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Exploring the relationship between spatial ability, individual characteristics and academic performance of first-year students in a French engineering school

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ABSTRACT:

This study is concerned with spatial visualisation and its possible inferences as a necessary ability in French engineering education. It is completed as part of a French

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research programme, which aims at better understanding how multi-purpose 3-D modelling software is used by learners at different levels of schooling. Spatial ability may be measured thanks to paper tests and predicts choices and success in science, technology, engineering, and mathematics education and professions. It is often described as an ability composed of two factors, namely spatial orientation and spatial visualisation. The latter can be further developed into mental rotation and mental transformation. In order to evaluate the spatial visualisation skills of first-year students in a French engineering school specialised in mechanics, the Revised Purdue Spatial Visualization Tests: Visualization of Rotations, the Mental Rotation Test, which both aim at measuring mental rotation, and the Mental Cutting Test, which aims at measuring mental transformation, were administered to 137 engineering freshmen in September 2018. This data collection was completed with a selection of demographics and academic assessment scores. The purpose of this article is to explore, by carrying out an analysis of variance, how these students' spatial visualisation skills can be related to individual characteristics and how they contribute to academic performance.

1 INTRODUCTION

Spatial visualisation is a component of spatial ability, which predicts success in engineering courses and professions [1]. Although, numerous studies addressing this issue have been carried out in engineering education around the world [2, 3], no similar research has been led in France to our knowledge. In 2016, the French government decided to investigate the impact of the current transformations education is experiencing through the increasing role played by digital tools, by sponsoring research programmes addressing this issue². EXAPP_3D, an e-FRAN projects, aims at better understanding how multi-purpose 3-D modelling software is used by learners at different levels of schooling. This project provides the opportunity to investigate spatial visualisation and its possible inferences as a necessary ability in French engineering education. More specifically, this work aims at studying whether spatial visualisation, as measured by pen-and-paper tests, can predict academic success for first-year students in an engineering school specialised in mechanics. A secondary objective is to explore whether pre-engineering school specialisations and gender are linked to spatial visualisation scores.

2 RESEARCH CONTEXT

Science, Technology, Engineering and Mathematics (STEM) require students to visualise, manipulate and understand two-dimensional (2-D) and three-dimensional (3-D) shapes. Chemistry students analyse the spatial structure of molecules, medicine students learn anatomy, and engineering students model 3-D objects from 2-D representations and analyse mechanisms from 2-D and 3-D representations. Wai, Lubinski and Benbow's longitudinal study highlighted how high school students' spatial ability predicts choices and success in STEM education and careers [1]. The authors studied the evolution of 306,665 subjects from Project Talent [4], who were assessed on their verbal, mathematical and spatial skills while in high school in 1960. The analysis of the eleven-year follow-up after high school graduation established that the likelihood of obtaining an advanced qualification in STEM disciplines, i.e. a master's degree or a doctorate, increased with the spatial ability demonstrated in high-school. It also showed that the individuals who held positions in STEM domains had obtained higher spatial ability scores while in high school.

2.1 Spatial ability

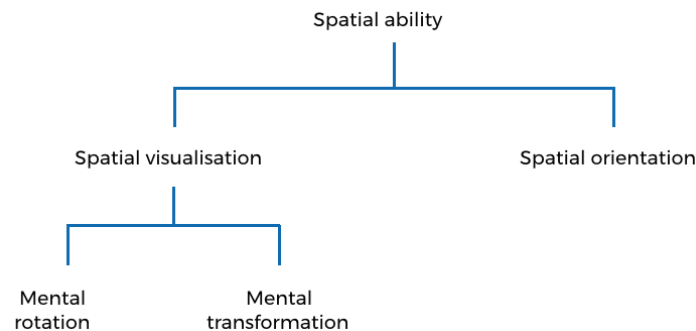
Often described as a set of skills, spatial ability is rarely defined as a single concept [5]. Its most frequently quoted components are spatial visualisation and spatial orientation [6, 7, 8]. This study focuses on spatial visualisation, therefore, spatial orientation will not be detailed.

2.2 Spatial visualisation

Spatial visualisation, as defined by McGee, implies "*the ability to mentally rotate, manipulate, and twist two- and three-dimensional stimulus objects*" [7, p. 896]. This skill is characterised by the mental manipulation of objects. Kersh and Cook [9, cited by 8] further decompose this skill in two sub-skills, namely mental rotation and mental transformation, as illustrated in *Figure 1*. The authors justify this distinction by the size of the transformation: mental rotation concerns the total transformation of an object, whereas mental transformation concerns the partial transformation of an object.

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.

Fig. 1. Spatial skills classification [Adapted from 8, Figure 3.1]



2.2.1 Mental rotation

Mental rotation “*describes the mental movement of an entire object to a different position*” [8, p. 30]. This term was coined by Shepard and Metzler in 1971, after carrying out an experiment requiring eight subjects to decide whether two perspective drawings of 3-D objects, presented before and following a rotation, were similar [10]. The authors noticed the response time rose with the increase of the angular discrepancy between the two representations of the object.

2.2.2 Mental transformation

This capacity implies “*different operations on separate parts of the mental image*” [9, p. 8, cited by 8, p. 31]. Tartre distinguishes four categories:

- the transformation of a 2-D representation to a 2-D representation, as in mental tangrams;
- the transformation of a 2-D representation to a 3-D representation, as when one mentally folds a pattern to form an object;
- the transformation of a 3-D representation to a 3-D representation, as when one mentally builds a complex object from simple objects;
- the transformation of a 3-D representation to a 2-D representation, as when one mentally unfolds an object.

2.3 Measuring spatial visualisation

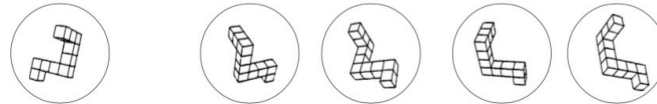
Numerous pen-and-paper tests exist to assess spatial ability. The most frequently quoted tests are the Mental Rotation Test [11], the Special Aptitude - Spatial Relations, better known as the Mental Cutting Test [12], and the Purdue Spatial Visualization Test: Visualization of Rotations [13].

2.3.1 Pen-and-taper tests measuring mental rotation

The Mental Rotation Test (MRT) is a pen-and-paper test designed by Vandenberg and Kuse consisting of twenty questions [11]. For each question, a shape is presented and must be identified, once rotated, among four choices. The rotations are carried out according to a central symmetry. Each stimulus corresponds to the isometric drawing of a 3-D object. Half the questions present distractors in the shape of rotated mirror images of the stimulus, and the other half present distractors in the shape of rotated images of one or two of the answer choices. Respondents need to select the two correct answers to score a point. This marking scheme aims at preventing guessing. There are two parts to the test, which are separated by a pause. The time limit for the

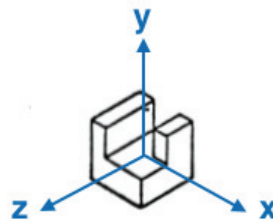
questions and the pause depend on the test battery and the respondents' experience (A.R. Kuse, personal communication, 25 June, 2018). Albaret and Aubert provide a French version of the test [14].

Fig. 2. Sample question from the MRT



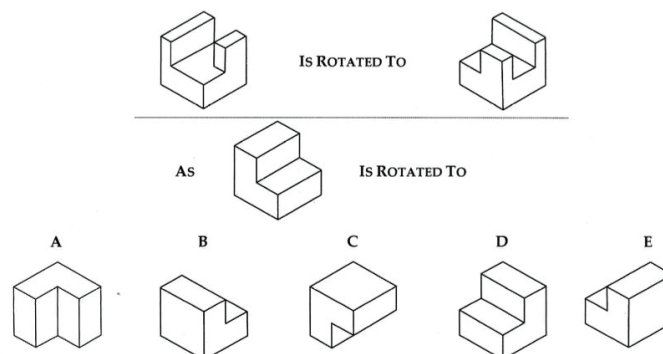
The Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) is a 20-minute multiple-choice pen-and-paper test consisting of thirty questions. Each presents a 3-D object represented in two positions. The respondent needs to identify the sequence of rotations required to move the object from the first position to the second, and apply it to a second object, to find the corresponding position it has reached out of four possible answers. The rotations are in 90° multiples, and follow the directions of the object using the right-hand rule. The test displays objects with plane, curved and inclined surfaces. It is designed to restrict analytical processing and “to measure a specific type of spatial visualizing ability that requires imagining movement according to explicit directions” [15, p. 9].

Fig. 3. Stimulus from the PSVT:R presented in a 3-D Cartesian coordinate system



The Revised Purdue Spatial Visualization Tests: Visualization of Rotations (R PSVT:R) [17] results from Yoon’s revision work, with Guay’s permission. In this version of the test, a single problem is displayed per page and the questions are presented in an increasing order of difficulty. There is no time limit to this test.

Fig. 4. Sample question from the R PSVT:R

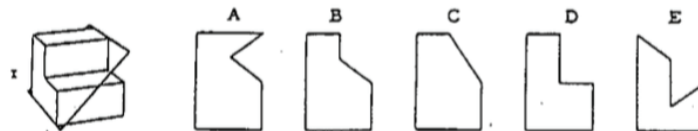


2.3.2 Pen-and-taper test measuring mental transformation

The Special Aptitude test in Spatial Relations, better known as the Mental Cutting Test (MCT), is a 20-minute pen-and-paper multiple-choice questions which contains twenty-five questions [12]. Each problem presents a 3-D object cut by a plane. The respondent

must choose the correct resulting cross section out of five possible answers. Some of the questions can be solved by selecting the shape of the cross section, and some further require to take the measure of the sides and of the angles into consideration [16]. Steinhauer [3] studied the correlation between students' performance on the MCT and their 3-D modelling ability. She concluded that a significant relationship existed between the two abilities. She suggested that the efficient use of 3-D modellers and the solving of the MCT problems both require *“the ability to discern the correct 2-D profiles associated with a solid model”* (p. 48).

Fig. 5. Sample question from the MCT



2.4 Research question

Spatial ability predicts student choices and success in engineering [1]. It is linked to the ability to use 3-D modellers [3] and gender [2, 6, 7, 14, 18], and can be measured thanks to pen-and-paper tests. One of spatial ability components, spatial visualisation, enables the total or partial manipulation of 2-D and 3-D objects. This study is aimed at determining whether spatial visualisation, as measured by the MCT, the MRT and the R PSVT:R, can predict engineering students' performance in academic assessments. A secondary objective is to explore whether performance on spatial visualisation tests can be linked to undergrad specialisation and gender. Previous studies [2, 3] allow us to the formulate the hypothesis that spatial scores will predict student performance in assessments which require the mental manipulation of 2-D and 3-D representations, and that male students will outperform female students on the spatial tests. We also predict that students who received training in complex system analysis and modelling will outperform students who did not benefit from such experience.

3 RESEARCH DESIGN

3.1 Participants

Students join Supméca, a French engineering school specialised in mechanics, upon successful qualification through several recruiting processes : they need to pass competitive entry exams, after completing intensive preparatory courses, the first two years of a university degree or obtaining a vocational qualification (DUT). Students coming from intensive preparatory courses are specialised in Mathematics and Physics (MP), Physics and Chemistry (PC), Physics and Engineering (PE), Physics and Technology (PT), or Technology and Industrial Science (TIS). PT, PE and TIS students are taught about complex systems form 4 to 8.5 hours a week, whereas this course is optional for MP students and not part of the PC students' curriculum.

Table 1. Hourly volumes of subjects in the MP, PC, PE, PT and TIS courses

	Mathematics	Physics	Chemistry	Industrial science
MP	12	7	2	(2)
PC	9	9	5.5	-
PE	10	7.5	2.5	4
PT	9	6	2	8.5
TIS	10	6	2	7

Note: Industrial science courses cover complex mechanism analysis and modelling.
() indicates these lessons are optional.

The students were aged between 18 and 23, mean 20.35. 137 students ($N_F = 37$ [27%] women and $N_H = 100$ [73%] men) took the MCT and the MRT. 131 students ($N_F = 36$ [27.48%] women and $N_H = 95$ [69.34%] men) took the R PSVT:R.

3.2 Instruments and procedure

3.3.1 Spatial tests

In September 2018, 137 freshmen took the MRT and the MCT and 131 freshmen took the R PSVT:R:

- MRT: the students were given three minutes to complete the first part and three minutes to complete the second part of the test. They benefited from a two-minute break. Such timing was deemed appropriate for our sample by one of the authors (A.R. Kuse, personal communication, 25 June, 2018). We used the French version of the test [14].
- MCT: the students were given twenty minutes to complete the test, as prescribed on the test paper. We used our own translation.
- R PSVT:R: the students were given a time limit of one hour, for timetabling reasons and based on the author's indication that most students complete the test in thirty minutes (S.Y. Yoon, personal communication, 16 May 2018). We used our own translation, which was approved by the author (S.Y. Yoon, personal communication, 18 October 2018).

We decided to translate the tests for which a French translation was not available 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 answers sheets for the MCT and the R PSVT:R, but answered on the question papers and reported their answers on the answer sheets during the break and after the test for the MRT. The students were instructed to not guess the answers. The order of the tests was chosen depending on the time slots. Some groups took the MRT and the MCT during the same session, and the R PSVT:R at a different time on the same day. Other groups took the MRT and the MCT during the same session, and the R PSVT:R on a different day.

3.3.2 Academic assessment

Individual assessment scores and assessment descriptions for the first term were collected from the student office and teachers. They were part of the following courses: Applied Mathematics (APMA), Mechanism Analysis (MEAN), and Algorithmic and Programming (ALPR). All the data were anonymised.

APMA addresses distributions of real variables and the Laplace transform. The assessment focused on distributions, convolutions, the Laplace transform and the Fourier transform.

MEAN aims at teaching students how to analyse an industrial mechanism to sketch its kinematics schematic representation, identify the necessary technological conditions for its efficient operation, check its performances using calculations, and propose a manufacturing method for some of its components. The assessment included 2-D representations of a 3-D object from different perspectives, horizontal and vertical cross sections (*Figure 6*), and an exploded view. Students had access to a digital

model in CATIA [19], with which they could generate different representations of the system they were analysing, as illustrated in *Figure 7*.

Fig. 6. Examples of perspectives and cross sections presented in the MEAN assessment

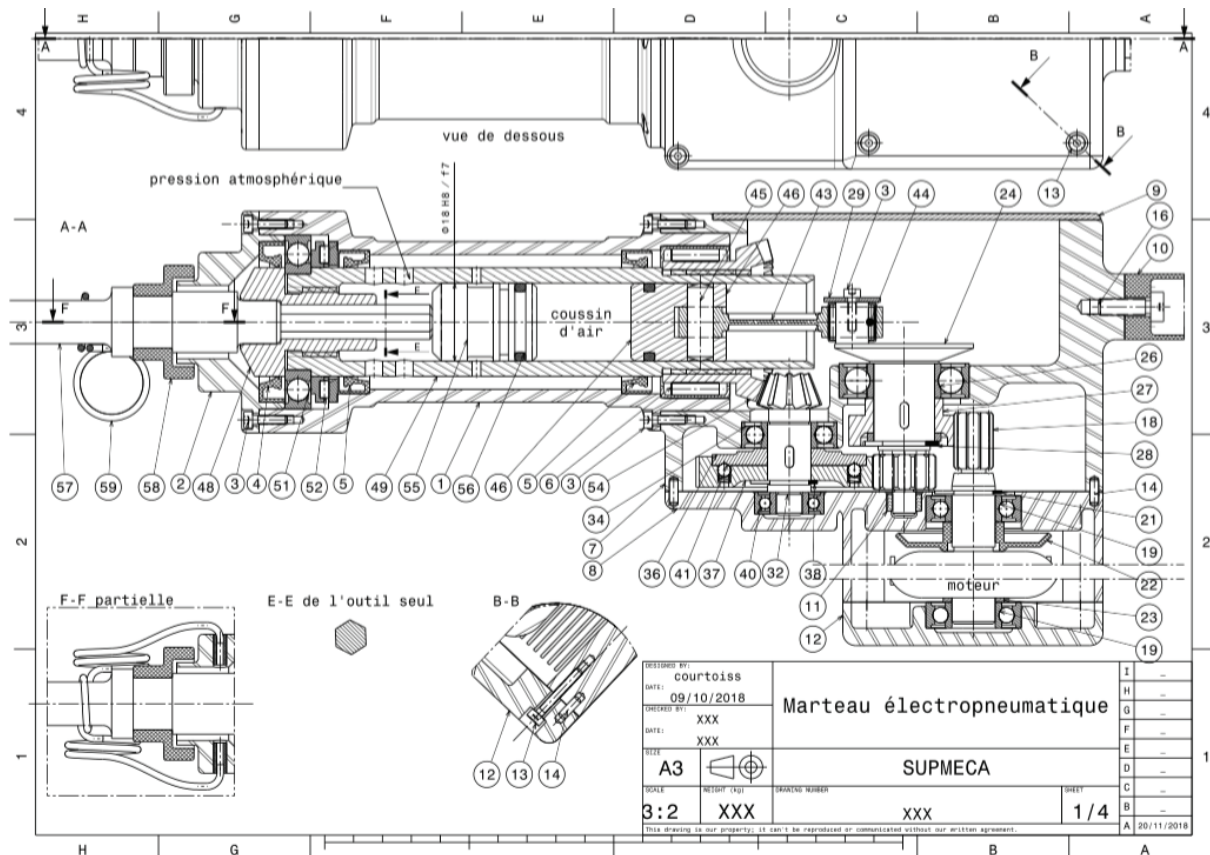
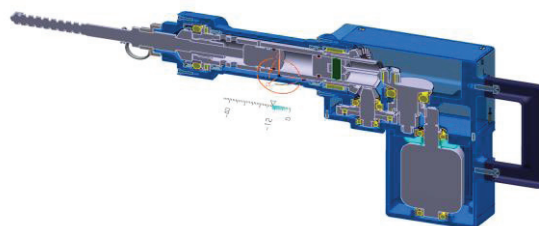


Fig. 7. Example of a perspective representation of a cross section generated in CATIA



ALPR deals with the acquisition of basics in algorithmic, fundamental data structures, and C programming language. Assessment ALPR1 focused on the understanding of code and the writing of simple functions. ALPR2 focused on algorithmic and C programming language.

3.3.3 Data analysis

An analysis of variance (ANOVA) was performed to explore the link between student performance on spatial tests and academic assessments, using SPSS. For each analysis, the spatial test score was used as the independent variable and the academic result was used as the dependent variable.

Means and standard deviations for each group, i.e. males, females, undergrad specialisations, were calculated to compare performance on the spatial tests.

4 RESULTS

Students' spatial scores are presented in *Table 2* and results for APMA, MEAN, and ALPR in *Table 3* respectively.

Table 2. Spatial scores

Spatial test	Highest score possible	Mean	Standard deviation	N
MCT	25	15.14	5.60	137
R PSVT:R	30	24.12	4.25	131
MRT	20	12.24	4.23	137

Table 3. Academic results

Course	Highest score possible	Mean	Standard deviation	N
APMA	20	11.40	3.68	140
MEAN	20	13.02	2.53	138
ALPR1	20	15.12	3.23	138
ALPR2	20	12.65	4.35	134

The significant results following the ANOVA are presented in *Table 4*.

Table 4. Analysis of variance

Dependent variable	Predictor	P-value	Coefficient	Constant
ALPR1	MCT	0.007 **	0.139	13.050
ALPR1	R PSVT:R	0.041 *	0.140	11.847
ALPR1	MRT	0.012 *	0.171	13.060
ALPR2	MCT	0.036 *	0.145	10.420
APMA	MCT	0.038 *	- 0.116	13.127
APMA	R PSVT:R	0.049 *	- 0.145	15.024
MEAN	MCT	0.001 **	0.241	9.394
MEAN	MRT	0.016 *	0.240	10.277

Note : ** $p \leq 0.01$

* $0.01 < p \leq 0.05$

The ANOVA revealed a low significant prediction capacity of the R PSVT:R ($p = 0.041$) and the MRT ($p = 0.012$) for performance on ALPR1, and of the MCT ($p = 0.036$) for performance on ALPR2. It also showed a highly significant prediction capacity ($p = 0.007$) of the MCT for performance on ALPR1. It indicated a low significant prediction capacity of the MCT (0.038) and the R PSVT:R ($p = 0.049$) for performance on APMA. Finally, this analysis brought to light a highly significant prediction capacity ($p = 0.001$) of the MCT and a low significant prediction capacity ($p = 0.016$) of the MRT for performance on MEAN.

The mean scores for undergrad specialisations are presented in *Table 5*. Those for men and women are presented in *Table 6*.

Table 5. Spatial scores according to undergrad specialisation

	MCT		R PSVT:R		MRT	
DUT	Mean	17.4 (SD= 5.16, N= 5)	Mean	26 (SD= 2.19, N= 5)	Mean	13.2 (SD= 4.87, N= 5)
	Mean %	69.6	Mean %	86.66	Mean %	66
MP	Mean	13.5 (SD= 5.46, N= 44)	Mean	24.35 (SD= 3.93, N= 44)	Mean	11.47 (SD= 4.42, N= 44)
	Mean %	54	Mean %	81.19	Mean %	57.38
PC	Mean	14.10 (SD= 5.39, N= 19)	Mean	24.36 (SD= 4.45, N= 19)	Mean	12.31 (SD= 3.74, N= 19)
	Mean %	56.41	Mean %	81.22	Mean %	61.57
PE	Mean	15.91 (SD= 4.88, N= 45)	Mean	23.64 (SD= 4.01, N= 42)	Mean	12.33 (SD= 4.09, N= 45)
	Mean %	63.64	Mean %	78.80	Mean %	61.66
PT	Mean	20.45 (SD= 4.05, N= 11)	Mean	25.5 (SD= 3.44, N= 10)	Mean	15.72 (SD= 3.13, N= 11)
	Mean %	81.81	Mean %	85	Mean %	78.63
TIS	Mean	22 (SD= 2.16, N= 3)	Mean	28.33 (SD= 1.69, N= 3)	Mean	14.33 (SD= 2.62, N= 3)
	Mean %	88	Mean %	94.44	Mean %	71.66

Table 6. Spatial scores for men and women

	MCT		R PSVT:R		MRT	
Men	Mean	14.86 (SD=5.42, N=100)	Mean	24.26 (SD= 3.75, N= 95)	Mean	12.19 (SD= 4.16, N= 100)
	Mean %	65.12	Mean %	82.94	Mean %	66.10
Women	Mean	12.08 (SD= 4.81, N= 37)	Mean	22,11 (SD= 4.75, N= 36)	Mean	9.62 (SD= 3.06, N= 37)
	Mean %	48.32	Mean %	70.70	Mean %	48.10

Men outperformed women in all tests. Students with technical backgrounds, i.e. DUT, PT, PE and TIS, outperformed students with other backgrounds, i.e. PC and MP, in the MCT and MRT, although the limited size of the samples of students with technical backgrounds does not enable us to draw conclusive comparisons.

5 DISCUSSION

The ANOVA showed there is a weak to strong significant relationship between the spatial tests used in this study and the academic assessments for ALPR. Although these did not contain spatial elements, correlations between spatial ability and computer science have been established: Wai et al.'s study showed that Project Talent's subjects who gained masters or doctorates and held positions in computer science demonstrated higher spatial ability in high school [1].

The analysis revealed a weak significance of the capacity of the MCT and the R PSVT:R to predict performance in APMA. This assessment did not contain visual elements, but the negative correlation indicates that high scores on the spatial tests predict failure in this subject, whereas low scores predict success. According to the assessment's author, solving the problems presented in this assessment requires abstraction (S. Dugowson, personal communication, 3 April 2019). Does this mean that individuals with high spatial skills lack this ability? Inversely, does this mean that individuals who possess it are characterised with low spatial skills? There is a notable difference between the ANOVA results for the MRT and the R PSVT:R, which both claim to measure mental rotation, but whose administration procedures are different.

The MRT is time-limited, as time restriction discourages analytical processing [6]. Analytical processing, which allows subjects to decompose objects in smaller elements to enable comparison, does not make use of mental rotation [6], which involves the mental manipulation of visual objects. Post-test consultation of respondents' solving strategies shows that the MRT allows for a variety of strategies [14, 15]. On the contrary, the R PSVT:R is not limited in time to avoid female underperformance, as women tend to get lower scores when they take time-limited tests [18]. As far as we know, no study has described the use of analytical processing in solving the R PSVT:R items. The difference in the ANOVA results for the MRT and the R PSVT:R could be explained by the fact that the R PSVT:R is a more reliable instrument to measure mental rotation.

Using visual information presented in perspectives and cross sections implies the ability to understand and interpret different means of representation of the same information. The significant correlations between the MCT and the MRT scores and the MEAN results can lead to several interpretations: the spatially weak students could not interpret and use the visual information provided in the assessment, use the 3-D modeller successfully [3], nor benefit from the information available in the modeller because their weak internal representations did not allow them to access external representations [20]. The absence of a correlation between the R PSVT:R and the MEAN results, whereas there is one with the MRT, could be explained by the fact that the MEAN assessment does not make use of mental rotation.

The well-documented lower performance of women on spatial tests [2, 6, 7, 14, 18] is confirmed in our study, which also highlights a difference in performance according to the undergrad specialisation. Students with more technical backgrounds, i.e. DUT, PT, PE and TIS, outperformed other students in the MCT and the MRT, although this conclusion must take into consideration the small size of the samples of students with TIS, PT and DUT backgrounds. Interestingly, the PT, PE and IST students are taught about complex systems for 4 to 8.5 hours a week, whereas it is optional for MP students and absent from PC students' curriculum. The very close scores of PE and PC students on the MRT and the R PSVT:R seem to indicate that this course has a greater impact on performance on the MCT.

4.4 Limits and perspectives

The students were not asked which strategies they adopted while taking the spatial tests. It is therefore difficult to assert which spatial skill, if any, was made use of during the tests. Further experiments including the collection and the encoding of these data are necessary to clarify this variable.

The MEAN assessment allowed students to access CATIA, where they could create richer isometric views – the views are in colours and shadows represent depth - and 2-D representations: e.g., possibility to hide and reveal parts and to choose a point of view or a cross section. The students' activity on the software was not recorded. A complementary study is necessary to explore how student use, or lack of use, of the software is related to their spatial skills and performance on the assessment.

6 CONCLUSIONS

The spatial visualisation skills of French first-year engineering students, who joined the school after a two-year undergrad course, were measured with the MCT, which aims at measuring mental transformation, the MRT and the R PSVT:R, which aim at

measuring mental rotation. The students took the tests at the beginning of the academic year. An analysis of variance of these scores and their performance on assessments focusing on applied mathematics, system analysis, algorithmic and C language programming revealed a highly significant capacity of the MCT to predict performance on mechanism analysis and C language understanding and programming. It also highlighted a low significant capacity of spatial visualisation skills to predict performance on the ability to understand codes and write simple functions in C language, as well as a low significant capacity of the MRT to predict performance on mechanism analysis. Finally, it brought out a fairly significant negative correlation between spatial visualisation and the ability to solve problems focusing on distributions, convolutions, the Laplace transform and the Fourier transform. Our hypothesis that spatial visualisation and performance in assessments including 2-D and 3-D representations has been validated. Our study revealed a link between spatial visualisation and the ability to understand codes and write simple functions in C language, confirming previous research that spatial ability and performance in computer science are related [1]. A negative correlation was also found between spatial visualisation and performance in applied mathematics. The well-documented underperformance of female students, compared to male students, was confirmed in our study and a better performance for students coming from undergrad technical backgrounds was observed. The capacity of spatial tests to predict performance in engineering courses [1] and the malleability of spatial skills have been established [5]. These findings open the possibility to design and implement remedial courses, prior to the beginning of the academic year, to support French engineering student learning and performance [2], and give students access to a larger choice of specialisations in their academic career.

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