The Role of Gender and Curriculum in Mental Rotation & Perspective Taking

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Abstract

Spatial abilities and their developmental trajectory are an important part of human intelligence and have been the subject of numerous studies, including mental rotation and perspective taking. However, little is known about these processes in under-represented populations. Here we report a study on 10-year-old children in such a context who participated in four spatial tasks – animal picture mental rotation, abstract figures mental rotation, memory for object location, and picture perspective taking. Results revealed no male advantage on any task, and better performance in the abstract figures task for girls following an alternative school program in mathematics. Furthermore, the analysis found no correlation between the mental rotation and perspective taking performance. Research on under-represented populations is an important drive towards greater generalizability of findings and conclusions.

Keywords: mental rotation, perspective taking, spatial ability, gender

Introduction

Numerous studies on cognitive processing and intelligence have emphasized the significance of spatial skills. Spatial visualization, for example, has been identified as an important component in theories of intelligence. Most spatial research has been skeptical of the notion of a singular defining concept for spatial ability (Newcombe & Shipley, 2015; Uttal et al, 2013) and has demonstrated the existence of a wide range of abilities found to differ significantly among individuals. Spatial visualization itself may involve rather different and potentially unrelated components such as are found to play a role in processing information in object-based or layout/scene based mental manipulation. One type of experimental task that has stood the test of time is mental rotation (MR) which tests participants' ability to imagine views of objects when rotated in a certain direction and at a certain angle that differ from the way they are presented and perceived. In this case, the viewer's position and viewpoint remain stable and a certain pattern of rotation is imputed to the object being viewed. The use of classic examples of this task and their variations have contributed a great deal to our understanding not only of spatial ability but also of the role of individual differences in mental reasoning. Although there has been recent criticism on the topic (Bartlett & Camba, 2023), sex/gender differences have been highlighted in studies across the lifespan (Voyer & Hou, 2006; Lauer, Yhang, & Lourenco, 2019). Furthermore, the age of 10 years has been seen as crucial in this respect (Titze, Jansen, & Heil, 2010).

Individual differences of this kind and scale are an important research topic both for basic research and for the applied examination of their role in human development with a particular focus on young children's growing abilities, school performance, and career choices as seen in the link between spatial intelligence and STEM disciplines in school and beyond. In fact, variations in spatial abilities among individuals have been linked to differential success in science and technical fields, including relevant skills such as mathematical reasoning. While potential explanations for these links have been suggested, more research is required to validate these theories.

In recent years, researchers in several countries have been mapping the trajectory of development of mental rotation in preschool and elementary school years in children from 3 to 10 years of age (Frick, Möhring, & Newcombe, 2014; Frick & Pichelmann, 2023; Titze, Jansen, & Heil, 2010). As a result, we now understand much better the role of gender in developmental trajectories of spatial ability and the impact of social factors such as stereotype threat (e.g., Titze, Jansen, & Heil, 2010).

However, these efforts have been limited geographically and culturally with the bulk of studies originating from North America and Western Europe, akin to a bias in the research literature in fields of psychology and cognitive science. Little is known about children's spatial ability in the region of Eastern Europe, for example, where the current study is situated. Although it may be reasonable to expect limited variation in spatial development across countries and cultures generally, systematic comparisons of cross-country differences are hard to find.

Despite some recent critique (e.g., Andersson & Sandgren Massih, 2023), the Programme for International Student Assessment (*PISA*) survey is a well-established international assessment format that measures 15-year-old students' reading, mathematics, and science literacy every three years. In this country, Bulgaria, average 2022 results were down compared to 2018 in mathematics and reading, and students have scored less than the OECD average in mathematics, reading and science consistently over the last decade. It is worth noting however that boys and girls performed at similar levels on average in mathematics in this country as well as in 24 others while boys outperformed girls in 40 other countries,

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that is there is no evidence for a gender gap in mathematics in the PISA assessment for this country while there is sufficient data to indicate cross-country variation in performance in mathematics overall and in terms of the existence of a gender gap in particular.

In this context we report a study investigating the role of gender and school curricula in the development of spatial skills in fourth-grade students. In order to overcome weaknesses in the standard school curriculum, alternative subject programs are used in the hope that the innovative methods would enhance school children's performance, motivation, and attitude towards subjects that are perceived as challenging and difficult to master such as mathematics. Such programs may not only improve school performance but can also contribute to reducing math anxiety and produce generally positive school attitudes (Solomon, Dupuis, O'Hara, Hockenberry, Lam, Goco, ... & Tannock, 2019; Ramirez, Gunderson, Levine & Beilock, 2013). The particular alternative program in this study is JUMP math, a program aimed at facilitating the learning of mathematics for elementary school children regardless of their level of logical-mathematical skill whose central tenets are empirically supported (Solomon et al., 2019). Overall, the use of JUMP Math has been found to increase both teachers' and students' confidence and create better attitudes towards the subject (Vancouver School Board, 2007).

Gender is an important factor to consider in spatial abilities and their development. In particular, sex differences in mental rotation performance are among the largest in cognitive psychology with men outperforming women by up to 1 SD in psychometric mental rotation tests although there may be no or only small sex differences for chronometric tests. Jost & Jansen (2023) provide a theoretical review of test features and new data in an online experiment with 838 middle-aged German-speaking participants (Mage = 42.58) based on which they conclude that they could not offer explanations for sex differences in mental rotation as they did not observe meaningful sex differences at all.

While differences between tests and their features may affect performance, explanations for sex differences are yet to offer compelling definitive arguments. More specifically, we need more investigation of these potential differences, including possible effects and interactions with age, education, and cultural context.

The current study examines two important factors – gender and education – across four different spatial tasks in fourth-grade students. In this design every child performed all tasks which allows for (a) direct comparisons across task format and difficulty with respect to gender and curriculum; and (b) testing for relative independence or associations in performance among the tasks. The four tasks were chosen to represent different levels of difficulty but also different components of spatial ability. They were: (i) mental rotation of animal pictures; (ii) mental rotation of abstract cube-figure shapes; (iii) memory for object location; and (iv) picture-based visuo-spatial perspective taking.

Mental rotation and perspective taking scores have been seen as reflective of independent spatial skills (e.g., Hegarty & Waller, 2004). Psychometric results have supported a distinction between mental abilities that require the spatial transformation of a perceived object (e.g., mental rotation) and those that involve imagining how a scene looks like from different viewpoints (e.g., perspective taking). In our study, children perform both types of tasks tapping into their respective component abilities. On the other hand, we also vary the level of difficulty of the spatial tasks as some findings indicate that the emergence of gender differences may depend on such a factor and become more prominent in more challenging tasks. One aspect of difficulty relates to the nature of objects represented in mental rotation tasks and their level of familiarity vs. abstraction being especially relevant to young children. Thus, we included both an easier MRT with animal pictures and a harder MRT with abstract figures.

If level of difficulty plays a significant role in task comparisons, then we expect to find an association in performance between tasks of similar difficulty, i.e., the animal rotation task and the object location memory task. If on the other hand, the underlying spatial reasoning outweighs the level of difficulty, then children's scores on the animal rotation task and the abstract figure rotation tasks should be clearly associated.

Mental Rotation

We first tested participants in a classical mental rotation task (MRT) with two versions which differed in difficulty and familiarity with the stimuli images – an animals rotation task and an abstract cube-figures rotation task. Based on findings in previous studies situated elsewhere we could expect a male gender advantage to emerge in the analysis, especially in the more difficult abstract figures task. However, a stereotype threat study with a different sample from the same age and grade in this country (Andonova, manuscript in preparation) revealed no reliable gender differences in performance on either the animal rotation task or the cube-figures rotation task in the control no-threat condition which is the equivalent to the design here. Finally, we tested 4th-graders from two schools which followed different mathematics programs (curricula) – the standard business-as-usual program and the alternative program (JUMP math).

The study aimed at answering the following questions:

(1) Is there a male advantage on MRT in 4-grade students in this country, and if so, does it depend on stimulus type (Titze et al. 2010; Neuburger, Jansen, Heil, & Quaiser-Pohl, 2011)?

Cube figures should produce a larger gender difference whereas animal pictures should produce less of a gap. We expected a more pronounced male advantage in tasks with cube figures than in tasks with animal pictures because cube figures are more gender stereotyped.

(2) Are different school programs in mathematics associated with variation in MRT performance, and if so, could an alternative mathematics program enhance the skills

of both boys and girls, or would it produce a selective advantage for girls in comparison with their counterparts in the standard mathematics program?

Participants

The sample consisted of sixty 4th-grade school children from two schools whose parents gave their informed consent. They were 28 girls and 32 boys between 10 and 11 years old which is the typical age for this educational grade in the Bulgarian educational system (M = 126.3 months; SD = 3.50; range 121 – 138 months). Each child was tested in all spatial tasks in the same order and the two mental rotation tasks (animal pictures, cube figures) came first and second in this sequence.

Stimuli

The mental-rotation tasks were similar to the ''Mental Rotations Test'' (MRT, Vandenberg & Kuse, 1978). In the animal-pictures task, colored drawings of familiar animals were used. In the cube-figures task, drawings of three-dimensional cube figures were used, and only picture-plane rotations were involved in both cases. Each item consisted of one target on the left side and four comparison stimuli on the right. Two of the four comparisons were ''correct'' (picture-plane rotated versions of the target), and two were ''incorrect'' (mirror images of the target). Participants had to cross out the two ''correct'' comparisons. In both versions, the mental-rotation tasks consisted of 16 test items.

Procedure

Children were tested in classrooms during regular school time. An experimenter administered the tests in class-based groups (5–20 children). After a short introduction, the mental-rotation task was explained based on four example items. In the animal-pictures version, participants were given two minutes for the 16 items. In the cube-figures condition, children had four minutes for the 16 items.

Results

To answer the two research questions above, an analysis of variance was conducted with gender (girls, boys) and school curriculum (standard vs. alternative) as independent variables and the score on each of the mental rotation tasks as a dependent measure.

There were no main effects and no interactions in the animal-pictures task, all $p_s > .10$ (Table 1). The results revealed no advantage for boys in this task in alignment with findings from a previous study sampling 4th-grade students here (Andonova, manuscript in preparation). In fact, the highest score was achieved by girls in the alternative program, although there was no reliable positive effect registered in the overall performance of students following the alternative math program at school.

Table 1: Mean scores for the animal-pictures mental rotation task by gender and school program.

	Mean (SD)	N
Girls Alternative	10.43 (6.68)	14
Girls Standard	8.71 (4.78)	14
Boys Alternative	9.38 (6.26)	16
Boys Standard	9.75 (5.01)	16

An entirely different pattern of results emerged in the analysis of performance on the abstract cube-figures mental rotation task. There were significant main effects of both gender and curriculum and an interaction between these factors. Overall, students in the alternative curriculum program solved more mental rotation items correctly than students in the standard program, $F_{(1,56)} = 7.21$, $p = .010$, $\eta_p^2 = .11$. The gender effect showed an advantage for girls, $F_{(1,56)} = 6.99$, $p = .011$, $\eta_p^2 = .11$. The main effects were modulated by a reliable interaction, $F_{(1,56)} = 4.88$, $p = .031$, $\eta_p^2 = .08$. The performance of girls in the alternative program was better than the other three conditions (Table 2).

Table 2: Mean scores for the abstract cube-figures mental rotation task by gender and school program.

	Mean (SD)	N
Girls Alternative	7.00 (3.35)	14
Girls Standard	3.79 (1.85)	14
Boys Alternative	3.81 (2.66)	16
Boys Standard	3.50 (2.07)	16

Object Location Memory

After the two versions of the mental rotation task (MRT) children's spatial abilities were tested on the object location memory task in an object location switch. Despite some mixed results, findings from previous studies have emphasized a female location memory advantage (Silverman & Eals, 1992) and have received a favorable interpretation from an evolutionary psychology viewpoint. Few studies however have examined gender differences on this task in children, although exceptions are available, for example, Barnfield (1999)'s study of recall for location using simplified arrays based on stimuli from Silverman & Eals (1992).

Participants

The same 60 children also performed the object location memory task.

Stimuli

In this task in its object location switch condition, participants were shown 11 objects in a simplified version of the same array used by Silverman & Eals (1992) on a sheet of paper.

Procedure

Children were tested in classrooms during regular school time. An experimenter administered the tests in class-based groups (5–20 children). Upon examining the array for 1 minute, the sheets of paper were taken away, and a new array was presented to them. The new (response) array consisted of the same set of drawings as in the original array (11 objects) but with some in exchanged positions within the array – 5 were in the same position, and 3 pairs of objects (6 objects in total) had their positions exchanged. Participants were asked to circle any objects which were in the same position and cross out those which they believed to have moved.

Results

As in the easier mental rotation task with pictures of animals, in the memory for object location task there were no main effects of gender or curriculum, and there was no reliable interaction between these factors on the memory score of the children, all $p_s > .10$.

Table 3: Mean scores for the object location memory task by gender and school program.

	Mean (SD)	N
Girls Alternative	9.21 (3.09)	14
Girls Standard	9.00 (3.28)	14
Boys Alternative	9.00 (2.68)	16
Boys Standard	10.26 (1.29)	16

Perspective Taking

Lastly, children participated in a picture perspective-taking task modeled closely after Frick, Möhring & Newcombe's (2014) study.

Participants

The same 60 children performed this task.

Stimuli

The stimuli were modeled after the Frick, Möhring & Newcombe (2014) study and included small plastic toys representing two photographers, a cube, a cylinder, and a pillar. Both figures called Peter and Lydia were holding a toy camera pointing it at the non-axial objects (cube, cylinder) at three different angles (0◦, 90◦ and 180◦) in terms of angular difference to the child's line of sight. The setup with two photographers was used as in Frick, Möhring & Newcombe (2014) and Hegarty & Waller (2004), showing that different positions of photographers afford different perspectives. Materials were, including the four response alternatives were presented as color printouts.

Procedure

Participants were tested individually in a quiet room at their school. The procedure followed closely that of Frick, Möhring & Newcombe (2014), including instruction and practice trials, stimuli familiarization, and task instruction. After the task introduction phase, children did 12 test trials for which they were instructed to point at the picture taken by Lydia/Peter from where s/he was standing, imagining looking at the scene from their point of view.

The test trials presented stimulus scenes/layouts that were a combination of three different angles (0◦, 90◦ and 180◦) and two levels of complexity (two or four objects in the scene) and four choice alternatives showing the same objects from different perspectives. The choice alternatives were distributed horizontally below the layout picture. One of the alternatives showed the correct view and three were foils, in which the orientation or spatial relations among the objects would not match the photographer's perspective. On 0◦ trials the child's own perspective was the correct answer; on 90◦ and 180◦ trials the child's perspective served as one of the foils. All layout pictures were taken from an oblique angle and all objects in the array were clearly visible. There was no time limit to complete a trial.

Test trials varied in the angular difference between the photographer's and the child's perspectives (0, 90, or 180◦) and complexity (2 or 4 objects in the layout). Each of these combinations was presented twice, with different objects and a different photographer, amounting to a total of 12 test trials. The number of objects in the layout was blocked, such that complexity increased from block to block. The different angles were presented in a pseudo-random order, with no angle twice in a row. The position of the correct choice was quasi-randomized across trials. A trial was scored with one point if the correct picture was selected, and with zero points if any of the three foils were chosen, for a total score of 12 maximum.

Results

A 3 (angle: 0, 90, or 180◦) x 2 (complexity: 2 vs. 4 object arrays) x 2 (gender: boys vs. girls) x 2 (school program: standard vs. alternative) repeated measures analysis of variance on percent accuracy on the perspective taking task was carried out. Angle and complexity were within-participant variables whereas gender and school program were between-groups variables. We found a main effect of angle $F_{(1,56)} = 17.99$, $p < .001$, $\eta_p^2 = .39$, a main effect of complexity $F_{(1,56)} = 5.36$, $p = .024$, $\eta_p^2 = .09$, and an interaction between the two, $F_{(1,56)} = 6.96$, $p = .002$, $\eta_p^2 = .20$.

The means for the within-participant conditions (angle x complexity) are plotted in Figure 1 below.

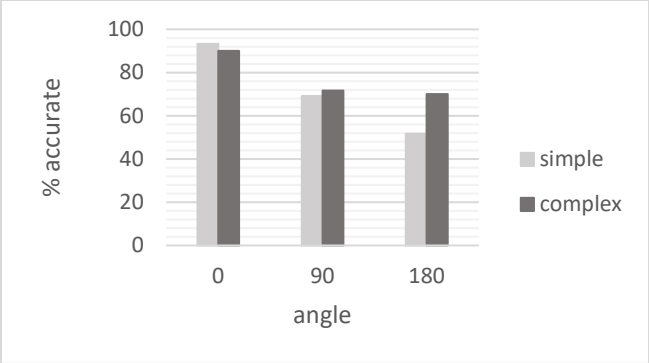

Figure 1: Mean percent accuracy on the perspective taking task (angle x complexity of layout).

There were no effects of the between-groups variables gender or school program, and no further interactions. The interaction result presented a puzzle. Whereas accuracy dropped significantly increase of angular difference to the line of sight in response to simple two-object arrays, a slightly different pattern emerged on the complex arrays – after a drop of correct responses from 0◦ to 90◦ there was no considerable change from 90◦ to 180◦. However, the interaction did not reach significance and is reported here for completeness. Apart from this exception, the results align with the findings by Frick, Möhring & Newcombe (2014).

Correlations across Tasks

The design in this study included measurements on four tasks run within-participants: mental rotation on the animal-pictures task, mental rotation on the abstract cube-figures task, object location memory, and picture perspective taking. This allowed us to address the question of separability of the different components of spatial ability that underlie performance and analyze correlations across tasks.

The analysis revealed significant correlations between children's performance on the two mental rotation tasks, r = .36, p = .005 which is not surprising given the shared task format and instruction. There was also a significant association between the simpler animal-pictures rotation task and the object location memory task, r = .41, p = .001. This relationship may be indicative either of the use of a memory component in the simple MRT, or the similarly low level of difficulty of these two tasks. Finally, and importantly, there was no correlation between performance on the picture perspective taking (PT) task and any of the other three tasks, either in terms of overall accuracy on the PT task or in terms of accuracy on any of the angle x complexity conditions within the design.

Discussion

In this study sixty 10-year-old children in their 4th grade at school completed four spatial tasks – two on mental rotation of objects, one on memory for object location, and a picture perspective taking task. The children's age and grade were chosen to match similar samples in other countries as closely as possible to allow for cross-cultural (international) comparisons. The tasks were selected on the same principle of enabling comparisons with previously published data at the same age range. In addition, they represented spatial skills that are typically considered as distinct and sometimes independent components of spatial ability. In fact, the overall pattern of results here aligns well with findings from some recent studies with children of the same or similar age, for example Frick, Möhring & Newcombe (2014) and Frick & Pichelmann (2023).

The first research question concerned replicability of the male advantage in children found in previous studies (e.g., Neuburger et al., 2011). We have found no evidence to support such a hypothesis. Gender appeared to play a role in only one of the tasks, presumably the hardest one of all four, the abstract figures MRT, and only in combination with the school curriculum variable. Furthermore, the modest gender "gap" was in the opposite direction – girls in the alternative school mathematics program performed better than girls in the standard school program and boys in both schools. This may appear contradictory to previous research, but we need to consider the following points in our interpretation. First, no male advantage has been established in studies with other samples from the same population in this country, or in school performance in mathematics in the PISA assessment. Second, findings from work in other countries have revealed positive effects of alternative mathematics programs benefiting girls. Third, the null effect is in line with more recent studies with school children of the same or similar age. For example, Frick & Pichelmann (2023) report that they found no sex differences in several spatial tasks they ran with six- to nine-year old children except one.

Our second research question aimed at testing the association of different school programs (standard vs. alternative) with variation in spatial task performance, and more specifically, if girls could benefit more from an alternative mathematics program. The results show this to be the case in the abstract figures rotation task. As a reminder, boys in the alternative program did not have an advantage in comparison with boys in the standard program, i.e., the positive association did not apply generally but to only one of the genders. Alternative mathematics programs such as *JUMP math* have been found to enhance behavioral results and attitudinal constructs especially for children who may be typically disadvantaged or under social stereotype threat.

These effects of gender and curriculum emerged only in the task which turned out to have the highest level of difficulty (compare the means in Tables 1, 2, and 3). None of the other three tasks produced such differences. The memory for object location task may have been too easy and led to a ceiling effect with mean values close to the maximum score of 11. However, this was not the case in the animal rotation task where mean values hovered around 9 correct responses to 16 items in total. Neither was the picture perspective task too easy as seen in the average percentage accuracy (Fig. 1). Therefore, while a high level of difficulty may be necessary to bring into the light individual differences, it is not the only

factor. It is possible that variable performance emerges with more abstract, and non-naturalistic stimuli such as the cube figures used in a traditional style MRT experiment. After all, the picture stimuli in all other three tasks were representative of real-world objects, animals, or people.

Finally, in addressing the last research question we carried out a correlation analysis on the performance of children in the four tasks and found that children's successful completion of the two mental rotation tasks (animals vs. abstract figures) was correlated. Given the shared task structure and presumably shared underlying mechanisms, this was to be expected. However, it was important to establish if performance on two typologically different tasks such as mental rotation and perspective taking showed signs of a dissociation or association. As has been claimed previously (see above), there was no clear association between the two. The ability to imagine views of objects after rotation and the ability to imagine alternative displaced viewpoints on a visual scene/layout appear to be unrelated in 10-year-old children. To some degree this finding stands in contrast with a recent outcome of analysis where a correlation between four MR scores and Perspective task were discovered in 6- to 9-year-old children (Frick & Pichelmann, 2023), although when age was controlled for, they were non-significant. As age was held constant in our study, it remains unclear whether it could play a role as well.

Conclusion

Individual differences in spatial ability deserve further investigation both in order to uncover underlying mechanisms and also to benefit real-world applications of our understanding of the intricate network of relations between ability, task, and context of use. It is especially important to track their developmental trajectory in traditionally under-researched populations which would allow us to draw productive comparisons and generalizable conclusions.

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