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Gender differences in mental rotation test: a geometry-teaching perspective

Diferencias de género en test de rotación mental: una perspectiva desde la enseñanza de la geometría

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ABSTRACT

According to reports in the literature, males score higher on certain mental rotation tests and complex problem-solving exercises than females. This study analyzes the types of errors made in the Primary Mental Abilities (PMA) space relations sub-test test by 328 secondary school students (ages 13 to 16), 143 of whom, having exhibited complex mathematical problem-solving abilities, were participating in a mathematical talent enhancement programme. The error types detected are defined in terms of angle of rotation of the object and the presence of symmetries in the items of the test. The findings show significantly higher performance in the more mathematically gifted students. Gender differences are only evidenced in the total score of the test and the number of non-answered items, where boys got higher scores than girls. Moreover, there is no significant interaction between the independent variables gender and complex mathematical problem-solving abilities. The conclusions drawn from those findings introduce nuances in the understanding of the gender difference traditionally identified in visualisation, particularly in connection with geometric properties in mental rotation tests. It is stressed that educational research focuses on other aspects, like emotional or behavioural ones that can impact test execution, like speed or the use of less efficient strategies.

Keywords: mental rotation, PMA test, complex problem solving, gender differences

RESUMEN

De acuerdo con la literatura, los hombres obtienen puntuaciones superiores a las mujeres en ciertas pruebas de rotación mental y en ejercicios de resolución de problemas complejos. Este estudio analiza los tipos de errores cometidos en la subprueba de relaciones espaciales de habilidades mentales primarias (PMA) por 328 estudiantes de secundaria (edades comprendidas entre los 13 y 16 años). De ellos, 143 participaban en un programa de estímulo del talento matemático, dado que habían mostrado habilidades en la resolución de problemas matemáticos complejos. Los tipos de errores detectados se definen en términos del ángulo de rotación del objeto y la presencia de simetrías en los ítems del test. Los resultados muestran un rendimiento significativamente mayor de los alumnos con alta habilidad matemática. Las diferencias de género únicamente se evidencian a favor de los chicos en la puntuación global del test y en el número de ítems no contestados. Sin embargo, no se encuentran diferencias de género en ninguno de los tipos de errores asociados a las propiedades geométricas de los ítems. Además, no existe interacción significativa entre las variables independientes género y habilidad para la resolución de problemas complejos. Las conclusiones extraídas de esos hallazgos introducen matices en la comprensión de las diferencias de género identificadas tradicionalmente en las habilidades de visualización, particularmente en relación con las propiedades geométricas en las pruebas de rotación mental. Se enfatiza que la investigación educativa puede focalizarse en otros aspectos, como pueden ser los emocionales o actitudinales que afectan al proceso de realización de los test, como la rapidez o el uso de estrategias menos eficientes.

Palabras clave: rotación mental, test PMA, resolución de problemas complejos, diferencias de género

INTRODUCTION

The literature has identified differences by gender, with males scoring higher in performance on standardised tests measuring a command of mathematics (Hyde et al. 1990; Scheiber et al. 2015, among others) or spatial abilities (Halpern et al., 2007; Voyer & Saunders, 2004), mental rotation in particular (Hyde, 2014; Xu et al., 2016). Gender differences are less obvious when other measuring tools are used, however (Ganley & Vasilyeva, 2011; Gibbs, 2010). Some studies, assessing classroom learning or skills defined in the curriculum, have found girls to score higher than boys (Corbett et al. 2008; Liu & Wilson, 2009; Voyer & Voyer, 2014; Yarbrough et al., 2017). A number of authors have observed women to perform better as a rule in tests measuring numerical skills, and men in tasks calling for mathematical reasoning (Gibbs, 2010; Scheiber et al., 2015).

These differences have clear educational implications, as the practice with spatial tasks can bridge the gender gap in this type of reasoning (Rodán et al., 2022; Wu & Shah, 2004). As an example, evidence was found that mental rotation training can improve performance in mathematical tasks like calculation problems (Cheng & Mix, 2014). In this sense, visual-spatial abilities can condition success in STEM areas (Science, Technology, Engineering and Mathematics), where girls take advanced courses or related degrees to a lesser extent (Reinking & Martín, 2018). Research literature on gender differences documents the intertwined nature of spatial and mathematical development, suggesting that the activities aimed to increase spatial abilities can have positive effects on mathematics learning by students (Johnson et al., 2021). If the differences obtained stemmed from the implied mathematical contents, then the results would provide guidelines for the design of tasks and learning process, because those differences would need to be attended through proper diversity awareness instruction. This would also have consequences in the design of curricular programs, training of teachers and classroom planning, because the tasks presented would be more effective if the educational potential is maximized by bridging the differences (Rodán et al., 2022). However, recent meta-analysis showing that spatial training is effective to improve mathematical understanding and performance highlights a poor understanding of the mechanisms that support transfer and demands more theoretically-guided studies (Hawes et al., 2022).

The first stage in that endeavour is the establishment of relationships between spatial skills and mathematics. Some authors have contended that spatial abilities may determine mathematical performance, particularly as regards geometry (Ganley & Vasilyeva, 2011). A possible explanation of the role of mental rotation in mathematical scores is related to problem-solving strategies (Delgado & Prieto, 2004). Geometric problem solving, unlike simple arithmetic or numerical tasks, may be impacted by factors other than mathematical ability, such as visuo-spatial aptitudes (Clements, 1980; Delgado & Prieto, 2004; Harris et al., 2021). The effect of spatial abilities might explain the differences in solving complex problems where they are required. Some authors have found men to be better at solving geometric problems requiring visualisation (González-Calero et al., 2018; Ramírez-Uclés et al., 2013). Others, in contrast, have reported that although gender differences can be found among secondary school students in spatial visualisation and performance in geometric tasks, no such differences were observed in the ability to reason or in the strategies used to solve geometric problems (Battista, 1990). At the same time, several studies have shown that greater mathematical ability to solve problems translated into higher mental rotation test scores (Ramírez-Uclés et al., 2013) and in geometrical tasks involving visualization (for example, Rabab'h & Veloo, 2015; Ramírez & Flores, 2017; Rivera, 2011).

In an attempt to explain that variability, several reviews and meta-analyses have identified complexity as a factor with a bearing on gender differences in mathematics performance (Else-Quest, et al., 2010; Lindberg et al., 2010). Studies on gender differences that detected no significant variation in numerical errors, geometric notions or basic mathematical concepts and competence in addition, nonetheless reported men to solve complex mathematical problems more effectively than women (Stewart et al., 2017). In that same vein, other authors who observed no gender differences in simple tasks or spatial ability found boys significantly better able to deal with more difficult tasks (Manger & Eikeland, 1998). Such gender differences have also been identified in tests that measure mathematical talent (Benbow & Stanley, 1996).

In this research the tool at issue was broached from a descriptive perspective, given that a number of studies have detected evidence that the characteristics of a given task may explain the gender differences observed in mental rotation tests (Lauer et al., 2019). The aim here focused on understanding gender-related differences in performance on a mental rotation test depending on the geometric complexity of the test item. More specifically, the question posed was: can the uneven performance between girls and boys be attributed to the geometric characteristics of the mental rotation test itself? The primary aim would be to ascertain whether gender differences are due to the geometric properties of mental rotation in terms of the presence of symmetries and different angles of rotation. No universally accepted indication supports the premise that such characteristics specifically determine gender differences. The processes carried out during the test determine the participants' efficiency in solving a spatial task, so differences might well stem from factors identified in other studies, such as test scoring, response time limitations or the use of effective strategies (Contreras et al., 2012).

In this sense, attempts have also been made to understand the differences between boys and girls not only in their cognitive ability to solve complex problems requiring mathematical reasoning, but also in their approach to schoolwork and learning strategies, classroom behaviour or self-regulation, mathematical self-efficacy and planning and attention strategies (Yarbrough et al., 2017). Gender differences have been detected in self-confidence, with women exhibiting less (Preckel et al., 2008), for instance, in situations in which they scored lower if they were aware that the task at hand was intended to reveal gender differences (Spencer et al., 1999) or in competitive contexts where they proved to be more sensitive to pressure (Niederle & Vesterlund, 2010). Bench et al. (2015) provided helpful insight into self-confidence. When completing a mathematics test, men were observed to judge their success more highly than women, creating a positive bias. Nonetheless, women who had scored earlier success in mathematics likewise over-estimated their own performance (Bench et al, 2015). Consequently, in this study subjects' mathematical ability was deemed of significance in understanding the gender differences associated with stereotypes in mathematics.

Gender differences were broached essentially from a psychometric perspective, analysing subjects' performance on a standardised test (Steinmayr & Spinath, 2008; Wach et al., 2015). Some earlier studies have identified test administration or scoring procedures, such as limiting the time allowed (Maeda & Yoon, 2016; Peters, 2005) or using raw scores (Goldstein et al., 1990; Stumpf, 1993), that may condition such differences, whereas other authors have found no evidence of the effect of such factors (Voyer et al., 2004; Yoon & Mann, 2017). This research deployed the Primary Mental Abilities spatial relations tool (PMA-SR, Thurstone & Thurstone, 1943), a mental rotation test in which men and subjects with complex problem-solving ability have been observed to perform better, although no interaction between those two variables has been detected (Ramírez-Uclés & Ramírez Uclés, 2020).

Gender differences in the PMA-SR sub-test

Gender differences have been identified in PMA-SR performance (Campos, 2014; Lauer et al., 2019; Linn & Petersen, 1985; Stericker & LeVesconte, 1982). PMA-SR elements may be effectively analysed with both spatial strategies (differentiating among rotated reflection symmetries) and 'analytical' problem solving, which involves comparing the characteristics of the stimuli to identify matching features (shape, for instance). The latter procedure has been observed to be used more by women than by men (Linn & Petersen, 1985). Men may rely more on spatial strategies that entail visualising the rotation of objects or parts thereof, whereas women may rely more on strategies that involve comparing the characteristics of stimuli (such as size, shape and colour of the components and their inter-relationships) (Just & Carpenter, 1985; Pezaris & Casey, 1991). Although the reasons for gender differences in strategy use are unknown, the deployment of different strategies has been reported to be a source of inter-sex variation in mental rotation skills during child development (Lauer et al., 2019). Investigations with tasks similar to PMA items, with rotated letters in mirrored form, showed that the strategy used comprised mental rotations of the images until being vertically oriented, and then another rotation out of the plane to return it to normal position (Núñez-Peña & Aznar-Casanova, 2009). When carrying out such process to identify the correct answers in the PMA test, items related to larger angles or presenting symmetries required more time for checking. This strategy, applied to the PMA test (see the example shown in Figure 1), could differentiate between the actions required in image A (rotate 90 degrees to compare with the sample) and B (rotate 45 degrees and apply a symmetry). However, another strategy could be to compare between the different alternatives, as when B is rotated 45 degrees to yield C, which is directly equal to the symmetrical of the sample. Although gender difference does not help in correctly solving the task, it can condition the selection of a certain process that can be more efficient in finding the solution (Contreras et al., 2007; Peña et al., 2008).

Some strategies can be rooted in geometric rationale, eschewing a strictly visual approach. When realising that a composition with two symmetries was tantamount to rotation, for instance, one of the students correctly identified the plane-rotated figures by applying symmetries to the incorrect answer. As an example, answer D (Figure 1) can be rotated to obtain a figure that is symmetrical to C, which is in turn symmetrical to the sample, and therefore D can be obtained as a rotation of the sample. A better spatial sense (National Council of Teachers of Mathematics, 2000) rather than spatial visualisation alone would infer higher potential performance in this test, for certain elements of background knowledge and geometric relationships could likewise be called into play.

That supports the utility of exploring items' geometric characteristics, for several studies on spatial tests have shown the angle of rotation and presence of symmetries to affect scores. The time needed to find the correct answers varies depending on the angle of rotation and rises with the presence of reflections (Petrusic et al., 1978; Núñez-Peña & Aznar-Casanova, 2009). Wider angles of rotation have also been associated with a rise in complexity and a decline in performance (Alansari et al., 2008; Xu et al., 2016). Nonetheless, in some PMA items with a fairly high rate of erroneous replies a larger angle of rotation was not found to induce greater complexity (Cruz & Ramírez, 2018). As noted in earlier papers, that may have been because the impact of certain biased items on the total score was marginal only (Maeda & Yoon, 2016).

In light of the lack of research on the properties of spatial tests, specific research is demanded on the geometric characteristics of the direction and angle of rotation contained in items associated with gender differences (Maeda & Yoon, 2016) and on the complexity of the geometric shapes used in such tests (Arendasy & Sommer, 2012). This study is a response to such calls for research to determine whether cognitive processes may differ depending on the characteristics of the stimuli (such as object shape, rotation direction and angle, rotational task complexity) and whether the way some of those features are deployed is sex-related (Maeda & Yoon, 2016). This article addresses two types of mistakes made on the PMA spatial relations sub-test, characterised in terms of two geometric properties, angle of rotation and presence of symmetries. The aim is to analyse differences between boys and girls and between more and less mathematically skilled students. From the above premises, the study stems from the following hypothesis: 1) subjects with better mathematical abilities obtain better results in the analyzed test; 2) boys get higher scores in tests tan girls, but no gender differences are observed derived from the geometrical properties; and 3) there could be an interaction between the independent variables gender and mathematical ability in relation to the dependent variable test score.

METHODOLOGY

Participants

The sample comprised 328 secondary school students between the ages of 13 and 16 (mean: 15; standard deviation: 0.97), 143 of whom (sub-sample Complex Problem, CP) were participating in a mathematics talent enhancement programme underway in two Spanish regions, specifically Andalucía and Castilla-León. The uneven distribution by gender in this sub-sample was the result of the smaller number of girls in the programme, an issue faced in earlier studies as well (Hyde, 2014). The 184 subjects in the control sub-sample (No Complex Problem, NCP) were enrolled in different secondary schools in the same regions as the CP students, none of whom had been identified by their teacher as having complex mathematical problem-solving abilities (Table 1).

Table 1.
Sample distribution by gender and complex problem-solving skill

	CP	NCP	Total
Men	103	96	199
Women	40	89	129
Total	143	185	328

Note. CP (Complex Problem), NCP (No Complex Problem).

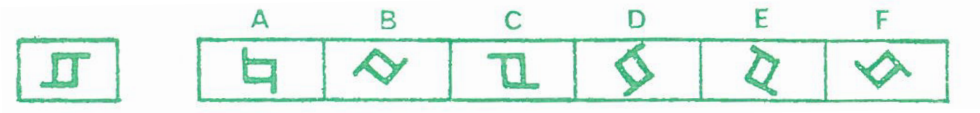
Instruments

The Spanish language version of the Thurstone (Thurstone & Thurstone, 1976) Primary Mental Abilities Test - Spatial Relations published by TEA Ediciones was used in this study. The Cronbach's alpha index calculated for this sample was 0.89, which compares to 0.93, the value indicative of reliability or internal consistency. This test measures the ability to interpret and recognise objects that change their position in space while retaining their internal structure. It is a tool often used in classroom evaluations, it is administered in five minutes and can be administered to a whole group with a few simple instructions. Each of its 20 items depicts a sample figure and six others, some of which were the result of rotating the sample around a central point (plane rotation). The remaining options were images involving symmetries and plane rotations. Each correctly identified plane-rotated figure scored as a correct answer whereas defining symmetries as plane rotations constituted an incorrect answer.

No geometric terminology (rotation, angles, symmetries) was used in the instructions for taking the test, which referred to the correct options as the figures 'that are exactly the same as the sample but in a different position'. For the incorrect answers the instructions were 'None of the others is identical to the sample, for even if you set them upright, they are backwards or upside-down'.

Allusion was made to visual strategies to identify them: 'You only need to set them up straight to see they're exactly the same'; 'Don't turn the test sheet around. Leave it flat without lifting it off the desk. You have to turn [the figures] around mentally to see what they would look like'. Three examples with the respective answers were given, noting that 'the total number of identical figures may vary from row to row'. In Figure 1, for instance the correct answers were identified as A, D and F.

Figure 1
Example provided in the test instructions



One of the particulars of the tool is that as subjects have no way of knowing the number of correct options in each item or the scoring criteria, they cannot determine the possible advantage of omitting or responding to an item when in doubt. The total score was computed as the number of correct less the number of incorrect choices, whilst two types of errors were possible: excluding a rotation or including a symmetry.

Procedure

The 143 subjects participating in the mathematics enhancement programme (sub-sample CP) were assumed to have complex mathematical problem-solving ability. To be eligible for the programme they had to pass an entrance exam based on solving complex, non-routine problems involving logic, arithmetic or geometry. The following is an example:

> *"A magic square is a 3x3 matrix such that adding the numbers in all the rows, columns and diagonals gives us the same sum. That value is the square's 'magic sum'. Could there be a magic square with nine consecutive odd numbers, seven of which are prime numbers? What would those numbers be?"*

The tests were administered to each group collectively, with examinees answering on paper and within the 5 min allowed. Participation in the test, administered by the researchers in the programme classroom for sub-sample CP and the standard classrooms for sub-sample NCP, was voluntary.

Design and variables

The independent variables in the 2x2 bifactorial intergroup design were (boy or girl) and mathematical ability (CP, in possession of complex mathematical problem-solving ability; or NCP, control sub-sample). The dependent variables were the total score in PMA test, the sets of error indicators and the types of error (described below).

Type of error

Imperfect performance in an item was the result of failing to checkmark all the identical options or incorrectly labelling one or more of the non-identical figures as identical. Since the identical figures were rotations and the non-identical figures symmetries, two types of errors were defined: exclusion of rotations and inclusion of symmetries. The geometric characterisation of those errors entailed envisioning the re-positioning needed to convert the initial sample figure into the figure shown in each proposed answer. An analysis of the items revealed that rotations could have acute angles ranging approximately from 30º to 60º, obtuse angles from around 120º to 150º and perpendicular directions forming right angles (Cruz & Ramírez, 2018). Given those characteristics, rotations were classified under four headings: 0º to 90º; 90º; 90º to 180º; and 180º (which in some figures could be interpreted as 0º if composed with the respective symmetry). Counter-clockwise rotation was defined as positive, while the first seven types of error were associated with excluding rotations. Including a symmetry as one of the four types of rotations led to a further seven types of errors (Table 2). Error type 6, for instance, was made when students failed to identify a correct choice in which the figure was rotated 90º relative to the sample. Students making error type 14, in contrast, incorrectly identified a figure obtained with a -90º rotation symmetry as a rotation. One additional type of error consisted in the failure to identify any figure as identical to the sample (type 0 = no answer).

Table 2

Type of error associated with recognition of symmetries and angle of rotation

	0º to 90º	90º	90º to 180º	180º
PR: Positive Rotation excluded	1	2	3	4
NR: Negative Rotation excluded	5	6	7	X
PS: Positive rotation Symmetries included	9	10	11	12
NS: Negative rotation Symmetries included	13	14	15	X

Note. Error types 8 and 16 are included in types 4 and 12 respectively, for the same figure is obtained whether rotated in the positive or negative direction.

Grouping the error types associated with rotations and symmetries yielded the error sets defined in Table 3.

Table 3
Error sets

Indicator	Characteristic	Error types included
PR	Positive Rotations excluded	1+2+3
NR	Negative Rotations excluded	5+6+7
R	Rotations excluded	1+2+3+4+5+6+7
PS	Positive Symmetries included	9+10+11
NS	Negative Symmetries included	13+14+15
S	Symmetries included	9+10+11+12+13+14+15

RESULTS

The data were analysed with 2 x 2 ANOVAs, with the dependent and independent variables as described in the methodology. *Partial eta squared* (η^2_p) was adopted to compute effect size. Statistical significance was set at a confidence interval of 95 %, with $p < .05$ as the criterion. Analyses were run on SPSS software (v. 19 for Windows).

Further to the findings for the total scores in PMA, students with complex problem-solving ability (CP) performed better than the controls (NCP) [$F(1, 324) = 59.43$, $p = .000$; $\eta^2_p = .155$] and girls (F) obtain lower scores than boys (M) [$F(1, 324) = 6.20$, $p = .013$, $\eta^2_p = .019$]. Nor the interaction between the two independent variables was observed to have any significant effect on subjects' performance.

Error sets

As Table 4 shows, the CP students made significantly fewer errors than the NCP controls in all the error indicator sets. They excluded fewer rotations: on the whole (R) [$\eta^2_p = .110$]; and whether positive (PR) [$\eta^2_p = .107$]; or negative (NR) [$\eta^2_p = .085$]. They also included fewer symmetries (S): [$\eta^2_p = .076$], whether positive (PS) [$\eta^2_p = .065$]; or negative (NS) [$\eta^2_p = .075$]. No significant gender-based differences were observed for any of the error sets. Nor was any significant effect found for the possible interaction between independent variables.

Type of error

The findings likewise attested to the significantly fewer errors recorded for the CP students than for the NCP controls in all the error types analysed (see Table 5): Type 0 [η^2_p = .039]; Type 1 [η^2_p = .074]; Type 2 [η^2_p = .040]; Type 3 [η^2_p = .099]; Type 4 [η^2_p = .079]; Type 5 [η^2_p = .023]; Type 6 [η^2_p = .033]; Type 7 [η^2_p = .107]; Type 9 [η^2_p = .046]; Type 10 [η^2_p = .030]; Type 11 [η^2_p = .038]; Type 12 [η^2_p = .027]; Type 13 [η^2_p = .041]; Type 14 [η^2_p = .037] and Type 15 [η^2_p = .078]. As in the error sets, no significant differences were observed in the interaction between the two independent variables for any of the error types analysed. No significant gender-based differences were observed either for any of the error sets.

In relation to the gender differences found in error Type 0, table 6 shows the percentage of unanswered options by item.

Table 4

Mean, standard deviation, and F-values for error sets by gender and mathematical ability

	CP				NCP						
	Boys		Girls		Boys		Girls		F test: F-values (1, 324)		
	M	SD	M	SD	M	SD	M	SD	M. Ability	Gender	Interaction
Error set indicator											
PR	1.73	1.35	1.43	0.87	3.11	2.91	3.37	2.65	38.72** (*p*= .000)	.09 (*p*=.930)	1.09 (*p*= .297)
NR	1.08	1.33	1.00	1.24	2.30	2.55	2.71	2.91	29.92** (*p*= .000)	.37 (*p*= .541)	.81 (*p*= .368)
R	3.12	2.70	2.73	1.84	6.49	6.54	7.26	6.75	40.20** (*p*= .000)	.92 (*p*= .762)	.87 (*p*= .353)
PS	0.45	0.74	0.25	0.63	1.15	1.90	1.09	1.47	22.53** (*p*= .000)	.67 (*p*= .437)	.19 (*p*= .667)
NS	0.46	0.87	0.32	0.57	1.40	2.03	1.42	2.18	26.30** (*p*= .000)	.08 (*p*= .779)	.15 (*p*= .703)
S	1.16	1.89	0.77	1.25	3.14	4.73	3.11	4.09	26.63** (*p*= .000)	.23 (*p*= .630)	.18 (*p*= .670)

Note. **$p< .01$; *$p< .05$.

Table 5

Mean, standard deviation, and F-values for type of error by gender and mathematical ability

	CP				NCP						
	Boys		Girls		Boys		Girls		F-test: F-value (1, 324)		
	M	SD	M	SD	M	SD	M	SD	M. Ability	Gender	Interaction
	Type of error										
Total score PMA	32.26	9.98	30.55	10.05	23.40	12.57	18.28	11.72	59.43** (*p*= .000)	6.20*(*p*= .013)	1.54 (*p*= .215)
Type 0	6.38	3.83	7.30	3.67	7.66	3.94	9.29	3.73	13.00** (*p*= .000)	9.95** (*p*= .005)	0.62 (*p*= .431)
Type 1	1.23	0.88	1.13	0.68	1.71	1.17	1.91	1.18	25.95** (*p*= .000)	0.15 (*p*= .705)	1.57 (*p*= .211)
Type 2	0.18	0.46	0.20	0.33	0.40	0.71	0.59	1.16	13.41** (*p*= .000)	0.01 (*p*= .938)	0.05 (*p*= .822)
Type 3	0.31	0.59	0.10	0.30	0.81	1.14	0.90	1.11	35.77** (*p*= .000)	0.33 (*p*= .568)	1.57(*p*= .173)
Type 4	0.31	0.63	0.30	0.46	1.07	1.65	1.18	1.68	27.87** (*p*= .000)	0.09 (*p*= .757)	0.14 (*p*= .706)
Type 5	0.28	0.51	0.30	0.61	0.29	0.54	0.55	0.85	7.47** (*p*= .007)	0.16 (*p*= .688)	0.03 (*p*= .852)
Type 6	0.33	0.72	0.37	0.63	0.66	1.03	0.78	1.07	10.94** (*p*= .001)	0.56 (*p*= .456)	0.11 (*p*= .736)
Type 7	0.47	0.70	0.32	0.57	1.15	1.29	1.38	1.67	38.76** (*p*= .000)	0.12 (*p*= .733)	1.83 (*p*= .177)
Type 9	0.20	0.45	0.13	0.40	0.48	0.95	0.55	0.88	15.59** (*p*= .000)	0.02 (*p*= .966)	0.71 (*p*= .398)
Type 10	0.09	0.28	0.05	0.22	0.28	0.69	0.22	0.52	9.88** (*p*= .002)	0.64 (*p*= .424)	0.27 (*p*= .870)
Type 11	0.16	0.41	0.08	0.35	0.39	0.70	0.31	0.57	12.91** (*p*= .000)	1.38 (*p*= .248)	0.05 (*p*= .942)
Type 12	0.25	0.81	0.20	0.40	0.59	1.28	0.61	1.23	9.03** (*p*= .003)	0.25 (*p*= .874)	0.69 (*p*= .783)
Type 13	0.18	0.52	0.15	0.36	0.54	1.06	0.54	1.00	14.02** (*p*= .000)	0.34 (*p*= .854)	0.03 (*p*= .872)
Type 14	0.07	0.25	0.00	0.00	0.21	0.54	0.22	0.55	12.38** (*p*= .000)	0.25 (*p*= .619)	0.66 (*p*= .417)
Type 15	0.20	0.45	0.18	0.38	0.65	0.87	0.65	0.90	27.46** (*p*= .000)	0.02 (*p*= .896)	0.84 (*p*= .843)

**p< .01; *p < .05.

Table 6
Percentage of unanswered options by item

	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10
Boys	1.98	2.97	3.96	2.97	2.47	4.95	5.44	12.37	14.85	21.78
Girls	1.55	1.55	3.10	1.55	1.55	6.2	10.82	25.58	20.93	31.00
	Item 11	Item 12	Item 13	Item 14	Item 15	Item 16	Item 17	Item 18	Item 19	Item 20
Boys	35.14	40.09	46.53	53.96	60.39	72.27	76.73	83.16	87.62	89.10
Girls	44.96	52.71	62.01	71.31	78.29	86.04	90.69	92.24	91.47	93.79

DISCUSSION AND CONCLUSIONS

In light of the present findings, the analysis of two types of errors identified in the PMA test can be said to introduce a nuance in the gender- and mathematical ability-based differences observed in earlier studies.

In this study significant differences were found between students with and without the ability required to solve complex mathematical problems. The former made significantly fewer mistakes of all the types analysed, more effectively differentiating between rotation and symmetry irrespective of the angle of rotation. That finding was consistent with earlier reports that associated greater mathematical competence with higher performance in this type of assessment tools (Ramírez-Uclés et al., 2013)

Gender was not found to have a significant effect on any of the errors or error sets derived from the geometrical properties. No gender differences in performance were detected in connection with angles of rotation or symmetries. In other words, being a boy or a girl did not affect the presence of errors consisting in omitting correct answers for a given angle of rotation or incorrectly including a symmetry. That finding would afford an initial response to one of the issues identified in the literature to be in need of attention (Maeda & Yoon, 2016), inferring that the gender differences found in test performance must be due to other factors. Such factors appear to be related to the fact that boys answer more items (Goldstein et al., 1990; Maeda & Yoon, 2016; Peters, 2005). Contrary to earlier reports (Alansari et al., 2008; Petrusic et al., 1978; Xu et al., 2016), no greater complexity was perceived with wider angles of rotation or the presence of symmetries.

However, significant gender differences were observed in the test score and the number of non-answered items, especially those resulting from lack of time (Ramírez-Uclés & Ramírez Uclés, 2020). Table 6 shows that, from item 11 onwards, more than 50% of girls do not answer thus pointing to the use of strategies that demand more time in the response. Given the specific characteristics of the test and the fact that the subjects are unaware of the number of correct options, we find it interesting to study in future works whether differences stem from personality traits related with poor self-confidence or the need to constantly check the results.

Nor was the interaction between the two independent variables (gender and complex mathematical problem-solving ability) observed to have any significant effect. In the items analysed, a command of complex problem-solving was the feature that determined higher test performance, with no gender-based differences observed. These findings introduce considerable nuance in the understanding of the gender differences traditionally identified in visuo-spatial aptitudes and more specifically in mental rotation. Here more mathematically skilled subjects exhibited higher performance on the test, irrespective of gender. Higher performance may be attributable to other factors forming part of geometric rationale, such as an understanding of properties unaltered by isometry (parallelism, perpendicularity and relative position are all retained), order 2 compositions (a composition with two symmetries is a rotation; one with two rotations a third rotation; one with a rotation and a symmetry, a second symmetry) or analytical strategies (Linn & Petersen, 1985).

Mathematics educators have long stressed the importance of drawing connections between visuo-spatial ability and problem solving (Arcavi, 2003; Clements & Battista, 1992). In addition to visualisation, the classroom development of a sense of space (National Council of Teachers of Mathematics, 2000) entails other features of geometric knowledge, such as movements in a plane and in space. Mental rotation items could be performed more efficiently by subjects with a more highly developed sense of space. Nonetheless, tasks associated with that sense such as those requiring physical construction, mental conversion of foldable or non-rigid objects; or the identification of simple shapes embedded in more complex shapes, not usually deemed mental rotation tasks, are excluded from certain meta-analyses (Lauer et al. 2019). The gender differences detected in mental rotation tests might be more fully understood if research focused at the same time on the geometric rationale involved in performing the tasks in an attempt to address the controversy identified in a number of studies (such as Battista, 1990; and González-Calero et al., 2018). Boys' ability to work faster on this test led to higher performance, for instance. Another area worthy of study would be personality traits, above and beyond cognitive factors, that might affect the deployment of more effective and efficient strategies (Preckel et al., 2008; Yarbrough et al., 2017). Factors such as self-confidence may be an outcome not only of a subject's gender, but also of their mathematical ability (Bench et al., 2015). Given that mental rotation abilities are reportedly improved by fostering motivational beliefs and improving selfcompetence perceptions, motivational aspects get relevance in the educational processes to improve mental rotation abilities (Moè, 2021).

Among the limitations of this study, we can highlight that no general intelligence test is included that relates the ability to solve complex problems with the intellectual G factor. In future studies it would be interesting to include both variables to observe the potential relationship between the corresponding constructs. Another limitation of the work is given by the study of a concrete test and a particular sample in which there were different numbers of boys and girls. However, we consider that the results provide interesting educational information in relation to the gender differences found in STEM. In a test traditionally showing gender differences it wasn't proved that such differences stemmed from the geometrical characteristics analyzed.

The fact that the mathematical contents did not cause the differences could shift the focus of the educational process towards saving the differences in emotional and behavioral aspects, such as self-confidence.

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