PSICOLÓGICA

Visuospatial and Motor Ability Contributions in Primary School Spatial Geometry

Laura M. Fernández-Méndez[1], Chiara Meneghetti[2], Agustín Martínez-Molina[3], Irene C. Mammarella[4], María José Contreras[5]

[1]Departament of Psychology, Rey Juan Carlos University, Madrid (Spain).
[2]Department of General Psychology, University of Padova, Padova (Italy).
[3]Department of Social Psychology and Methodology, Autonomous University of Madrid, Madrid (Spain).
[4]Department of Developmental and Social Psychology University of Padova, Padova (Italy).
[5]Department of Basic Psychology I, National Distance Education University (UNED), Madrid (Spain).

Abstract

Geometry is a subject frequently associated with mathematical performance or science interest, as well as with reasoning and spatial skills. Within the school context, geometry achievement has been connected with visuospatial abilities but less frequently with motor skills, where the embodied cognition approach seems especially important to explain the emergence of complex cognitive representations based on motor processes.

To date, few studies have assessed the contribution of both spatial and motor abilities to predict geometry performance. Thus, in this study, we aimed to examine the role of visuospatial (mental rotation and visualization) and motor skills (fine and gross motor skills) in spatial geometry achievement in primary schoolers. A total of 215 students from the second and third year of basic education participated in this study. The participants were enrolled in several tasks that involved spatial, motor and cognitive abilities. A multiple linear regression model showed that the geometry variable was explained by age, mental rotation and manual dexterity at 22%. The results suggest that geometry performance was supported by specific spatial skills (mental rotation) and fine motor (manual dexterity), but not gross motor ability in primary schoolers.

Keywords: Spatial ability, Motor ability, Geometry, Primary Education

Psicológica (2024)

DOI
10.20350/digitalCSIC/16046

Corresponding author
Laura M. Fernández-Méndez
Laura.fernandez@urjc.es

Edited by
Santiago Pelegrina

Reviewed by
Elena Isabel Rodríguez Martínez, Tracy Logan

Introduction

Geometry is a rich subject that connects and informs many areas of mathematics, science, and art as well as develops students' reasoning and spatial skills (Schifter et al., 2002; Smith & Neumann, 2014). The Program for International Student Assessment (PISA) considers that spatial ability and mathematical success involve "understanding perspectives, creating and reading maps, transforming shapes with and without technology, interpreting views of 3D scenes from various perspectives, and constructing representations of shapes" (OECD, 2019, p. 85). In fact, some of the items that assess mathematical competence in the PISA test include content related to shape and space, which are key to overall performance on the test (Sorby & Panther, 2020). Therefore, the development of geometry competence in Primary Education is a relevant question regarding academic competence. Concerning the factors that can promote geometry competence acquisition, spatial and motor abilities can play an important role (Frick, 2019).

Spatial ability and geometry performance

Spatial ability is “the capacity to create, retain and transform well-structured visual images” (p. 112; Lohman, 1996). There are some studies that sustain a positive relation between spatial and mathematical performance from childhood to adulthood (Delgado & Prieto, 2004; Gunderson et al., 2012; Mix et al., 2016; Verdine et al., 2017) but the factors that underpin this relationship are not well understood (Frick, 2019; Lowrie et al., 2019). For this purpose, it becomes necessary to distinguish among different mathematical contents and detect “subfactors” (Carroll, 1993) of spatial abilities that can be involved in a specific way. Concretely, mental rotation (MR) and visualization (VZ), among the variety of spatial skills (Uttal et al., 2013), seem to play a special role. Both can be categorized as intrinsic-dynamic abilities, following the categorization made by Uttal et al., (2013) because MR requires rotating (dynamic) two or three-dimensional objects (intrinsic) in the mind (Linn & Petersen, 1985). In a similar way, visualization refers to the ability to imagine a complex, multi-step spatial transformation (dynamic) within an object (intrinsic) (Frick, 2019; Linn & Petersen, 1985). Regarding the different contributions of some spatial abilities with respect to specific mathematical content, Frick’s study (2019) showed that the perspective taking ability showed the strongest relationship with the part of the math test that tapped into Arithmetic Operations, whereas MR was strongly related to Numeric-Logical and Spatial Functions, as well as geometry performance. These findings revealed that rotation abilities with different properties are involved in mathematical performance and their role can change as a function of the type of task in relation to age. In fact, Bates et al.’s (2021) study deals with the term spatial visualization in the context of Kosslyn’s (1980) model of Mental Imagery (MI). This model establishes that there are different and separable components in MI, namely: image generation, image maintenance, image transformation, and image scanning. Their results showed a specific role of MR, accounting for 5.9% of unique variance in calculation skill in 92 primary school children aged between 6-11 years. The finding supports the idea that spatial transformation (process required to solve MR tasks) would contribute to math competence (in missing number problems) over generation, scanning o maintenance of visual images.

Concerning geometry, MR is related with rotating geometric pieces and learning about polymers (Wu & Shah, 2004), visualizing length or sizes (Delgado & Prieto, 2004), or composing and decomposing 2D and 3D figures, proving symmetry (Cheng & Mix, 2014). Regarding this concern, the study applied by Gilligan-Lee et al. (2019) showed significant correlations between geometry performance and spatial abilities in eight-year-old children. The study distinguished between two types of geometry items. In geometry shape items, the participants were asked to select the correct number of sides on the shape showed, while in geometry symmetry items the participants were asked to select the mirror image of the target shape. Significant correlations between geometry symmetry and mental rotation and spatial scaling were found, as well as between spatial scaling and geometry shape. Even more interestingly, this study compared different types of training in geometry performance. The results showed an improvement only in geometry shape items (not in symmetry ones) indicating a far transfer after a mental rotation and spatial scaling training. The authors suggested that the children could use spatial visualization (ability used in mental rotation tasks) to picture and rotate the shapes shown to count the number of faces. Thus, the participants could have improved their spatial scaling skills using proportional reasoning to answer shape items by counting. Instead of counting each individual side (face), participants may divide the task: first, segmenting the shapes presented (all of which were symmetrical) into halves or thirds, then counting the sides (faces) in a single segment, and finally multiplying this to account for all segments.

In the same line, Harris et al. (2020) examined the contribution of three spatial reasoning constructs (mental rotation, spatial visualization, and spatial orientation) to mathematics performance across different mathematical content (geometry-measurement and number sense) in grade 5 (Study 1) and grade 8 (Study 2). Geometry-measurement items included tasks assessing location and transformation as well as units of measurement. In Study one, the regression analyses showed that spatial construct measures accounted for 40% of the variance in geometry-measurement with MR and VZ, significantly contributing to the model (β = 0.47 and 0.25, respectively). Additionally, an interesting result was obtained with the inclusion of gender and its interaction with some variables; spatial factors accounted for 35% of the variance in geometry-measurement performance for females with no singular significant predictor, while for males, spatial factors accounted for 49% of the variance in geometry-measurement scores with MR as the only individual significant predictor. In Study two, a verbal variable was included as a control variable. The regression analyses by gender revealed that spatial orientation contributed with the largest proportion of variance (β = 0.30) followed by verbal reasoning and MR (β = 0.25, and β = 0.13, respectively). In the male group, spatial factors and verbal reasoning were significant predictors, with spatial orientation being the strongest predictor (β = 0.25). The authors suggested that the geometry task became more complex and dependent on formal content knowledge, where spatial processes may be less influential, shifting towards operational thinking in the eight more complex items (Harris et al., 2020).

Both studies (Harris et al., 2020; Gilligan-Lee et al., 2019) contemplated a different contribution of spatial factors in geometry competence in relation to gender and age, with much more proportion of variance explained in the younger sample than in the older sample. These studies also provide evidence regarding the different nature of geometry and spatial abilities although the question remains open, as some authors assume that geometry content is intrinsically linked to spatial reasoning due to the inherently spatial nature of the material (Battista et al., 2018; Bruce & Hawes, 2015; Clements & Battista, 1992). In spite of that, spatial reasoning skills provide different patterns of relationships across different mathematical content (Frick, 2019; Harris et al., 2020), where MR may have a more specific role in supporting particular types of problem-solving in geometry (e.g., in area measurement tasks; Bruce & Hawes, 2015). It seems that MR and VZ support the need to separate these types of tasks when examining predictors of mathematics performance (Harris et al., 2020), as each one contributes uniquely when examining spatial predictors of mathematics performance (Verdine et al., 2014). In fact, Fernández-Méndez et al. (2020) showed how MR was a relevant predictor of mathematical performance after controlling the effect of VZ in children aged between six and eight years. The generalized linear regression analysis carried out showed different patterns of contributions of MR and VZ. While MR contributed to math ability across all ages, VZ accounted for mathematical ability especially among six- and seven-year-olds but not in eight-year-old children.

Another important question to engage with is how other cognitive abilities can share resources to explain math (and geometry) performance. In fact, the association between math and spatial skills may depend on the shared influence of other systems such as working memory or general intelligence. Working memory, in particular visuo-spatial working memory, has shown strong relationships with mathematics performance (Reuhkala, 2001). Following Lourenco et al. (2018), this is a challenging question to address and, although some studies have made efforts to address the specificity of visuospatial and math reasoning by controlling for individual differences across other abilities, these controls are scarcely ever exhaustive, and it is rarely the case that full models are conducted to determine the potential interactions of different systems. Thus, to examine the role of different spatial abilities in geometry performance could be interesting, taking into account other variables such as working memory or intelligence. Maybe there are other unexplored variables not included in previous models that could be more explicative than those analyzed in previous research.

Motor skills and geometry performance

Motor Skills can be defined as learned sequences of movements that are combined to produce a smooth, efficient action in order to master a particular task (Davis et al., 2011). Classically, motor skills can be separated into gross and fine motor skills. The first one involving the large, force-producing muscles of the trunk, arms, and legs (Clark, 1994), such as throwing, catching, or jumping (Logan et al., 2012), while fine motor skills can be defined as movement that requires mostly muscles or muscles groups of the body (Payne & Isaacs, 2008) such as manual dexterity (Logan et al., 2012). Furthermore, according to Bruininks & Bruininks (2005), motor proficiency would include fine motor integration (visual motor integration), manual dexterity, as a component of fine motor skills; and upper limb coordination, bilateral coordination, balance, speed and agility, and strength as a component of gross motor skills.

Motor proficiency has been related to academic achievement from childhood to adolescence (Carlson et al., 2013; Davies et al., 2016; Diamond, 2010; Geertsen et al., 2016; Haapala et al., 2014). In this regard, Bornstein et al. (2013), in a 14-year longitudinal study, showed that 5-month-old babies that had better control ability and who explored their environment more actively achieved higher scores in intelligence at the age of four and 10 years, and they obtained better academic achievement when the children were assessed at 10 and 14 years of age. This result exposed that motor competence in early stages of the development can initiate a cascade effect that would affect subsequent stages of child intellectual functioning that, in turn, help shape academic achievement in adolescence. This study supports the embodiment perspective, where the authors suggested that the amount of learning that one child acquires can be constrained by the child's own motor abilities.

Geometry tasks, and mathematical tasks in general, in the first grades of primary education, involve practical and concrete activities, such as manually moving objects and body movements to understand geometry principles, like sorting figures or copying drawings, or mathematical ones, such as arranging cardboards depicting numbers in ascending order, placing common objects in boxes, and discarding the non-common ones (Fernández-Méndez et al., 2020). Therefore, it seems logical to support the role of motor skills in relation to performance in school subjects such as geometry.

The particular role of fine motor skills as a predictor of mathematical tasks related to number and shape, relative size, addition, subtraction, multiplication, and division or ordinality and sequence has been reported (Grismmer et al., 2010; Luo et al., 2007). Kim et al. (2018) linked the performance of fine motor coordination at the beginning of kindergarten with the math competence (measured by numeration, measurement, and geometry tasks) at the end of first grade (this relationship was mediated by visuo-motor integration). Concretely, geometry measured children's ability to analyze two- and three-dimensional shapes, as well as their understanding of spatial relationships and reasoning. This finding seems to establish that fine motor proficiency contributes to math competence as soon as children begin formal reading and mathematical skills math learning.

With respect to gross motor abilities, Lopes et al. (2013) have shown a lower probability of obtaining academic success in fourth-grade school children categorized with low scores in motor coordination, such as balance, jumping laterally, or shifting platforms, when those were compared with their peers that showed a normal motor coordination. In the same line, Westendorp et al.'s study (2011) showed that 7- to 12-year-old children with learning disabilities showed worse performance in gross motor abilities and academic achievement compared to children without learning disabilities.

In the case of specific mathematical content and gross motor abilities, motor coordination has been related with arithmetic skills among eight- to fourteen-year-old children (Fernandes et al., 2016) and balance in six-year-old children has been related to spatial and reasoning skills in mathematics one year later (Frick & Möhring, 2016).

In a cross-sectional study (Geertsen et al., 2016), a total of 423 children aged between eight and ten years were evaluated with a visuomotor accuracy-tracking task (corresponding to fine motor measure), a whole-body coordination task (corresponding to gross motor measure) and academic performance in mathematics, where geometry concepts were included, among other measures. A linear mixed-effects model showed that a shorter time to complete the gross motor task and a higher accuracy in the fine motor task correlated with mathematics performance.

Overall, it seems relevant to examine the different contribution of motor abilities on academic success as it is probable that some of them have a stronger influence than others in children (Da Silva Pacheco et al., 2016). In this sense, Morales et al.'s study (2011) showed that fine and motor abilities predicted math competence (calculations, addition, subtraction, multiplication, and division, simple problems, and geometrical problems) in nine- to 12-year-old children, while for older children (13- to 16-year-olds) fine motor skills remained as a significant predictor whereas gross motor ability was not.

The present study considered measuring geometry competence through exercises that capture the spatial nature of geometry. Geometry reasoning implies reasoning about forms and shapes, being the mental transformation of shapes a basic element of geometry competence. For this reason, the selected exercises (visuospatial type) correspond to those considered as geometry exercises at the primary school level. Although other studies have used this type of visuospatial exercises to measure geometry competence (Dehaene et al., 2006; Gilligan-Lee et al., 2019; Hawes et al., 2017; Pittalis & Christou, 2010), measures such as geometry problems or geometry knowledge have not been included, hence the measure used in this study has been named as spatial geometry performance.

The hypotheses of the present study are the following:

1. Spatial abilities, in terms of mental rotation and spatial visualization, are expected to be significant predictors of spatial geometry performance in second- and third-year courses of primary school, given the evidence available on the contribution of spatial abilities in geometry (e.g. Harris et al., 2020). Also, the potential interactions of working memory and fluid intelligence with spatial abilities will be examined (Lourenco et al., 2018).

2. Motor abilities (fine and gross) are expected to explain geometry performance in primary school children (Morales et al., 2011) and also, to test whether one can prevail over the other. The possibility of an age-related dependence of the motor contribution to geometry performance across ages would be analyzed.

Methods

Participants

In this study, 215 school children, ranging in age from 5 to 9 years (Mage = 7.65; SDage = 0.61; 51% boys) from the second and third grades of basic education in Northern Italy, took part. The University of Padova's Research Ethics Committee granted approval for the study (Reference: 8B7B34CA379BBD8A0AA069C2E4B0F0FC), and parents provided informed consent for their children's participation in the research.

Materials

Mental Rotations Task (adapted from Jansen & Kellner, 2015). This task measures the ability to mentally rotate representations of two-dimensional and three-dimensional objects. Seven animal pictures (duck, camel, mouse, donkey, sheep, dog, and rabbit) were presented as stimulus. To familiarize participants with the task, the practice trials were composed by three stimulus pairs, and for the experimental trials, four different stimulus pairs were used. The test was composed by 5 practice trials with different angular disparities: 0º, +45°, -90º, +135º, 180º, and 32 experimental trials with the following angular disparities: +45°, +90º, +135º, 180º, -135º, -90º, and -45º) with 4 items for each angle, except 180°, which was composed by 8 items. The setup was identical for all participants. The internal consistency of this test in the current sample was α = 0.76.

The test was run with E-Prime software (version 2.0) and projected on a 17-inch screen. Two stimuli were presented simultaneously, where the left one always appeared in an upright position and the right stimulus was identical or mirror-reversed with respect to left one. The stimuli were rotated in a clockwise direction, corresponding to a positive angle, or in a counterclockwise direction, corresponding to a negative angle. The task was to decide whether the two stimuli presented are the same or mirror reversed by pressing one of two marked keys of the laptop (‘‘M’’ or ‘‘Z’’ keys on the keyboard for ‘‘Same’’ or ‘‘Different’’, respectively). The participants were informed to mentally rotate the right stimuli to align it with the left. One point was given for each correct response, with a maximum total score of 32 points.

Block Design (from Wechsler Intelligence Scale for Children, WISC-IV; Weschler, 2003; Italian version by Orsini et al., 2013). This test measures the ability to analyze and synthesize abstract visual stimuli by manipulating them in a spatial way. It is adequate for children aged between six years and six months and 16 years and 11 months. The test is composed by nine blocks (with two red, two white and two bicolored red-white sides) and one notebook that contains different block images. There are 14 items of incremental difficulty, i.e. using four (from item four to 10) or nine (from item 11 to 14) blocks within a given time limit. The time limit depends on the items, with 30 (item 1), 45 (items 2 to 5), 75 (items 6 to 10), or 120 seconds (items 11 to 14) to make the figure. For the first three items, the participants had to reproduce a model made by the experimenter, while for the following items, the participant reproduced the image shown in the notebook. The maximum score was 68 points. When the child gave two consecutives wrong answers, obtaining zero points, the test ended. This test showed a good internal consistency (α = .82 WISC-IV; Italian adaptation, Orsini et al., 2013).

Movement Assessment Battery for Children – Second Edition (MABC-2; Henderson et al., 2007; Italian version by Biancotto et al., 2013). This battery aims to identify the movement ability of children and adolescents aged between three and 16 years to evaluate their motor coordination through subscales entitled: Manual Dexterity, Throwing and Holding, and Balance.

The *Manual Dexterity* subscale measures fine motor skills and is composed of three tasks: Placing Pegs, Threading Lace, and Drawing Trail. The Placing Pegs task consists in inserting pegs into holes within a surface (there are two attempts for each hand). The Threading Lace task consists of inserting a cord through six holes aligned on a table (there are two attempts); the Drawing Trail task consists of drawing a line following a pathway (there are two attempts).

The *Throwing and Holding* (defined as Grab-throw variable) subscale measures gross motor skills and is composed by two tasks, Catching with Two Hands and Throwing Beanbag onto Mat. In each task, the participant has five practice items and 10 experimental items. Catching with Two Hands consists of throwing a tennis ball towards a wall from a distance of two meters and catching it with two hands. The Throwing Beanbag onto Mat task requires throwing a little bag onto a tappet placed at 1,8 meters of distance.

The *Balance* skills subscale measures gross motor skills and is composed of three tasks, *One-Board Balance, Walking Heel to Toe Forwards*, and *Hopping on Mats 2*. In the *One-Board Balance* task, participants were asked to maintain their balance on one leg on top of a table (there are two attempts for each leg). The *Walking Heel to Toe Forwards* task involves walking over a strip of adhesive tape 4.5 meters long, placing the heel of one foot on the tip of the other at each step (there are two attempts). Finally, the *Hopping on Mats 2* task consists in jumping forward with one leg onto six mats placed in a row until the last, the target mat, is characterized by an orange circle (there are two attempts for each leg). The total raw scores for each task were then converted into standard scores based on the normative data for each test (Italian norms; Biancotto et al., 2013). The final score for each of the three abilities (*Manual Dexterity, Throwing and Hold, and Balance*) were calculated by summing the standard scores of the constituent tests. The raw scores were converted into standard scores following the Italians norms (Biancotto et al., 2013). The Cronbach's alpha coefficients for all domains were = .77-.80).

Reynolds Intellectual Assessment Scales (RIAS; Reynolds & Kamphaus, 2003). This test measures the overall ability of nonverbal reasoning (fluid intelligence). This scale is designed to be applied to an age range of 3-94 years.

The task consists in the presentation of a series of sheets that contain five to seven figures or drawings each. One of these figures or drawings has a distinctive feature, which makes it different from the remaining figures/drawings on the sheet. The participant was asked to choose the figure or drawing that was different from the rest. They had two attempts to complete the trial. Two points were awarded if the correct answer was given in the first try (with a maximum time limit of 30 seconds) and one point if it was given in the second attempt (with a maximum time limit of 20 seconds). The test ended when the participant obtained a score of zero points in three consecutive elements. The maximum possible score of this test was 94 points. The raw scores were transformed into standard scores. This test has a Cronbach's alpha reliability of 0.91 (Santamaría, 2007).

*Working Memory (*Lanfranchi et al., 2004). The task measures the ability to maintain visuospatial information in sequential order in working memory. The child was shown a path made by a small frog on a 3x3 or 4x4 matrix, then he/she had to recall the pathway immediately after presentation by moving the frog from square to square, reproducing the experimenter's moves. There were six levels of difficulty (with two series of items each one), depending on the number of steps in the frog's pathway and the size of board (3x3 for 1st level with 2 steps, 4x4 for levels with 2, 3, 4, 5 and 6 steps, respectively). Prior to starting with the experimental trial, the task was preceded by instructions and practice trials at the simplest levels of the task. The experimental phase started only if the child had understood the task by responding correctly on a practice trial. With respect to score, one point was obtained for each series recalled correctly, being the maximum total score of 12 points. The test ended when the participant failed the recall in the two series of the same level of difficulty. The task had Cronbach alpha of .59 and the reliability was .36.

Spatial Geometry task

Assessment tests for primary and lower secondary school (Mammarella et al., 2012). The test consists of three subtests - *Geometric knowledge, Geometry problems and Visuospatial ability*. The participants were presented with 16 exercises related with Visuospatial ability. Visuospatial exercises were divided in four categories: *Shaping of figures, Composition of figures, Development of solid figures, and Hidden figures.*

In the *Shaping figures* exercise, the participant was shown a figure composed by different geometric pieces on the top of a sheet. The task of the child consisted in choosing the geometric pieces set that configures the composition shown in the top, among three different alternatives. In the *Composition of figures* exercise, the participant was shown different geometric figures on the top of a sheet and the participant had to imagine the figure that links all figures shown and had to choose one figure among three alternatives. In the *Development of solid figures*, the participant was shown a figure, and he/she should choose the alternative that corresponds with this figure if she/he fold by the dashed line, among three possibilities. In *Hidden figures*, the task consisted in identifying (and color) a simple geometric figure presented within a complex image shown on the right part of the sheet. Each type of exercise was composed by four items, resulting in 16 items in total. One point was obtained for each correct answer. The maximum score was 16 points. The Cronbach alpha was .74. The variable was named *Spatial Geometry* task as only visuospatial exercises were included.

Procedure

There were three sessions: two individuals and one collective (30 min each one, approximately) in a 15-day interval carried out at school. While the first two sessions were carried out individually in a quiet room, prepared to prevent distractions and increase concentration, the collective session was performed in a classroom in presence of teachers.

In the first individual session, children completed, in this order, the *Mental rotation* task and the *MABC-2* tests. In the second individual session, they were presented with *the Block Design* test, the *Working memory* task and the *Fluid Intelligence* test. In the third session, children were presented with the *Geometry* test.

Results

Data analysis.

Initially, a basic descriptive analysis was conducted using the direct scores of the primary variables of the study. These direct scores were subsequently used in the remaining analyses. After the descriptive analysis of the participants' performance (see Table 1), a multiple linear regression model was performed using a Structural Equation Modeling (MLR estimator in Mplus software v. 7.4; Muthén & Muthén, 2014).

The model describes the relationships between all the study variables at various levels of independence (see Figure 1).

On a first level of independence, the variables *Sex* and *Age* were placed (completely independent). In a second level, the *Working Memory* (WM) and *Mental Rotation* (MR) variables were situated as basic cognitive processes. The third level was composed by two high-level cognitive variables; *Fluid intelligence* (*gf*) *and Visualization* (VZ). In a fourth level, the intermediate or *Basic manual performance* variables were placed; *Dexterity* (DE), *Grab-throw* (GT) and *Balance* (BA). And finally, in the fifth level, *Spatial Geometry* (SGE) was placed as the more complex performance dependent variable. For statistical and interpretation purposes, the *sex* variable was dummy coded (0 = girls; 1 = boys).

Except for the *Balance* variable, no asymmetry bias was observed in the assessed variables. In general, Pearson relations were of low and medium magnitude. The Sex and Age variables showed a significant relationship each, i.e., *Age* was related only with *Spatial Geometry*, and *Sex* was related with *Grab-Throw* (the dummy coding carried out means that there was a difference in performance in favor of the boys only in this variable). *Fluid intelligence, Working Memory*, and *Visualization* were related with almost the rest of the variables (but not with *Age* or *Sex*). *Geometry* (the last dependent variable of the model) was related significantly with *Age, Fluid Intelligence, Visualization, Mental Rotation* and *Dexterity*.

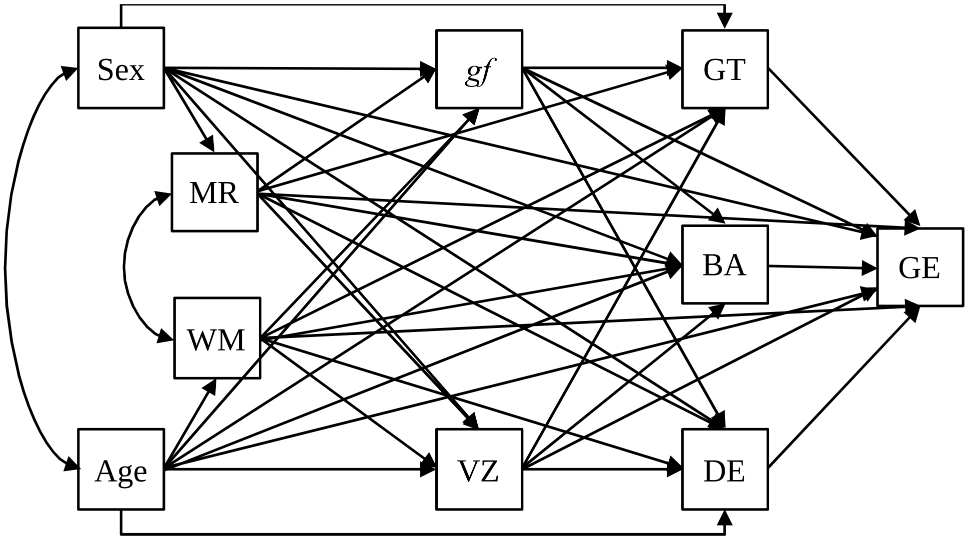

Figure 1. Conceptual model of the study. gf = fluid intelligence; WM = Working Memory; VZ = Visualization; MR = Mental Rotation; DE = Dexterity; BA = Balance; GT = Grab-Throw; SGE = Spatial Geometry.

As we have commented previously, a multiple linear regression model is represented in Figure 1 with the study variables based on their level of independence. The model highlights the relationships that were significant after modeling the data.

The regression weights that do not appear in the model figure were not significant (see Figure 2). The model described coefficients of determination (explained variance) for the dependent variables of small and medium size: $\chi2(4) = 48.41$, $\chi2/df = 12.10$, CFI = 0.842; AIC = 10356.18; $R^2_{gf} = 0.136$; $R^2_{Vz} = 0.279$; $R^2_{MR} = 0.019$; $R^2_{GT} = 0.181$; $R^2_{BA} = 0.121$; $R^2_{DE} = 0.185$; $R^2S_{GE} = 0.223$. *Spatial Geometry* was explained by *Age*, *Mental Rotation* and *Dexterity* at 22%.

Descriptive indices

Descriptive statistics and correlations between all variables are reported in Table 1.

Table 1. Basic statistics and correlation indices.

	Age	Sex	*gf*	WM	VZ	MR	DE	BA	GT	GE
Sex	- .072									
gf	.030	.049								
WM	.122	.117	**.280**							
VZ	.116	.153	**.308**	**.507**						
MR	- .030	.135	**.284**	**.176**	**.191**					
DE	- .105	- .094	**.282**	**.267**	**.293**	.010				
BA	.104	- .127	**.154**	**.266**	**.235**	.105	**.338**			
GT	- .083	**.209**	.011	**.258**	**.332**	.096	.120	**.294**		
GE	**.275**	.044	**.199**	.152	**.257**	**.223**	**.244**	.129	- .003	
M	7.7	0.5	47.8	7.5	22.9	24.0	28.6	32.7	16.4	12.2
SD	0.6	0.5	15.1	1.7	11.1	4.9	6.0	5.6	4.3	2.5
As	0.4	0.0	- 0.6	- 0.2	0.3	- 0.3	- 0.5	- 1.3	0.5	- 0.7
Kr	- 0.6	- 2.0	- 0.8	0.5	- 0.5	1.0	1.4	1.4	- 0.2	- 0.2

Note. *gf* = fluid intelligence; WM = Working Memory; VZ = Visualization; MR = Mental Rotation; DE = Dexterity; BA = Balance; GT = Grab-Throw; GE = Geometry. In bold $p < 0.01$.

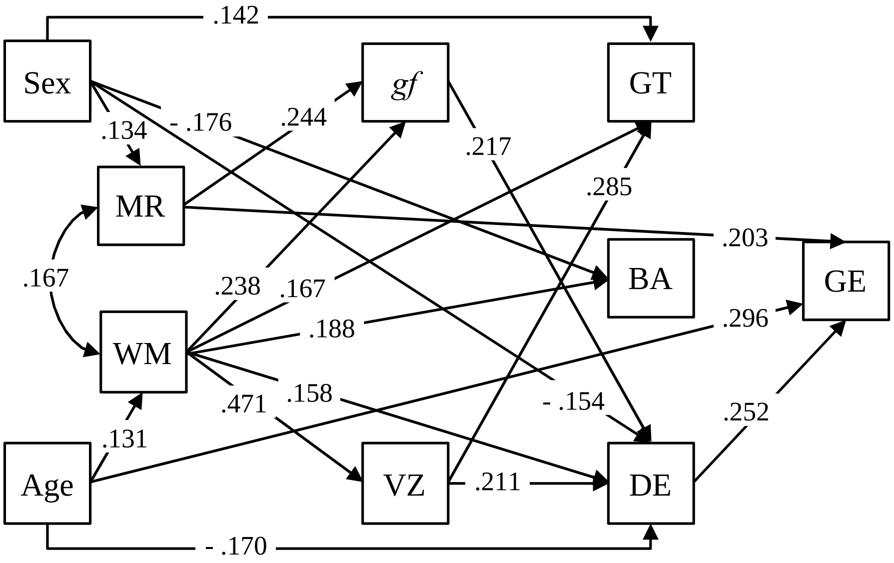

Figure 2. MLR estimated model of the study. gf = fluid intelligence; WM = Working Memory; VZ = Visualization; MR = Mental Rotation; DE = Dexterity; BA = Balance; GT = Grab-Throw; SGE = Spatial Geometry. Only significant relations are shown.

Discussion

The main goal in the present study was to determine the contribution of spatial (MR and VZ) and motor abilities (fine and gross skills) to explain the performance in spatial geometry competence in children of second and third year of Primary Education.

Several studies have tried to establish the factors that underlay the performance in math ability in children (Mix et al., 2016) evidencing that math performance is related to spatial skills (e.g., Gunderson et al., 2012), being those separate factors (Hawes et al., 2019; Mix et al., 2016). However, this objective has tried to disentangle these relationships by separating the specific factors of cognitive variables that could impact in a different way depending on math content. Also, it is possible that the relationship between spatial and math performance seems to change with age, not having the same pattern across different age groups. In this sense, this study is the first one that examines the roles of spatial and motor abilities, taking into account working memory and intelligence in a specific field of mathematics (geometry) in primary school children, contributing towards the evidence available regarding this topic.

In this study, the data were modeled using a Structural Equation Modeling (SEM), which offers several advantages. Firstly, the model simultaneously considers all effects on the dependent variables together. It is important to note that traditional multiple linear regression models do not account for different levels of dependency at the same time (i.e., varying roles of variables within the same model). Secondly, this model offers a better modelling of unexplained variance. In this instance, all effects were considered for this data within a single model, even while controlling for sociodemographic variables (e.g., sex dummy coded). And finally, the simplicity of these type of models makes them accessible because they often are complemented by diagrams that greatly clarify the intricate relationships identified, promoting the evolution of new theoretical frameworks.

The results of regression model show a significant contribution of the mental rotation capacity in performance in spatial geometry. The spatial visualization is correlated to geometry performance but the final regression model did not highlight it significant effect. The contribution of mental rotation is in line with previous studies that have shown the importance of this spatial ability, specifically in a particular type of content in mathematics, geometry (Cheng & Mix, 2014; Delgado & Prieto, 2004; Wu & Shah, 2004). Having the ability to mentally rotate images seems to play a relevant role when solving problems related to shape and space, such as area estimation tasks (Bruce & Hawes, 2015), image transformation or location estimation (Harris et al., 2020). In this sense, the tasks carried out in this study involve the transformation of geometric shapes, breaking them down or locating them among a set. Spatial ability may be especially important in mathematics in the early years, and both MR and VZ have been shown to be the most predictive spatial factors (Mix et al., 2016). However, it is important to point out the controversy that exists when relating spatial and mathematical abilities in development. Some authors, through factorial studies, show that both are related depending on the type of spatial ability and, depending on age, on performance in mathematics. In this sense, MR and VZ abilities (measured by the Block Design task) have a greater predictive weight in preschoolers, with MR continuing as a predictor in 3rd grade, ceasing to be predictive in 6th grade (Mix et al., 2016). It is possible that spatial processes may be more involved in mathematical tasks during the first grades when students are faced with new mathematical content (e.g., Uttal & Cohen, 2012). Another point of view is to consider that, throughout development, the involvement of spatial processes in mathematics performance grows because spatial resources are strategically or automatically involved in solving problems, that is, children become more adept in using their spatial abilities (Hawes et al., 2022).

Regardless of this controversy, the results of the present study, together with those provided by Fernández-Méndez et al., (2020) contribute towards a greater understanding of how the type of content in mathematics and different spatial abilities are related according to age. It is important to point out the contribution of VZ in spatial geometry performance through manual dexterity, which did contribute significantly in the regression model. Regarding the different contribution of VZ and RM in geometry performance, similarly to the study by Fernández-Méndez et al. (2020), where a unique contribution of MR was evidenced independently of VZ in mathematics in children from six to eight years of age, the results favor the idea of the importance of MR as a predictor of geometry in a direct way not mediated by another factor. Likewise, Bates et al.’s (2021) study supports these results in other math areas, such as calculation skills, highlighting the importance of transformation processes like MR in math reasoning.

Further the results of regression model show the role of motor abilities and specifically of the Manual Dexterity ability, a fine motor skill, necessary to coordinate the movements of the hands and fingers to manipulate objects (Makofske, 2011), was a predictor of performance in geometry.

Skills categorized as gross motor skills such as Grab and Throw and Balance do not appear to have explanatory power in the model. These results are in line with those reported in a previous study, where manual dexterity (and not gross motor skills) emerged as a distinguishing factor in mathematics performance (Fernández-Méndez et al., 2020).

These results support the role of motor skills in explaining the development of cognition through the embodied cognition approach (Shapiro, 2019; Wilson, 2002). Lakoff and Núñez (2000) link mathematics with the physical dimension of the body and movement, where mathematical ideas acquire meaning by being based on sensorimotor processes (Nathan et al., 2021).

Referring to specifically geometric content, other studies have reported similar findings, showing that a greater fine motor skill in preschool education was related to better scores in geometry tasks (analyzing shapes in two-dimensional and three-dimensional figures, understanding of spatial relationships and reasoning tasks) at the end of the first year of Primary Education (Kim et al., 2018). Other studies have shown that both fine and gross motor skills are related to success in mathematics, where geometric concepts were included (Geertsen et al., 2016), although it is possible that, depending on age, different relationship patterns emerge. In this sense, the work of Morales et al. (2011) showed that fine motor skills remained constant as predictors of mathematics performance in children aged 9 to 12 years, whereas gross motor skills lost predictive power in subsequent years (between 13 and 16 years). Our results, together with those reported by Fernández-Méndez et al., (2020) and Kim et al., (2018) seem to support the importance of manual dexterity in the performance of mathematical tasks between the ages of 6 and 8 years. Future works may focus on evaluating the different contribution of both types of motor skills at different developmental stages with diverse mathematical content, given the mixed findings found in various studies.

Another important issue of the present study is the inclusion of other cognitive factors that can explain part of the performance observed in geometry, such as working memory or fluid intelligence. The results show the contribution of working memory in fluid intelligence, as well as in spatial skills (both MR and VZ), and in the different motor skills evaluated (Manual Dexterity, Throwing and Hold, and Balance). It seems relevant to underline the role of working memory, as it also indirectly contributes towards performance in geometry through manual dexterity and MR. Similarly, fluid intelligence would also have an impact on performance in geometry through manual dexterity.

In relation to the limitations of the present study, the fact that the factors reported as predictive in the model are limited only to the geometric tasks used must be taken into consideration, and they may not be replicable with other tasks that do not require spatial or motor skills. Likewise, it is possible that the model would be different in another age range, as the relationships between the factors studied may change depending on age. In addition, other factors not considered in the model could explain more variance in geometry performance. However, alternative models not tested in this study may also explain the empirical data.

One limitation of the present study may be that the geometry tasks used to measure geometry competence can be tested by other tasks such as geometry problems or geometry knowledge. However, the Geometry Knowledge test implies semantic information about geometry concepts (for example, lexical recognition about shapes) and the exercises involved in Geometry Problems imply verbal comprehension factors (for example, to follow the instruction "draw a triangle inside a square with only one side shared with the square's side). Given our objective was to establish the spatial component that predicts performance on spatial geometric tasks, we decided to consider visuospatial problems as the most relevant measure of geometry competence. For this reason and in spite of the exercises selected (Shaping of figures, Composition of figures, Development of solid figures, and Hidden figures) being visuospatial, it can be considered that they capture geometry competence in a spatial way and can be used to measure geometry at the primary school level. Mental transformation figure is a basic element of geometry competence, as this ability carries out the manipulation of the forms and figures inherently. In fact, other studies have involved this type of exercises in a similar way to that used in this study to measure geometry competence. For example, students had to complete a net in such a manner as to construct a triangular prism when folded or to manipulate different representational modes of 3D objects (Pittalis & Christou, 2010). Similarly, the important study of Dehaene et al., (2006) involved items in which it was necessary to carry out some type of spatial transformation, such as rotations or translations (test of basic concepts of geometry). The geometry symmetry items used by Gilligan-Lee et al., (2019) have used exercises where the participants had to select a mirror image from a target shape (which can be considered as mental rotation). Also, Hawes et al. (2017) used spatial items to measure geometry, where it was required to identify the item that fits perfectly within the white center space or to identify the two shapes that could be joined together to make the target shape (similar to Composition of figures exercise in this study). In sum, geometry is considered to be inherently spatial in nature (Lourenco et al., 2018), and, in this sense, competence in geometry can be measured by spatial measures such as the exercises used in this study, as other studies have included (Dehaene et al., 2006; Gilligan-Lee et al., 2019; Hawes et al., 2017; Pittalis & Christou, 2010). The overlap of different spatial abilities to resolve these types of geometry exercises is evident, but this study shows the mayor contribution of MR over that of VZ. This type of evidence is in line with studies that have shown a differential contribution to MR in math competence (Bates et al., 2021; Fernández-Méndez et al., 2020). For this reason, it is important to discriminate the type of spatial processes that can be involved in spatial geometry competence. Also, the measure used is composed by four types of different exercises to reason about forms and figures in different ways. In this sense, Mix et al. (2022) argued that spatial training overlaps directly with abilities tested in geometry tasks as they require reasoning about forms and shapes in space although they can be considered as separate constructs.

Furthermore, Educational Programs designed to teach geometry such as the one made by the National Council of Teachers of Mathematics (NCTM) establishes that children in grades 3-5 should be able to use visualization, spatial reasoning, and geometric modeling to solve problems. Specifically, and apart from other competencies, children should be able to create and describe mental images of objects, patterns, and paths; identify and build a three-dimensional object from two-dimensional representations of that object; and identify and draw a two-dimensional representation of a three-dimensional object. That is, the measures used in this study are appropriate to evaluate the level of geometric competence in tasks that involve reasoning about shapes and figures, these competencies being within the geometry teaching curriculum.

To understand when, why, and how spatial training transfer to mathematics is mandatory to make practice and policy recommendations (Hawes et al., 2022). To do this, it is necessary to comprehend how performance in mathematics is related to spatial abilities. The present study addresses this question, in addition to other cognitive factors (working memory and fluid intelligence) and motor factors to explain performance in a part of mathematical reasoning, geometry in spatial terms. The results show the importance of certain spatial skills, such as MR and manual dexterity, in geometry performance in children in the second and third years of Primary Education.

Funding

This work was partially funded by the Spanish Ministry of Science, Innovation and Universities (grant number RTI2018-098523-B-I00) and by the Spanish Ministry of Science and Innovation (grant number PID2021-125677OB-I00).

Acknowledgments

This work was conducted as part of the “use-inspired basic research” project for which the Department of General Psychology at the University of Padova has been recognized as a “Dipartimento di Eccellenza” by the Italian Ministry for the University and Research.

Conflict of interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Bard, C. Fleury, M. Teasdale, N. Paillard, J., & Nougier, V. (1995). Contribution of proprioception for calibrating and updating the motor space. *Canadian Journal of Physiology and Pharmacology, 73*, 246–254. https://doi.org/10.1139/y95-035

Bates, K. E., Gilligan-Lee, K., & Farran, E. K. (2021). Reimagining Mathematics: The Role of Mental Imagery in Explaining Mathematical Calculation Skills in Childhood. *Mind, Brain, and Education*, 15. https://doi.org/10.1111/mbe.12281

Battista, M. T., Frazee, L. M., & Winer, M. L. (2018). Analyzing the relation between spatial and geometric reasoning for elementary and middle school students. In K. S. Mix & M. T. Battista (Eds.), *Visualizing Mathematics: The role of spatial reasoning in mathematical thought* (pp. 195–228). Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-98767-5_10

Biancotto, M., Borean, M., Bravar, L., Pelamatti, M.G., & Zoia, S. (2013). *Adattamento italiano della Batteria per la Valutaziones Motoria del Bambino. Moment Assessment Battery for Children-2 MABC-2*. Firenze: Edizione Giunti O.S.

Bruce, C. D., & Hawes, Z. (2015). The role of 2D and 3D mental rotation in mathematics for young children: What is it? Why does it matter? And what can we do about it? *ZDM: the international journal on mathematics education, 47*(3), 331–343. https://doi.org/10.1007/s11858-014-0637-4

Bruininks, R., & Bruininks, B. (2005). *Bruininks-Oseretsky Test of Motor Proficiency (BOT-2)* (2nd ed.). https://doi.org/10.1037/t14991-000

Bornstein, M.H., Hahn, C.S., & Suwalsky, T.D. (2013). Physically developed and exploratory young infants contribute to their own long-term academic achievement. *Psychological Science, 24*, 1906–1917. https://doi.org/10.1177/095679761347997

Carlson, A.G., Rowe, E., & Curby, T.W. (2013). Disentangling fine motor skills' relations to academic achievement: The relative contributions of visual–spatial integration and visual–motor coordination. *Journal of Genetic Psychology, 174*, 514–533. https://doi.org/10.1080/00221325.2012.717122

Carroll, J. B. (1993). Human cognitive abilities: A survey of factor-analytic studies. New York, NY: Cambridge University Press. https://doi.org/10.1017/CBO9780511571312

Cheng, Y-L. & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development, 15* (1), 2-11. https://doi.org/10.1080/15248372.2012.725186

Clark, J.E (1994). Motor development. In V.S. Ramachandran (Ed.), *Encyclopedia of human behavior* (3rd ed). New York: Academic Press, 245 –255.

Clements, D. H., & Battista, M. T. (1992). Geometry and spatial reasoning. In D. A. Grouws (Ed.), *Handbook of research on mathematics teaching and learning* (pp. 420–464). New York NY: Macmillan.

Da Silva Pacheco, S.C., Gabbard, C., Kittel Ries, L.G., & Godoy Bobbio, T. (2016). Interlimb coordination and academic performance in elementary school children. *Pediatrics International, 58*, 967–973. https://doi.org/10.1111/ped.12972

Danilova, N.N. [Данилова Н. Н.] (1998). *Психофизиология: Учебник для вузов. [Psychophisiology: Manual for Universities].* Moscow. [In Russian].

Davies, S., Janus, M., Duku, E., & Gaskin, A. (2016). Using the Early Development Instrument to examine cognitive and non-cognitive school readiness and elementary student achievement. *Early Childhood Research Quaterly, 35*, 63–75. https://doi.org/10.1016/j.ecresq.2015.10.002

Davis, E. E., Pitchford, N. J., & Limback, E. (2011). The interrelation between cognitive and motor development in typically developing children aged 4-11 years is underpinned by visual processing and fine manual control. *British journal of psychology, 102*(3), 569–584. https://doi.org/10.1111/j.2044-8295.2011.02018.x

Dehaene, S., Izard, V., Pica, P., & Spelke, E. (2006). Core Knowledge of Geometry in an Amazonian Indigene Group. *Science*, 311 (5759), 381-384. https://doi.org/10.1126/science.1121739

Delgado, A. R. & Prieto, G. (2004). Cognitive mediators and sex-related differences in mathematics. *Intelligence, 32*(1), 25–32. https://doi.org/10.1016/S0160-2896(03)00061-8

Diamond, A. (2010). The evidence base for improving school outcomes by addressing the whole child and by addressing skills and attitudes, not just content. *Early Education and Development, 21*(5), 780–793. https://doi.org/10.1080/10409289.2010.514522

Fernandes, V.R., Scipião Ribeiro, M.L., Melo, T., Maciel-Pinheiro, P., Guimarães, T.T., Araujo, N.B. et al. (2016). Motor coordination correlates with academic achievement and cognitive function in children. *Frontiers in Psychology, 7:318*. https://doi.org/10.3389/fpsyg.2016.00318

Fernández-Méndez, L. M., Contreras, M. J., Mammarella, I. C., Feraco, T., & Meneghetti, C. (2020). Mathematical achievement: the role of spatial and motor skills in 6-8 year-old children. *PeerJ, 8*, e10095. https://doi.org/10.7717/peerj.10095

Frick, A. (2019). Spatial transformation abilities and their relation to later mathematics performance. Psychological Research, 83(7), 1465–1484. https://doi.org/10.1007/s00426-018-1008-5

Frick, A. & Möhring, W. (2016). A matter of balance: Motor control is related to children's spatial and proportional reasoning skills. *Frontiers in Psychology, 6: 2049*. https://doi.org/10.3389/fpsyg.2015.02049

Geertsen, S.S., Thomas, R., Larsen, M.N., Dahn, I.M., Andersen, J.N., Krause-Jensen, M., et al. (2016). Motor skills and exercise capacity are associated with objective measures of cognitive functions and academic performance in preadolescent children. *PLoS One, 11*: e0161960. https://doi.org/10.1371/journal.pone.0161960

Gilligan, K. A., Hodgkiss, A., Thomas, M. S. C., & Farran, E. K. (2019). The developmental relations between spatial cognition and mathematics in primary school children. *Developmental Science, 22*(4), Article e12786. https://doi.org/10.1111/desc.12786

Gilligan, K. A., Thomas, M., & Farran, E. K. (2020). First demonstration of effective spatial training for near transfer to spatial performance and far transfer to a range of mathematics skills at 8 years. *Developmental science, 23*(4), e12909. https://doi.org/10.1111/desc.12909

Grissmer, D., Grimm, K.J., Aiyer, S.M., Murrah, W.M., & Steele, J.S. (2010). Fine motor skills and early comprehension of the world: two new school readiness indicators. *Developmental Psychology, 46*(5), 1008–1017. https://doi.org/10.1037/a0020104

Gunderson, E. A., Ramirez, G., Beilock, S. L., & Levine, S. C. (2012). The relation between spatial skill and early number knowledge: the role of the linear number line. *Developmental Psychology, 48*(5), 1229-1241. https://doi.org/10.1037/a0027433

Haapala, E.A., Poikkeus, A.M., Tompuri, T., Kukkonen-Harjula, K., Leppänen, P.H., Lindi, V., et al. (2014). Associations of motor and cardiovascular performance with academic skills in children. *Medicine and science in sports and exercise, 46*(5), 1016–1024. https://doi.org/10.1249/MSS.0000000000000186

Harris, D., Lowrie, T., Logan, T., & Hegarty, M. (2021). Spatial reasoning, mathematics, and gender: Do spatial constructs differ in their contribution to performance? *The British journal of educational psychology, 91*(1), 409–441. https://doi.org/10.1111/bjep.12371

Hawes, Z., Gilligan-Lee, K.A., & Mix, K.S. (2022). Effects of Spatial Training on Mathematics Performance: A Meta-Analysis. *Developmental Psychology, 58*(1), 112 – 137. https://doi.org/10.1037/dev0001281

Hawes, Z., Moss, J., Caswell, B., Naqvi, S., & MacKinnon, S. (2017). Enhancing children's spatial and numerical skills through a dynamic spatial approach to early geometry instruction: effects of a 32-week intervention. *Cognition and Instruction*, *35,* 236–264. https://doi.org/10.1080/07370008.2017.1323902

Hawes, Z., Moss, J., Caswell, B., Seo, J., & Ansari, D. (2019). Relations between numerical, spatial, and executive function skills and mathematics achievement: A latent-variable approach. *Cognitive Psychology, 109*, 68–90. https://doi.org/10.1016/j.cogpsych.2018.12.002

Henderson, S.E., Sugden, D.A., & Barnett, A. (2007). *Movement Battery for Children-2 (Movement ABC-2). Examiner's Manual*. London: Pearson Assessment. https://doi.org/10.1037/t55281-000

Jansen, P., & Kellner, J. (2015). The role of rotational hand movements and general motor ability in children's mental rotation performance. *Frontiers in psychology, 6*, 984. https://doi.org/10.3389/fpsyg.2015.00984

Kim, H., Duran, C.A.K., Cameron, C.E., & Grissmer, D. (2018). Developmental Relations Among Motor and Cognitive Processes and Mathematics Skills. *Child Development, 89*(2), 476-494. https://doi.org/10.1111/cdev.12752

Kosslyn, S. M. (1980). *Image and mind*. Cambridge, MA: Havard University Press.

Lanfranchi, S., Cornoldi, C., & Vianello, R. (2004). Verbal and visuospatial working memory deficits in children with Down syndrome. *American journal of mental retardation: AJMR, 109*(6), 456–466.

Lakoff, G. & Núñez, R. (2000). *Where mathematics comes from: How the embodied brings mathematics into being*. New York: Basic Books.

Linn, M.C. & Petersen, A.C. (1985). Emergence and characterization of gender differences in spatial abilities: A meta-analysis. *Child Development, 56*, 1479–1498. https://doi.org/10.2307/1130467

Lohman, D. F. (1996). Spatial ability and g. In I. Dennis & P. Tapsfield (Eds.), *Human abilities: Their nature and measurement* (pp. 97-116). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Logan S.W., Robinson, L.E., Rudisill, M.E., Wadsworth, D.D., & Morera, M. (2012). The comparison of school-age children’s performance on two motor assessments: the Test of Gross Motor. Development and the Movement Assessment Battery for Children. *Physical Education and Sport Pedagogy, 19*, 48–59. https://doi.org/10.1080/17408989.2012.726979

Lopes, L., Santos, R., Pereira, B., & Lopes, V.P. (2013). Associations between gross motor coordination and academic achievement in elementary school children. *Human movement science, 32*(1), 9–20. https://doi.org/10.1016/j.humov.2012.05.005

Lourenco, S. F., Cheung, C. N., & Aulet, L. S. (2018). Is visuospatial reasoning related to early mathematical development? A critical review. In A. Henik, & W. Fias (Eds.) *Heterogeneity of function in numerical cognition* (pp. 177–210). Elsevier. https://doi.org/10.1016/B978-0-12-811529-9.00010-8

Lowrie, T., Logan, T., & Hegarty, M. (2019). The influence of spatial visualization training on students’ spatial reasoning and mathematics performance. *Journal of Cognition and Development, 20*(5), 729–751. https://doi.org/10.1080/15248372.2019.1653298

Lowrie, T., Logan, T., & Ramful, A. (2017). Visuospatial training improves elementary students’ mathematics performance. *The British Journal of Educational Psychology*, 87(2), 170–186. https://doi.org/10.1111/bjep.12142

Lowrie, T., Logan, T., Harris, D., & Hegarty, M. (2018). The impact of an intervention program on students’ spatial reasoning: Student engagement through mathematics-enhanced learning activities. *Cognitive Research: Principles and Implications, 3*(1), Article 50. https://doi.org/10.1186/s41235-018-0147-y

Luo, Z., Jose, P.E., Huntsinger, C.S., & Pigott, T.D. (2007). Fine motor skills and mathematics achievement in East Asian American and European American kindergartners and first graders. *British Journal of Developmental Psychology, 25*, 595–614. https://doi.org/10.1348/026151007X185329

Makofske, B. (2011). Manual Dexterity. In J.S. Kreutzer, J. DeLuca, & B. Caplan (eds), *Encyclopedia of Clinical Neuropsychology*. Springer, New York, NY. https://doi.org/10.1007/978-0-387-79948-3_1460

Mammarella, I. C., Todeschini, M., Englaro, G., Lucangeli, & Cornoldi, C. (2012). *Geometria test [Test of geometry].* Trento, Italy: Erickson.

Mix, K.S., Cheng, Y.-L., Hambrick, D.Z., Levine, S.C., Young, C., Ping, R., & Konstantopoulos, S. (2016). Separate but correlated: The latent structure of space and mathematics across development. *Journal of Experimental Psychology: General, 145*(9), 1206–1227. https://doi.org/10.1037/xge0000182

Mix, K. S., Levine, S. C., Cheng, Y.-L., Stockton, J. D., & Bower, C. (2021). Effects of spatial training on mathematics in first and sixth grade children. Journal of Educational Psychology. https://doi.org/10.1037/edu0000494

Morales, J., Gonzalez, L.M., Guerra, M., Virgili, C., & Unnithan, V. (2011). Physical activity, perceptual-motor performance, and academic learning in 9- to-16-years-old school children. *International Journal of Sport Psychology, 42*(4), 401–415.

Muthén, L.K. & Muthén, B.O. (2014). *Mplus User's Guide*. Seventh Edition. Los Angeles, CA: Muthén & Muthén.

Nathan, M.J., Schenck, K. E., Vinsonhaler, R., Michaelis, J.E., Swart, M.I., & Waskington, C. (2021). Embodied Geometric Reasoning: Dynamic Gestures During Intuition, Insight, and Proof. *Journal of Educational Psychology, 113* (9), 929 – 948. https://doi.org/10.1037/edu0000638

National Council of Teachers of Mathematics. (27 september 2023). *Principles and Standards for school Geometry*. https://www.nctm.org/Standards-and-Positions/Principles-and-Standards/Geometry/

OECD (2019). *PISA 2018 Assessment and Analytical Framework*. OECD Publishing, Paris, https://doi.org/10.1787/b25efab8-en

Orsini, A., Pezzuti, L., & Picone, L. (2013). *WISC-IV. Contributo alla taratura Italiana. [WISC-IV Italian Edition].* Firenze, Italy: Giunti, OS.

Payne, V.G. & Isaacs, L.D. (2008). *Human motor development*. New York: McGraw-Hill. https://doi.org/10.4324/9781315213040

Pittalis, M. & Christou, C. (2010). Types of reasoning in 3D geometry thinking and their relation with spatial ability. *Educational Studies in Mathematics, 75*,191–212. https://doi.org/10.1007/s10649-010-9251-8

Reuhkala, M. (2001). Mathematical skills in ninth-graders: Relationship with visuo-spatial abilities and working memory. *Educational Psychology, 21*(4), 387–399.https://doi.org/10.1080/01443410120090786

Reynolds, C.R., & Kamphaus, R.W. (2003). *RIAS: Reynolds Intellectual Assessment Scales*. Lutz, FL. Psychological Assessment Resources, Inc.

Rodán, A., Contreras, M.J., Elosúa, M.R., & Gimeno, P. (2016). Experimental but not sex differences of a mental rotation training program on adolescents. *Frontiers in Psychology,* 7:1050. https://doi.org/10.3389/fpsyg.2016.01050

Rodán, A., Gimeno, P., Elosúa, M. R., Montoro, P. R., & Contreras, M. J. (2019). Boys and girls gain in spatial, but not in mathematical ability after mental rotation training in primary education. *Learning and Individual Differences, 70*, 1–11. https://doi.org/10.1016/j.lindif.2019.01.001

Santamaría, P. (6-9 February 2007). *Diseño de la adaptación española del RIAS: una nueva herramienta para la evaluación de la inteligencia y la memoria* [Poster]. X Congreso de Metodología de las Ciencias Sociales y de la Salud, Barcelona, España.

Schifter, D., Bastable, V, & Russell, S.J. (2002). *Examining Features of Shape: Casebook.* Parsippany, NJ: Dale Seymour.

Shapiro, L. (2019). *New problems of philosophy: Embodied cognition* (2nd ed.). New York, NY: Routledge/Taylor & Francis Group. http://dx.doi.org/10.4324/9780203850664

Smith, C. & Neumann, M. (2014). Scratch it out! Enhancing Geometrical Understanding. Teaching Children Mathematics, 21(3), 185-188. https://doi.org/10.5951/teacchilmath.21.3.0185

Sorby, S. & Panther, G. (2020). Is the key to better PISA math scores improving spatial skills? *Mathematics Education Research Journal. 32* (4), 1-21. https://doi.org/10.1007/s13394-020-00328-9

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how? *Psychology of Learning and Motivation, 57*, 147–181. https://doi.org/10.1016/B978-0-12-394293-7.00004-2

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352–402. https://doi.org/10.1037/a0028446

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2014). Finding the missing piece: Blocks, puzzles, and shapes fuel school readiness. *Trends in Neuroscience and Education, 3*(1), 7–13. https://doi.org/10.1016/j.tine.2014.02.005

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2017). I. Spatial skills, their development, and their links to mathematics. *Monographs of the Society for Research in Child Development, 82*(1), 7-30. https://doi.org/10.1111/mono.12280

Wechsler, D., Kaplan, E., Fein, D., Kramer, J., Morris, R., Delis, D., & Maerlender, A. (2004). *WISC–IV:Wechsler Intelligence Scale for Children integrated technical and interpretive manual* (4th ed.). Minneapolis, MN: Pearson.

Westendorp, M., Hartman, E., Houwen, S., Smith, J., & Visscher, C. (2011). The relationship between gross motor skills and academic achievement in children with learning disabilities. *Research in Developmental Disabilities, 32*(6), 2773–2779. https://doi.org/10.1016/j.ridd.2011.05.032

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*, 625–636. http://dx.doi.org/10.3758/BF03196322

Wu, H. K. & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*(3), 465-492. https://doi.org/10.1002/sce.10126