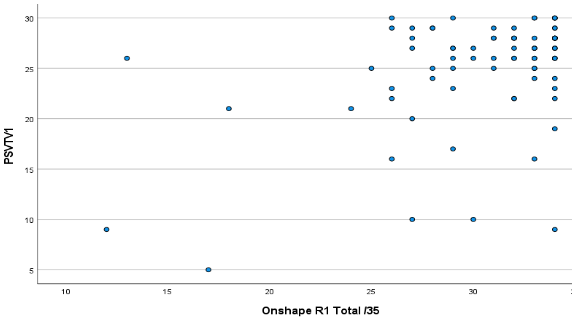

Fig. 8. Scatter chart of the modelling and the PSVT:V scores

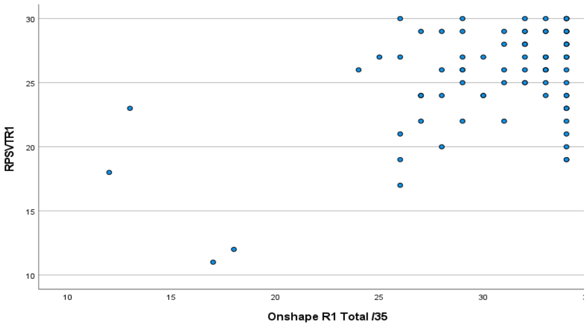

Fig. 9. Scatter chart of the modelling and the R PSVT:R scores

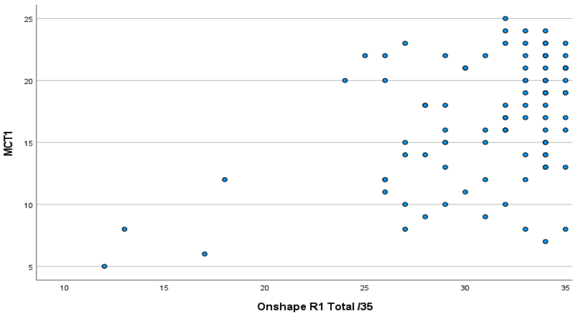

Fig. 10. Scatter chart of the modelling and the MCT scores

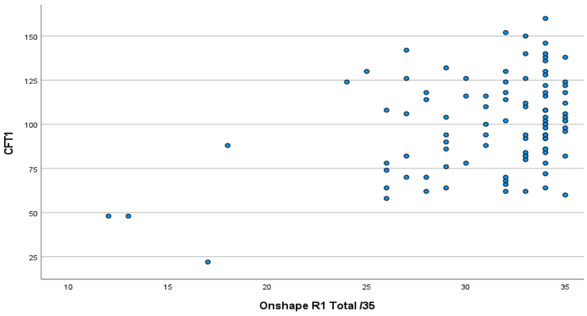

Fig. 11. Scatter chart of the modelling and the CFT scores

4.1.5 Relationship between the students' spatial ability and modelling strategies

The Kruskall-Wallis test reports a significant relationship between the performance at the PSV:T ($p < 0.01$), the R PSVT:R ($p < 0.05$), the MCT ($p < 0.01$), and the choice of strategy for defining the overall length of the part. On the other hand, a nonsignificant result is obtained for the MRT. The results are described in Table 4.

Table 4. Relationship between the length-definition strategy and the PSV:T, the RPSVT:R, the MRT and the MCT

Spatial test	$\chi^2(2)$	*p*
PSVT:V	10.19	0.006**
R PSVT:R	7.32	0.026*
MRT	3.43	NS
MCT	12.487	0.002**

Note. χ^2 = test statistic; () = degree of freedom; *p* = p value.

The one-way ANOVA comparing the CFT scores and the length-definition strategy indicates a significant result: F(2,94) = 6.24; $p = 0.003$. The box plots in Figures 12-15 show that the students who used Strategy 1 and 2, i.e. by constraining the length in one or several dimensions, obtained the best scores at the PSV:T, the R PSVT:R, the MCT and the CFT.

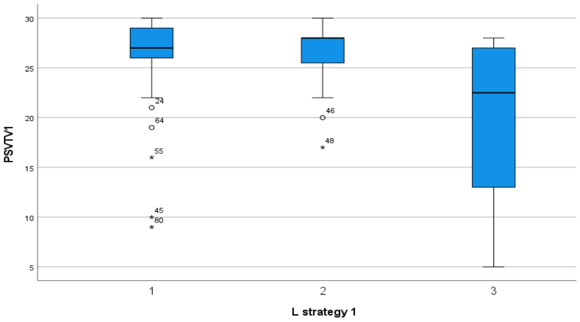

Fig. 12. Box plot of the PSVT:V scores according to the L strategy

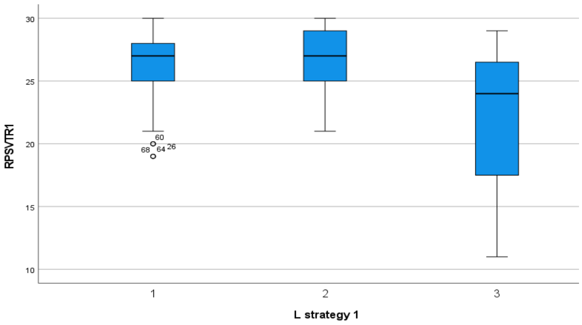

Fig. 13. Box plot of the R PSVT:R scores according to the L strategy

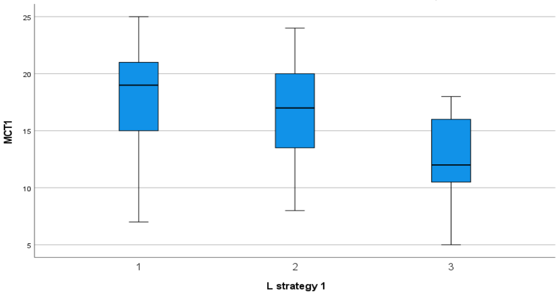

Fig. 14. Box plot of the MCT scores according to the L strategy

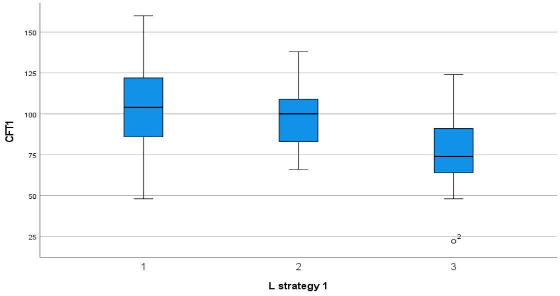

Fig. 15. Box plot of the CFT scores according to the L strategy

The Kruskall-Wallis test does not produce a significant result regarding the relationship between the performance at the PSV:T, the R PSVT:R, the MRT and the MCT and the key groove piercing strategy. We obtain a similar result with the one-way ANOVA for the CFT. These results suggest that spatial ability is not involved in the capacity to select the correct surface when extruding.

4.2 Evolution after the CAD course

4.2.1 *Accuracy of the model*

The sign test indicates a very significant result ($p < 0.01$) in the evolution of the modelling scores. The boxplots in Figure 16 show that the students' performance increased, and that the distribution of scores narrowed at the end of the term. Nevertheless, a few students progressed but underperformed at both assessments.

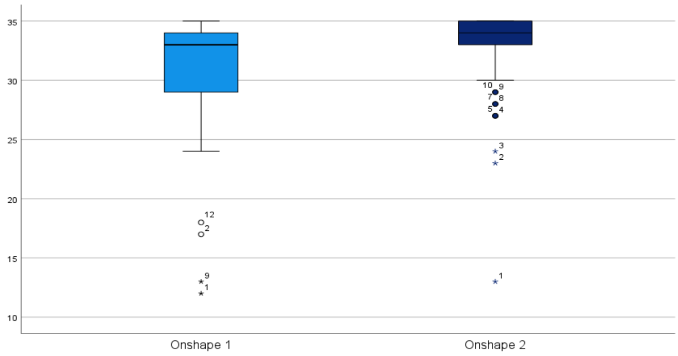

Fig. 16. Distribution of modelling scores before and after the modelling course

We calculated the amount of progression which can be attributed to the practice effect, that is "any change or improvement that results from practice or repetition of task items or activities" (American Psychological Association n.d.), as we used the same modelling task for both experiments. The increase in performance described in Table 5 ($0,5\sigma$) is greater than the practice effect, which accounts for 0.2σ improvement for identical tests, taken at an interval greater than three months (Hopkins 1998, 140). This suggests that part of the progression is due to the teachings the students received.

Table 5. Assessment of the practice effect

Mean gain	Standard deviation	Mean gain / Standard deviation
1.7	3.4	0.5

Unlike this overall progression, the number of students who defined the total length of the part did not evolve significantly: 53 [54.6%] students defined the total length of the part successfully, when 44 [45.4%] students did not. This suggests the CAD course helped the students model more accurately in general, but did not have an impact on the students' ability to either define, or calculate the total length of the part accurately.

4.2.2 Dimensioning of the length of the part strategy

The sign test to compare the number of students according to their length-defining strategy indicates a significant result ($p = 0.015$): the bar charts illustrated in Figures 17 and 18 show that more students used the combination strategy (Bar 1 in both illustrations) at the end of the term, that is to say they dimensioned several components of the overall length after calculating them; whereas fewer students failed to dimension the length of the part (Bar 3 in both illustrations).

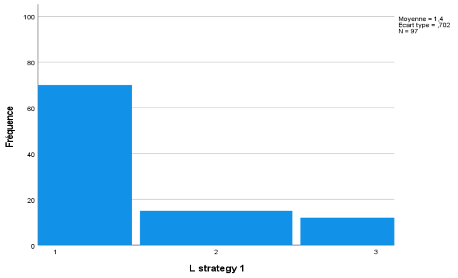

Fig. 17. Distribution of the length-defining strategies before the modelling course

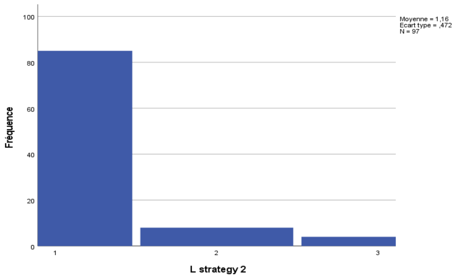

Fig. 18 Distribution of the length strategies-defining after the modelling course

4.2.3 Piercing of the central key groove strategy

The sign test to compare the number of students according to their key groove piercing strategy indicates a nonsignificant result, although fewer students (n = 3; 3.1%) obstructed the central key groove at one point of their modelling activity in December. This result may be due to the very low number of students (n = 9; 9.3%) who had this problem in the first experiment.

4.3 Limitations

The results presented here are limited by the methodology we adopted:

- As participation in the experiments was voluntary, it is possible that the students in our sample are characterised by a certain motivational profile and/or a certain aptitude for 3-D modelling. This was controlled with a Mann-Whitney *U* test to compare the performance of the students on the CAD course assessment according to their participation in the experiments. It showed a nonsignificant difference in performance between the students who took part (*n* = 123; 91%), and those who did not (*n* = 12; 9%).

- The order of the tests in our spatial battery may have affected the performance of the tests placed after the first test: the students may have acquired knowledge in the first test(s), which may have benefited their performance in the later tests (Kinnear and Gray 2015, 241). A random order of the tests would help to counterbalance this effect.

5 SUMMARY AND ACKNOWLEDGMENTS

This paper aimed at characterising engineering freshmen's performance in modelling tasks, as well as the strategies they adopt, before and after taking a 3-D modelling course. Our sample's initial modelling performance, which was fairly high, is significantly correlated to their spatial ability at four of the tests in our battery, although the coefficient is quite low. Furthermore, we observe a significant result for the link between spatial performance at four of the tests in our battery and the strategy for defining the total length of the part, that is not reflected in the relationship with the key groove piercing strategy. These results seem to indicate that spatial skills are more involved in the identification and comprehension of basic geometric information such as numerical representations relating to size, shape and orientation (Bertoline et al. 2009, 6), than the breaking down of a solid into elementary geometrical parts (Rynne and Gaughran 2007, 55). Our results also demonstrate the relevance of using spatial orientation tests to explore the relationship between spatial ability and 3-D modelling, when most studies tend to use spatial visualisation tests (Steinhauer 2012; Branoff and Dobelis 2012). In this study, both our spatial orientation tests were linked to modelling performance and strategy, unlike the MRT, a visualisation spatial test. The CFT especially has been relevant in identifying links between spatial ability and 3-D modelling performance and strategies in some of our other experiments (Charles 2023).

Our study shows a positive impact of the CAD course on the students' overall modelling performance and strategy, as more students adopt a length-defining strategy at the end of the term. These findings tend to confirm the transferability of 3-D modelling skills form one modeller to another (Hamade, Artail, and Jaber 2005, 306): 3-D modelling strategies acquired in the CAD course using CATIA were observed in the experiment using Onshape. However, we can notice that this change of strategy is not more efficient in producing the accurate dimension. This suggests that more work needs to be done on basic 2-D geometry relating to size and understanding of 2-D representations of 3-D objects at the engineering education level. This also confirms previous studies which have argued for more geometry to be taught in earlier education (Duroisin 2015; Maier 1996), so that students come fully equipped when they enter engineering education.

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