Mathematics Education Research Journal (2023) 35:255–279
https://doi.org/10.1007/s13394-021-00387-6

ORIGINAL ARTICLE

Can (perceived) mental-rotation performance mediate gender differences in math anxiety in adolescents and young adults?

Martina Rahe[1] · Claudia Quaiser-Pohl[1]

Received: 12 August 2020 / Revised: 10 April 2021 / Accepted: 10 May 2021 /
Published online: 22 July 2021

Abstract

Math anxiety is a negative affective reaction in situations concerning mathematics and is related to poor math performance and a lower mathematical self-concept. Gender differences appear in math anxiety even though gender differences in math abilities are non-existent or minimal in effect size. In the present study, gender and age differences in math anxiety, mental-rotation performance, and perceived mental-rotation performance are investigated as well as (perceived) mental-rotation performance as possible mediators of the relation between gender and math anxiety. Ninety-seven children (54 females) between 11 and 15 years and 84 undergraduate students (59 females) solved a mental-rotation test, rated their performance in this test, and filled out a questionnaire about math anxiety. Increasing gender differences with age were found for math anxiety, mental-rotation performance, and perceived mental-rotation performance. Mental-rotation performance and perceived mental-rotation performance were significant individual mediators for gender differences in math anxiety. Adequate measures should be discussed to enhance females' mental-rotation abilities and their perception of these skills to reduce gender differences in math anxiety.

Keywords Mental rotation · Gender differences · Math anxiety · Adolescence

Introduction

Mental rotation is defined as a spatial ability that requires participants to mentally rotate two- or three-dimensional objects accurately and rapidly (Shepard & Metzler, 1971). The relation of spatial and mathematic abilities is often examined and well established (Lowrie et al., 2020). Uttal et al. (2013) classified spatial abilities based

✉ Martina Rahe
rahe@uni-koblenz.de

[1] Institute of Psychology, University of Koblenz-Landau, Koblenz, Germany

on two distinctions (see also Newcombe & Shipley, 2015). First, the information can be intrinsic or extrinsic (Chatterjee, 2008; Kozhevnikov & Hegarty, 2001), and second, the task is static or dynamic (Chatterjee, 2008; Kozhevnikov et al., 2005). Mental rotation is an intrinsic and dynamic spatial skill: Intrinsic because the information in mental-rotation tasks focuses on the figure's shape and the arrangement of parts and relations between parts of the objects remain unchanged in mental-rotation tasks. The task is dynamic because participants have to move the objects mentally.

In Cattell's (1987) two-factor theory of intelligence, spatial and numerical abilities have higher factor loadings on fluid than on crystallized intelligence. They would therefore be considered part of fluid intelligence (Cattell, 1987). Fluid intelligence includes abilities like problem-solving, logical thinking, and pattern recognition. Crystallized intelligence correlates with abilities that are dependent on knowledge and experience (Cattell, 1987). Accuracy in mental-rotation performance is associated with fluid intelligence differences (Varriale et al., 2018). In functional magnetic reasoning imaging (fMRI) studies, Prescott et al. (2010) found that in math-gifted adolescents, the connectivity patterns used in a mental-rotation task are consistent with activations found in fluid intelligence tasks. Ebisch et al. (2012) could show that spatial abilities and fluid intelligence rely on similar cortical mechanisms. Furthermore, in a training study with mathematical and figural-spatial training tasks, training-related activation differences in the figural-spatial tasks considerably overlapped with the network of brain areas for mathematical tasks (Grabner et al., 2009). The close relation of spatial and mathematical abilities is apparent and confirmed in many studies and reviews (Lowrie et al., 2020; Reinhold et al., 2020; Sorby & Panther, 2020).

Behavioural data also shows close relations of mathematical and spatial skills (Mix et al., 2016; Young et al., 2018). Mental rotation was a significant predictor for mathematical skills in kindergarten and third-graders. For third- and sixth-graders, significant predictors were visual-spatial working memory, visuomotor integration, and perspective-taking (Mix et al., 2016). Battista (1990) found strong correlations between spatial visualization and geometric problem solving, especially in students with low levels of geometry. A possible explanation of this result could be that people with a low level of geometry might approach the tasks more visually than analytical (Battista, 1990). It might be an option to support specifically children who have problems with geometry, for example, by spatial training to improve their mathematical and geometrical strategies and skills.

A meta-analysis displayed that training with spatial tasks can improve the performance in the trained task. The improvement can even transfer to similar spatial performances, e.g., intrinsic static like the trained ability or transfer to other spatial abilities, e.g., from an extrinsic static to an intrinsic dynamic ability (Uttal et al., 2013). Furthermore, already one session of mental rotation training improved 6- to 8-year-old children's calculation problems (Cheng & Mix, 2014). In conclusion, mathematical and spatial skills are not only related but training one ability can transfer to the other ability.

Gender differences in mental rotation

Meta-analyses about gender differences in spatial abilities found males outperforming females in psychometric mental-rotation tests (Lauer et al., 2019; Linn & Petersen, 1985; Voyer et al., 1995). Small male advantages first emerged in elementary school-age children (Lauer et al., 2019). They increased with age from childhood to adolescence (Lauer et al., 2019) and from adolescence to adulthood (Voyer et al., 1995).

In mental-rotation tasks with 11- to 19-year-old participants, older adolescents outperformed younger adolescents in accuracy and reaction time (Kail, 1985). Analyzing age and gender effects in the same age group, Rahe and Quaiser-Pohl (2019) found no effect of age in general but a significant interaction of age group and gender indicating that only boys but not girls' accuracy in a mental-rotation task improved during adolescence. This is in line with increasing gender differences from adolescence to adulthood (Voyer et al., 1995). In the present study, we were interested in the effects of age on gender differences in mental-rotation performance, perceived mental-rotation performance, and math anxiety. Therefore, we recruited children in young adolescence and young adults as participants.

Reasons for male advantages in mental-rotation performance could be biological (Alexander & Son, 2007; Quinn & Liben, 2014) or strategical factors (Boone & Hegarty, 2017; Hegarty, 2018; Heil & Jansen-Osmann, 2008) as well as gender differences in confidence (Estes & Felker, 2012) or perceived spatial abilities (Rahe & Quaiser-Pohl, 2019). Additional reasons could be experimental factors, e.g., variances in time constraints (Voyer, 2011) or feedback about the individual answer in the test (Rahe et al., 2019a, b).

Gender differences in mental rotation appear not only in the mental rotation task itself but also in selecting the most successful strategy (Boone & Hegarty, 2017; Hegarty, 2018). When different shapes of the original figures are used instead of mirror images, using orientation-independent strategies can be more successful than rotating the objects. This is important for the malleability of the task because choosing the best strategy can be more successful than the mental rotation process itself. When men are more successful in mental rotation tasks, a possible reason can be that they have better abilities to encode and transform spatial objects (Hegarty, 2018). A holistic strategy where the object is rotated as a whole is more successful than a piecemeal strategy where the object is rotated piece by piece (Geiser et al., 2006; Hegarty, 2018). As men seem to use the holistic strategy more often than women (Hegarty, 2018) and as women prefer the piecemeal strategy more often than men (Geiser et al., 2006), this could affect gender differences in mental rotation.

In general, males display higher confidence in spatial abilities (Ariel et al., 2018) or general masculine activities than females. This affective dimension correlates with the cognitive (mental-rotation performance) dimension, especially in males (Cooke-Simpson & Voyer, 2007).

Besides higher confidence in male than female participants, parents of high school students believe that their sons have higher mental manipulation and navigation skills than their daughters do (Muenks et al., 2019). This effect was significant even when controlling for students' actual performances. These different parental beliefs could affect children's own beliefs and their performance as well. In the present study, gender and age group differences and interactions will be analyzed for mental-rotation performance, perceived mental-rotation performance, and math anxiety.

Math anxiety

Math anxiety is defined as a negative emotion or affective reaction in situations related to mathematical or numerical tasks (Ashcraft & Moore, 2009; Sokolowski et al., 2019). Moreover, math anxiety is related to poor math performance in adults (Ashcraft & Moore, 2009; Barroso et al., 2021) and children (Chang & Beilock, 2016; Ma, 1999; Ramirez et al., 2013) as well as to low mathematical self-confidence and could negatively affect working memory (Ashcraft, 2002). The close relation of math anxiety and math achievement appears as early as in first grade (Ramirez et al., 2013).

Math anxiety is not only related to cognitive dimensions but other affective constructs as well. People's math anxiety is associated with their self-confidence in math (Ashcraft, 2002; Hembree, 1990), their enjoyment of math, their self-concept and motivation in math, as well as their avoidance of math (Hembree, 1990). It seems essential to treat children's math anxiety and find pedagogical approaches that can help to ameliorate anxiety over the long term.

Gender differences in math anxiety

Many studies found gender differences in math anxiety with higher scores of anxiety displayed in females than in males (Ferguson et al., 2015; Hembree, 1990; Hopko et al., 2003; Lauer et al., 2018; Maloney et al., 2012). In a study with 6- to 12-year-old children, no gender differences in mathematical or spatial abilities were found, but girls reported higher math and spatial anxiety than boys (Lauer et al., 2018). Hence, gender differences in gender-stereotyped cognitive skills appear early in childhood and are independent of children's actual performance.

Bieg et al. (2015) collected data from 755 nine and tenth graders about math anxiety for trait and state math anxiety, math-related self-concepts, and math gender stereotypes. Males reported stronger math stereotypes, higher self-concept levels and less trait math anxiety. Correlations between self-concept and gender stereotypes were negative for girls and positive for boys indicating that girls who strongly believed math to be a male domain had a relatively low self-concept in mathematics. In contrast, boys benefitted from a strong gender stereotype in mathematical self-concept. Gender stereotypes also positively predicted girls' state-trait anxiety discrepancy, while this effect was negative for boys. Consequently, only in girls, stronger trait — compared to state — anxiety is related to a stronger belief that math is a masculine ability (Bieg et al., 2015).

A German study with more than 800 fourth graders found no significant gender differences in an objective math test but significantly better math grades in boys and gender differences favoring males for mathematical self-concept rated by teachers, parents, and the children themselves (Steinmayr et al., 2020). Hence, even though mathematical abilities do not differ between boys and girls (e.g., Halpern et al., 2011; Steinmayr et al., 2020), teachers, parents, and the children seem to think that boys' mathematical skills should be better than girls' skills. Self-concept and anxiety in mathematics are closely and reciprocally related to each other in seventh-grade students (Ahmed et al., 2012) and second-grade children (Jameson, 2014), and both are related to math performance (Douglas, 2000). Therefore, a lower mathematical self-concept in females could affect their mathematical anxiety and performance.

To analyze the influence of gender on preferences for mathematics or science compared to arts or language, Nosek et al. (2002) conducted a study with implicit measures of math attitude (compared to arts), math identity (compared to arts), math gender stereotypes, and gender identity. Results showed that females thought of math as masculine and negatively valued and themselves as females. Consequently, they think of math as not identified with themselves. Engagement with and higher abilities in math, science, and spatial tasks are related to a higher possibility of choosing STEM (science, technology, engineering, and mathematics) subjects in school or university (Wai et al., 2009). To inspire more girls to take an interest in STEM subjects, girls' affective reactions towards math and spatial tasks deserve more detailed consideration.

The present study aims to explain whether mental-rotation performance or perceived mental-rotation performance can more likely mediate the relation between gender and math anxiety. Furthermore, it seems necessary to investigate the relation between the intensity of math anxiety and gender differences in math anxiety and the influence of (perceived) mental rotation performances at different time points during adolescence. Only when this is known, it is possible to implement pedagogical approaches during sensitive periods of adolescents' development.

Mental-rotation performance and math anxiety

Spatial and mathematical skills are related (Kyttälä & Letho, 2008; Mix & Cheng, 2012), and specific spatial and mathematical tasks show overlapping domains (Mix et al., 2016). Both abilities are considered fluid intelligence (Cattell, 1987). Spatial skills are related to geometry (Battista, 1990; Weckbacher & Okamoto, 2014), and mental rotation is a strong predictor of mathematical abilities in high school students (Casey et al., 1995). Mental-rotation ability is also related to affective domains of math and geometry, like self-perception in geometry and algebra (Weckbacher & Okamoto, 2014). Other studies found correlations between mental-rotation performance and math-test performance in young adults that was stronger in males than in females (Rahe & Quaiser-Pohl, 2020) and between mental-rotation performance and geometry in adolescents (Kyttälä & Letho, 2008). A meta-analysis found significant correlations between mathematical abilities and intrinsic-dynamic spatial abilities (Xie et al., 2020).

Casey et al. (1997) found gender differences in mental rotation, math anxiety, and the Math Scholastic Aptitude Test (SAT-M) as well as correlations between mental rotation and math self-confidence, geometry, and SAT-M. A path analysis showed that relations of gender and SAT-M were mediated through boys' better mental rotation abilities and their increased self-confidence. A meta-analysis could show that math anxiety is negatively related to spatial ability (Hembree, 1990). Consequently, cognitive and affective dimensions seem to be closely related to each other and students' gender. The present study aims to look at gender differences in cognitive and affective aspects at different time points in adolescents' development. Furthermore, different correlations between these aspects for males and females will be analyzed.

Recently, many studies have focussed on the effects of spatial ability, spatial anxiety, and perceived spatial ability on the gender differences in math anxiety (for a thorough overview, see Sokolowski et al., 2019). Self-reported spatial skills mediated the relationship between gender and math anxiety in undergraduate students and adults between 18 and 78 years (Maloney et al., 2012). Furthermore, self-reported sense of direction, spatial anxiety, and mental-rotation skills predicted math anxiety (Ferguson et al., 2015). Even when gender was controlled, mental-rotation abilities, spatial and general anxiety, but not large-scale abilities (Money Test) predicted math anxiety in undergraduate students (Ferguson et al., 2015). A review of findings from studies analyzing gender differences in math performance, math anxiety, and spatial abilities suggests a "path from gender to spatial ability, from spatial ability to math anxiety and from math anxiety to math achievement" (Wang, 2020). Hence, examining gender differences in spatial abilities seems essential to explain gender differences in math anxiety. Mental rotation tasks produce the most considerable gender differences in spatial abilities (Voyer et al., 1995). Therefore, it appears reasonable to look at the relation between mental rotation performance and math anxiety. However, the review (Wang, 2020) did not differentiate between different age groups.

Sokolowski et al. (2019) could show that in undergraduate students, gender differences appeared for mental-rotation performance, perceived spatial abilities, spatial anxiety, and math anxiety, but not for mathematical abilities. The authors found mediating effects of cognitive (mental-rotation performance) and affective (perceived spatial ability and spatial anxiety) spatial dimensions on the relation between gender and math anxiety. Spatial anxiety became the most robust unique mediator, but both mental-rotation performance and perceived spatial ability could fully mediate the gender differences in math anxiety. Sokolowski et al. (2019) used the Spatial Imagery Questionnaire (SIQ) of the Object-Spatial Imagery Questionnaire (OSIQ, Blajenkova et al., 2006). That subscale measures spatial imagery and includes evaluations of participants' interests and abilities in visual representations, transformation processes, and spatial imagery. In the present study, the aim is mainly on the influence of mental-rotation performance and perceived mental-rotation performance on math anxiety and not on a self-evaluation of participants' spatial abilities in general. Hence, our self-evaluation focuses on participants' mental-rotation abilities. Furthermore, we aim to shed more light on the relations of (perceived) mental rotation and math anxiety at two critical educational time points. By means of our approach with two different age groups, the emergence of gender differences in cognitive and affective spatial dimensions and math anxiety and different relations between these dimensions can be analyzed in more detail.

In elementary school-aged children, mental-rotation abilities were negatively correlated to math and spatial anxiety and positively correlated to math achievement

(Lauer et al., 2018). This illustrates that early in development, the relation between spatial skills and mathematical abilities exists. Furthermore, mental-rotation performances were also related to math anxiety, which shows that relations between affective and cognitive dimensions are not all domain-specific (Lauer et al., 2018).

Math and spatial abilities are perceived as masculine-stereotyped abilities (Halpern et al., 2011; Moè et al., 2020). Consequently, females could be prone to stereotype threat (Steele & Aronson, 1995), which is the risk of confirming a negative stereotype about one's own group. Manipulating beliefs about men and women's mental-rotation abilities led to better performances in participants who got the instruction that their gender had an advantage in that skill (Moè & Pazzaglia, 2006). Another study with a perspective-taking task that is dissociable but highly correlated to mental rotation (Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001) could show similar results. Performing the same spatial perspective-taking task framed either as spatial or social ability, males outperformed females only in the spatial but not the social condition (Tarampi et al., 2016). Hence, especially females seem to be influenced by their own (or other peoples') stereotyped beliefs, and these beliefs could negatively affect their perceived performance and their actual performance in masculine stereotyped activities, like mathematics, sciences, or spatial tasks.

Individual and gender differences in mental rotation and perceived mental rotation performance can affect math anxiety and gender differences in math anxiety. Mediator analyses can help to understand whether the cognitive or the affective dimension of spatial abilities influences gender differences in math anxiety.

Goal of the study

Many possible factors influence math anxiety and gender differences in math anxiety. We want to investigate the influence of mental rotation performance as a cognitive spatial ability and perceived mental rotation performance as an affective spatial dimension. These influences will be analyzed at two different time points of adolescence to determine the best time to implement possible pedagogical interventions.

Hypotheses

(1) In line with the literature, we predicted males to outperform females in mental rotation (Voyer et al., 1995) and older participants to perform better than younger children (Rahe & Quaiser-Pohl, 2019). Gender differences should be more pronounced in the older than the younger age group (Voyer et al., 1995).

(2) For perceived mental-rotation performance, we predicted higher scores for males than for females (Estes & Felker, 2012) and for older than for younger participants and smaller gender differences in the younger than the older age group (Rahe & Quaiser-Pohl, 2019).

(3) For math anxiety, we predicted higher scores for females than for males (Ferguson et al., 2015; Hopko et al., 2003; Lauer et al., 2018; Sokolowski et al., 2019) and for older than for younger participants (Hopko et al., 2003) and smaller gender differences for the younger age group.

(4) We predicted cognitive (mental-rotation performance) and affective (perceived mental-rotation performance) spatial dimensions to mediate the relation between participants' gender and math anxiety (Sokolowski et al., 2019).

Methods

Participants

In this study, 97 children (54 females) between 11 and 15 years ($M = 12.51$, $SD = 1.09$) and 84 undergraduate students (59 females) between 18 and 39 years ($M = 22.24$, $SD = 4.38$) took part. The children were attending 6th, 7th, or 8th grade in a German school of the highest track (Gymnasium, more than 70% will attend a university). Undergraduate students were attending an introductory psychology class in a German university. Because the children were attending different classes in school, intraclass correlations (ICC) were calculated for the variables mental-rotation performance, perceived mental-rotation performance and math anxiety. ICCs were very low (all $ICC < 0.08$) and not significant (all $p > 0.34$); therefore, clustering children according to their classes was not necessary.

Material

Mental-rotation test

To analyze participants' mental-rotation ability, a paper–pencil mental-rotation test (MRT) (according to Vandenberg & Kuse, 1978) with 12 items consisting of cube figures was used. For each item, one cube figure on the left had to be compared to four figures on the right (Fig. 1). Two of the four objects were identical to the left figure and had to be crossed out. Both remaining figures were mirror images of the left object. All objects were rotated in depth. One point was given if both identical objects were crossed out and no mirrored object was. Internal consistency of the MRT can be regarded as given (Cronbach's alpha 0.849).

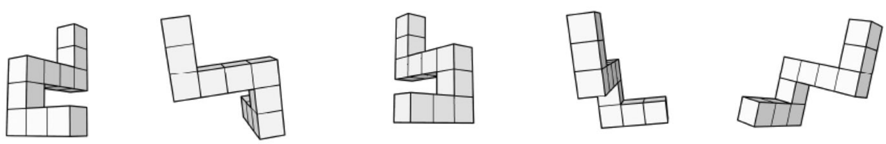

Fig. 1 Example item of the MRT

Perceived mental-rotation performance

The questionnaire consisted of three questions about participants' perceived mental-rotation performance answered on a six-point Likert scale ranging from 1 to 6. Subjects were asked how sure they were about their decisions, how good they rated their performance, and how difficult they thought the MRT was. The answers to the third question were inverted, and a mean score was calculated for participants' perceived mental-rotation performance (Cronbach's alpha = 0.828). High correlations between perceived mental-rotation performance and actual mental-rotation performance (Rahe & Quaiser-Pohl, 2020) underpin the measurement's validity.

Math anxiety

For the assessment of participants' math anxiety, the Abbreviated Math Anxiety Scale (AMAS, Hopko et al., 2003) was used, consisting of 9 questions, which had to be answered on a five-point Likert scale ranging from 1 (low anxiety) to 5 (high anxiety). A mean score was calculated for participants' math anxiety (Cronbach's alpha = 0.855). The authors report strong convergent validity for the AMAS (Hopko et al., 2003).

Procedure

All children were tested in their school classes in groups of 21 to 26. Undergraduate students were tested in their university classes in groups of 17 to 28. Before they filled out the MRT, two practice items were given to them. The correct solutions of both practice items were discussed in class to ensure all participants understood the task. Afterwards, subjects tried to solve 12 items in 3 min. Then, participants filled out the questionnaire about their perceived mental-rotation performance, math anxiety, gender, and age.

All parents of the children and all participants gave their written informed consent. The experiment was conducted according to the ethical guidelines of the Helsinki declaration. Ethical approval for this study was not required following the conditions outlined by the German Research Foundation, where research that carries no additional risk beyond daily activities does not require Research Ethics Board Approval.

Statistical analyses

To test the main and interaction effects of gender and age group for mental rotation (hypothesis 1), perceived mental rotation (hypothesis 2), and math anxiety (hypotheses 3), univariate ANOVAs were calculated with gender and age group as independent variables and the respective constructs as dependent variables. For hypothesis 4, mediator analyses were conducted with gender as predictor, math anxiety as criterion, and mental rotation and perceived mental rotation, respectively, as mediator. To examine whether mental rotation, perceived mental rotation, or a combination of both can best mediate the relation of gender and math anxiety, we entered both mediators into one analysis. Tests were calculated with a level of significance of $\alpha < 0.05$. Significance levels of 1% or 0.1% are explicitly reported.

Results

Gender differences in mental rotation

For gender and age differences in mental-rotation performance, we calculated an ANOVA with gender and age group as independent variables and mental-rotation performance as dependent variable. Main effects for gender, $F(1.177) = 48.882$, $p < 0.001$, $eta^2 = 0.216$, and age group, $F(1.177) = 23.929$, $p < 0.001$, $eta^2 = 0.119$, showed better performances for males than females and older subjects than younger ones (Fig. 2). A significant interaction of gender and age group, $F(1.177) = 15.722$, $p < 0.001$, $eta^2 = 0.082$, revealed small gender differences for the younger, $F(1.177) = 5.412$, $p = 0.011$, $eta^2 = 0.030$, and large differences for the older, $F(1.177) = 52.027$, $p < 0.001$, $eta^2 = 0.227$, age group. In only males, $F(1.177) = 30.607$, $p < 0.001$, $eta^2 = 0.147$, but not females, $F(1.177) = 0.598$, $p = 0.221$, $eta^2 = 0.003$, performance was better in the older age group than in the younger group. Regarding hypothesis 1, males outperformed females and older participants outperformed younger ones in mental rotation performance. Furthermore, gender differences were larger in the older age group than in the younger group.

Gender differences in perceived mental rotation

For gender and age differences in participants' perceived mental-rotation performance, an ANOVA was calculated with gender and age group as independent variables and perceived mental-rotation performance score as dependent variable. A

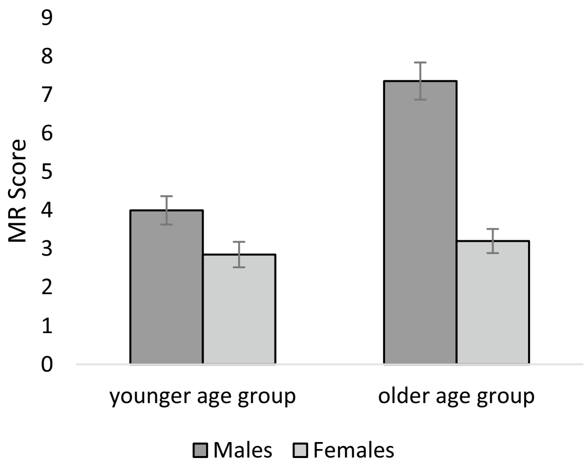

Fig. 2 Mental rotation score as a function of gender and age group. Error bars indicate *SE*

main effect of gender, $F(1.177) = 52.454$, $p < 0.001$, $eta^2 = 0.229$, illustrated higher perceived mental-rotation performance for males than for females (Fig. 3). No significant main effect of age group, $F(1.177) = 0.219$, $p = 0.320$, $eta^2 = 0.001$, could be found. A significant interaction of gender and age group, $F(1.177) = 19.894$, $p < 0.001$, $eta^2 = 0.101$, revealed gender differences with a small effect for the younger group, $F(1.177) = 4.573$, $p = 0.017$, $eta^2 = 0.025$, and a large effect for the older age group, $F(1.177) = 59.354$, $p < 0.001$, $eta^2 = 0.251$. While males' perceived mental-rotation performance was higher in the older than in the younger age group, $F(1.177) = 6.219$, $p = 0.007$, $eta^2 = 0.034$, the opposite effect was found for females, $F(1.177) = 16.901$, $p < 0.001$, $eta^2 = 0.087$. With regard to hypothesis 2, males rated their performance in the mental-rotation test higher than females and participants in the older age group scored higher in perceived mental-rotation performance than participants in the younger age group. Moreover, gender differences were smaller in the younger than in the older age group.

Gender differences in math anxiety

For gender and age differences in math anxiety, we calculated an ANOVA with gender and age group as independent variables and math anxiety as dependent variable. We found a large main effect for gender, $F(1.177) = 34.296$, $p < 0.001$, $eta^2 = 0.162$, but no effect for age group, $F(1.177) = 0.066$, $p = 0.399$, $eta^2 < 0.001$. The interaction showed a small significant effect, $F(1.177) = 3.071$, $p = 0.041$, $eta^2 = 0.017$ (Fig. 4), illustrating a small to medium effect for the younger age group, $F(1.177) = 9.951$, $p = 0.001$, $eta^2 = 0.053$, and a medium to large effect for the older age group, $F(1.177) = 25.089$, $p < 0.001$, $eta^2 = 0.124$. Regarding hypothesis 3, females reported higher math anxiety than males and gender differences were larger in the older age group than in the younger age group.

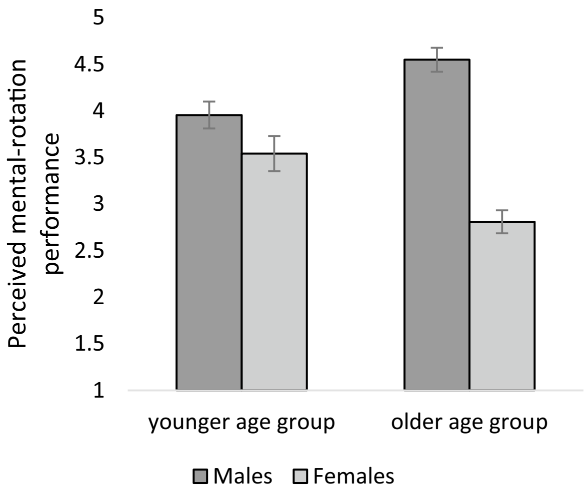

Fig. 3 Participants' perceived mental rotation performance as a function of gender and age group. Error bars indicate *SE*

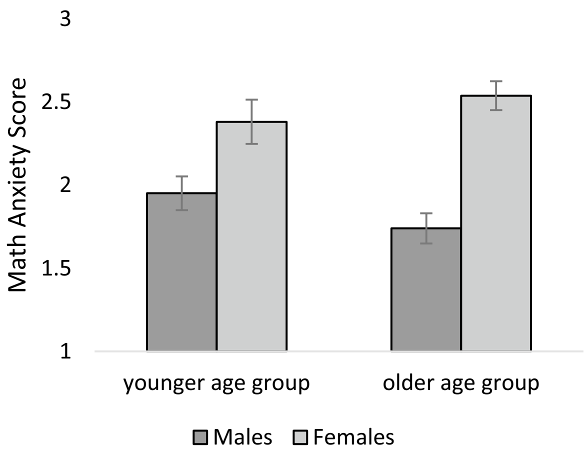

Fig. 4 Math anxiety as a function of gender and age group. Error bars indicate *SE*

Mental-rotation performance and math anxiety

Correlations between the dependent variables and age are illustrated for males and females separately (Table 1). These different relations illustrate the interactions of gender and age group on the dependent variables. In males, mental-rotation performance is better in the older age group while it remains stable in females. The opposite effect was found for perceived mental-rotation performance: Younger females rated their performance better than older females. For math anxiety, small, non-significant decreases in males and small, non-significant increases in females during adolescence illustrate the opposing trends. Furthermore, math anxiety is significantly related to mental-rotation performance only in males but not in females.

Mediator analyses

A mediator analysis was calculated using Process macro v 3.2.01 (Model 4) with math anxiety as criterion, gender as predictor, and participants' mental-rotation performance as mediator. In a first step, gender predicts mental-rotation performance, mental-rotation performance predicts math anxiety, and gender predicts math anxiety ($R^2 = 0.15$) (Table 2, model A). When mental-rotation performance is added as

Table 1 Correlations between mental-rotation performance (MR), perceived mental-rotation performance (PMR), math anxiety, and age for males and females

	MR	PMR	Math anxiety	Age
MR		0.618** (M)	−0.349** (M)	0.433** (M)
		0.445** (F)	−0.081 (F)	0.046 (F)
PMR			−0.393** (M)	0.193 (M)
			−0.345** (F)	−0.348** (F)
Math anxiety				−0.063 (M)
				0.091 (F)

Correlations for males (M) and for females (F)

$**p < 0.001$

Table 2 Mental-rotation performance and perceived mental-rotation performance as mediators of the relation between gender and math anxiety

	Model	Estimate	*SE/SE*$^{+}$	*p*	%C	99% CI
	Model without mediator					
	Intercept	1.87	0.08	< 0.001		1.66, 2.08
	Gender MA (c)	0.58	0.10	< 0.001		0.32, 0.85
	R^2: gender MA	0.15				
A	Model with MR as mediator					
(Fig. 5)	Intercept	2.14	0.12	< 0.001		1.81, 2.47
	Gender MR (a)	− 2.19	0.39	< 0.001		− 3.24, − 1.15
	MR MA (b)	− 0.05	0.01	0.006		− 0.10, − 0.00
	Gender MA (c’)	0.47	0.10	< 0.001		0.19, 0.76
	Indirect effect (a*b)	0.11	0.04		0.19	0.01, 0.23
	R^2: gender MR MA	0.18				
B	Model with PMR as mediator					
(Fig. 6)	Intercept	2.88	0.20	< 0.001		2.33, 3.42
	Gender PMR (a)	− 1.01	0.15	< 0.001		− 1.41, − 0.61
	PMR MA (b)	− 0.24	0.04	< 0.001		0.06, 0.62
	Gender MA (c’)	0.34	0.10	0.001		0.06, 0.62
	Indirect effect (a*b)	0.24	0.05		0.41	0.11, 0.41
	R^2: gender PMR MA	0.26				
C	Model with MR and PMR as mediator					
(Fig. 7)	Intercept	2.88	0.21	< 0.001		2.33, 3.42
	Gender MR (a)	− 2.19	0.39	< 0.001		− 3.24, − 1.15
	Gender PMR (a)	− 1.01	0.15	< 0.001		− 1.41, − 0.61
	MR MA (b)	− 0.00	0.02	0.790		− 0.06, 0.04
	PMR MA (b)	− 0.23	0.05	< 0.001		− 0.37, − 0.09
	Gender MA (c’)	0.33	0.10	0.002		0.05, 0.62
	Indirect effects (a*b)					
	Gender MR MA	0.01	0.04		0.02	− 0.10, 0.12
	Gender PMR MA	0.13	0.04		0.22	0.03, 0.26
	Gender MR,PMR MA	0.10	0.03		0.17	0.03, 0.20
	R^2: gender MR,PMR MA	0.26				

SE standard error for linear regression for direct effects, *SE*$^{+}$ bootstrapped standard error for indirect effects, *%C* percentage of the total effect accounted for by the indirect effect (a*b/c), *MR* mental-rotation performance, *PMR* perceived mental-rotation performance, *MA* math anxiety

a mediator, gender still predicts math anxiety. The indirect effect of gender on math anxiety mediated through mental-rotation performance is significant ($R^2 = 0.18$). Consequently, participants’ mental-rotation performance partly mediates the relation of gender and math anxiety. This is illustrated in Fig. 5, containing information about direct and indirect effects. Table 2 provides more additional data about these effects for all three models, e.g., level of significance, confidence intervals, and the percentage of the total effect accounted for by the indirect effect (%C).

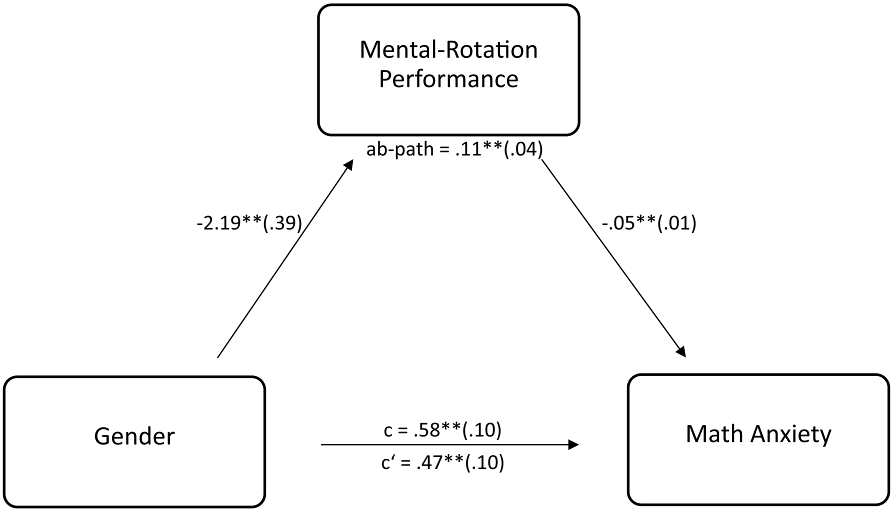

Fig. 5 Mediation of the effect of gender on math anxiety through mental rotation performance. Asterisks indicate significant coefficients, $^{**}p<0.01$. For statistics, see Table 2

A second mediator analysis was calculated using Process macro v 3.2.01 (model 4) with math anxiety as criterion, gender as predictor, and participants' perceived mental-rotation performance as mediator. In a first step, gender predicts perceived mental-rotation performance, perceived mental-rotation performance predicts math anxiety, and gender predicts math anxiety ($R^2=0.15$) (Table 2, model B). When perceived mental-rotation performance is added as a mediator, gender still predicts

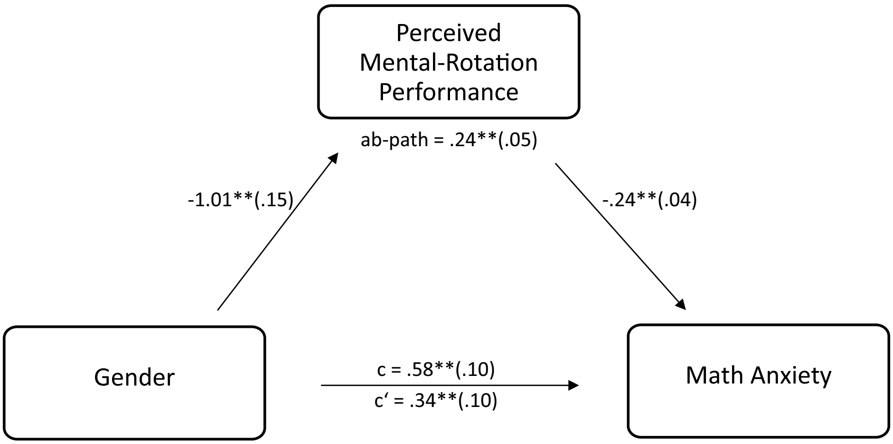

Fig. 6 Mediation of the effect of gender on math anxiety through perceived mental rotation performance. Asterisks indicate significant coefficients, $^{**}p<0.01$. For statistics, see Table 2

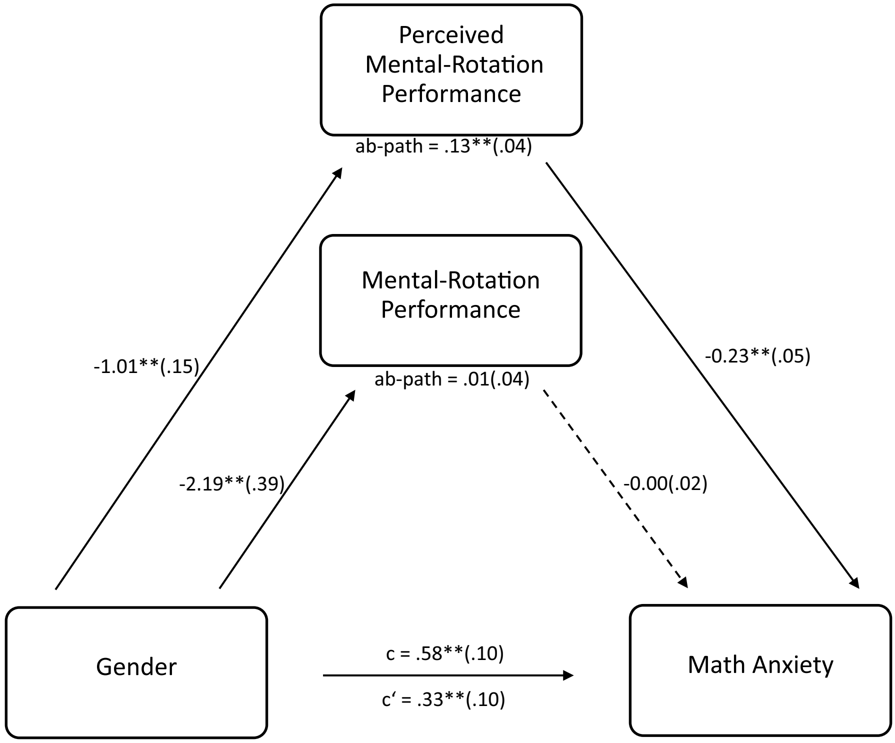

Fig. 7 Mediation of the effect of gender on math anxiety through mental rotation performance and perceived mental rotation performance. Asterisks indicate significant coefficients, **p < .01. For statistics, see Table 2

math anxiety. The indirect effect of gender on math anxiety mediated through perceived mental-rotation performance is significant ($R^2 = 0.26$). Consequently, participants' perceived mental-rotation performance partly mediates the relation of gender and math anxiety (Fig. 6).

A mediator analysis was calculated using Process macro v 3.2.01 (model 6) with math anxiety as criterion, gender as predictor, and participants' mental-rotation performance and their perceived mental-rotation performance as mediators (Table 2, model C). The combined mediator of mental-rotation performance and perceived mental-rotation performance significantly mediates the relation of gender and math anxiety ($R^2 = 0.26$) (Fig. 7). In this model, mental-rotation performance was no significant unique mediator. Perceived mental-rotation performance significantly mediates the relation of gender and math anxiety as a unique mediator.

Model B with perceived mental-rotation performance as mediator of the relation between gender and math anxiety was the best model with 26% of the variance of math anxiety explained by gender and perceived mental-rotation performance. The total indirect effect accounted for 41% of the total effect. Because the interaction of gender and age group had a medium effect on perceived mental-rotation

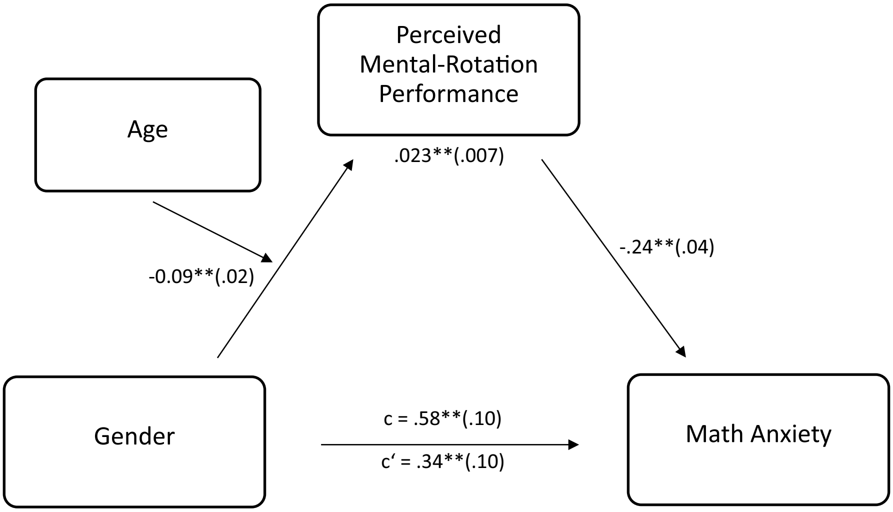

Fig. 8 Moderated mediation of the effect of gender on math anxiety through perceived mental rotation performance and moderated by age. Asterisks indicate significant coefficients, ** p < .01

performance, age is added as a moderator into the mediation analysis (Fig. 8). Age and gender explained 27% of the variance of perceived mental-rotation performance, and the index of the moderated mediation in total is 0.023 ($SE_{Boot}=0.007$, 99% CI [0.008, 0.046]). The direct effect of gender on math anxiety is 0.344 ($SE=0.107$, 99% CI [0.065, 0.622]).

Calculating the mediation model separately for both age groups, gender significantly predicts math anxiety in the younger age group ($beta=0.330$, $p=0.001$, $R^2=0.109$, direct effect). The indirect effect of gender on math anxiety mediated through perceived mental-rotation performance is still significant ($beta=0.264$, $p=0.006$). The model with perceived mental-rotation performance and gender explains 21.2% of the variance of math anxiety ($\Delta R^2=0.103$). The direct effect for the older age group is significant ($beta=0.456$, $p<0.001$, $R^2=0.208$), and the indirect effect is not significant ($beta=0.167$, $p=0.190$). The model with perceived mental-rotation performance and gender explains 30.5% of the variance of math anxiety ($\Delta R^2=0.098$).

Discussion

Gender differences in mental rotation

In line with Voyer et al., (1995), we found gender differences in mental-rotation performance favoring males that were increasing in the surveyed age span between children of about 12 years and undergraduate students. Adults also performed better than children (Kail, 1985). Males' mental-rotation performance increased, which is in line with other studies about increasing cognitive abilities or intelligence during adolescence (Berk, 2008). Females' performance remained stable, which led to increasing gender differences. The same results were found in a study with participants between 11 and 20 years (Rahe & Quaiser-Pohl, 2019). Consequently, only boys' mental-rotation performance seems to increase with age, while there appear to be limitations for girls, which lead to a stagnation of their abilities. One of these limitations could be a stronger belief that boys outperform girls in spatial abilities (Halpern et al., 2011). This gender-stereotype thinking seems to increase during adolescence. Another limitation for girls could be fewer opportunities to engage themselves with spatial tasks. Spatial skills can be improved by practice in adults (Meneghetti et al., 2016; Rahe et al., 2019a, b; Uttal et al., 2013) and children (Wiedenbauer & Jansen-Osmann, 2008). Consequently, practicing mental rotation, especially with girls, could help to reduce the gender difference.

Gender differences in perceived mental rotation

For participants' perceived mental-rotation performance, gender differences favoring males (Cooke-Simpson & Voyer, 2007) also increased with increasing age. In a study with 11- to 20-year-old high school students, females' perceived ability of stereotypically masculine activities (e.g., navigation, mental rotation) significantly decreasing during adolescence and remained stable in males (Rahe & Quaiser-Pohl, 2019). Contrary to our hypothesis, participants' perceived performance did not increase with age. On a closer look, males' perceived performance increased significantly with age, while college-aged females rated their performance significantly worse than girls. With increasing age, females could be more affected by their beliefs that spatial tasks are masculine stereotyped (Halpern et al., 2011). Above that, college-aged students should be more aware than 11- to 15-year-old children that males outperform females in spatial tasks. Due to social comparison processes during adolescence, this could then increase perceived performance in males and a decreasing belief about one's performance in females. As a flawed belief about females' ability is related to poor spatial skills performance (Moè & Pazzaglia, 2006), girls' decreasing beliefs in adolescence should receive more attention.

Comparing the influence of gender and age group on mental-rotation performance and perceived performance, males rate their performance better when they get older. This reflects in their actual performance. Females' actual performance remains stable while their perceived performance decreases. Consequently, the cognitive and the affective components of mental rotation are consistent in males while females' perceived performance lags behind their actual performance. This is in line with Cooke-Simpson and Voyer (2007) and Rahe and Quaiser-Pohl (2020), who found that undergraduate male students had a more accurate perception of their mental-rotation performance than females. Giving especially females feedback about their actual performance in spatial tasks could help strengthening their perception. Other possible approaches to improve females' perception could be to reduce their stereotype thinking about activities that are considered masculine. On the other hand, stereotypes about activities that are considered feminine are a negative predictor of adolescents' mental rotation performance (Rahe & Quaiser-Pohl, 2019). Consequently, not only stereotypes about masculine abilities but about feminine abilities as well should be diminished.

Another possible reason for males' better spatial abilities results could be that they play more video games in adolescence and adulthood (Borgonavi, 2016). Many studies show positive effects of video gaming on spatial cognition (e.g., Cherney, 2008; Feng et al., 2007). Hence, training females' spatial abilities with appropriate video games could be another option to reduce gender differences in spatial abilities.

Gender differences in math anxiety

Concerning math anxiety, we found higher scores for females (Hopko et al., 2003), especially in the older age group. In the present study, math abilities were not tested, but many studies show comparable results in males and females (Lauer et al., 2018; Steinmayr et al., 2020). Nevertheless, math anxiety seems to be higher in females. This could be induced by beliefs that math is a masculine-stereotyped ability. Even when girls achieve the same grades in school as boys, females still believe that males are better (Steinmayr et al., 2020). A less stereotyped education in school or at home could lead to girls' beliefs that their math abilities are as high as boys' skills. Consequently, girls' math anxiety could diminish to a reduced level.

Contrary to our hypothesis, participants' math anxiety did not increase in general with age. However, the significant interaction of gender and age group indicates increasing gender differences with age. This contrasts with the study conducted by Lauer et al. (2018), where gender difference in math anxiety remained stable during the age range of 6- to 12-year-old children. As our participants' age range was directly following Lauer's, it can be assumed that gender differences in math anxiety appear early in childhood, remain stable during elementary school, and increase during adolescence. Increasing beliefs about math as a masculine-stereotyped ability could be responsible for increasing gender differences with age (Halpern et al., 2011). When males had stronger beliefs that math is a masculine ability, they could identify themselves with math more than males who had less gender-stereotyped beliefs about math (Nosek et al., 2002). This could lead to stronger confidence in their math performance and, therefore, to less math anxiety. For females, on the other hand, stronger beliefs that math is stereotyped to the opposite gender could evoke decreasing identity with math, decreasing confidence in their math abilities and increasing math anxiety. It should be possible to strengthen each child's belief that their mathematical or spatial ability is sufficiently suitable independent of its gender or existing gender stereotypes.

Mental-rotation performance and math anxiety

Different models comparing various mediators for the relationship between gender and math anxiety indicated that the model with perceived mental-rotation performance as mediator is more suitable than the model with the actual performance itself. The affective dimension of mental rotation was a stronger mediator to the gender differences in math anxiety than the cognitive factor. Individually, mental-rotation performance and perceived mental-rotation performance could mediate the relation between gender and math anxiety. Sokolowski et al. (2019) found gender differences in math anxiety mediated by mental-rotation ability and spatial anxiety. They assumed that gender differences in spatial abilities and the use of spatial strategies in mathematic tasks could be related to gender differences in spatial anxiety. As males use the more successful holistic strategy in mental rotation more often than females and females use the less successful analytic strategy more often than males (Geiser et al., 2006; Hegarty, 2018; Heil & Jansen-Osmann, 2008), it could be speculated that males use a more spatial strategy not only in spatial but also in mathematical tasks. This could then link the affective factor of the spatial domain to the affective factor of the math domain. Consequently, higher spatial fear or worse perceived spatial abilities could be related to higher math anxiety.

To reduce females' math anxiety, it could be promising to strengthen girls' confidence about their spatial abilities and to practice these spatial skills (Sokolowski et al., 2019). Workshops or extra-curricular classes in the STEM field could help girls become more familiar with a domain they still feel uncertain about. As gender differences in math anxiety, mental-rotation performance, and perceived mental-rotation performance increase during adolescence, such classes or practices should be most promising in early adolescence. That could help to attenuate the increasing gender differences from childhood to adulthood.

A further implication of the mediating effect of (perceived) spatial abilities on the relationship between gender and math anxiety could be to add more spatial tasks to the mathematical curriculum at school. In doing so, girls could get more familiar with spatial tasks, which could again strengthen their assessment of their spatial abilities. This could be even more effective when children were separated by gender during such spatial tasks to avoid the social comparison processes of female students. It would be better still, to enrich the mathematical curriculum with spatial tasks in early elementary school, when children's gender stereotypical thinking is less pronounced than in adolescence. This could not only help to reduce gender differences in spatial abilities and perceived spatial abilities but in gender-stereotypical thinking concerning spatial abilities as well. Girls' spatial abilities and their perceived spatial abilities could be increased, and therefore, gender differences in math anxiety could be diminished. On the other hand, it could be assumed that math anxiety as an affective factor could be better diminished by enhancing the affective factor of spatial tasks or other affective factors of mathematical tasks, e.g., self-concept, motivation, or self-perception.

Because the STEM field is somewhat underrepresented in higher education in some countries, it seems advisable to enhance efforts to interest more young adults in this area. Negative thoughts towards mathematics and dissociating oneself from this subject will prevent girls from engaging in advanced STEM subjects. Encouraging especially females to engage themselves in math or science could be a promising approach to prevent the lack of specialists in this field (Stieff & Uttal, 2015; Reilly et al., 2017; Uttal et al., 2013; Wai et al., 2009). A study with elementary school-age children who attended a 31-week robotics training showed increasing abilities in spatial visualization and mental rotation and improved attitudes towards STEM

(Sisman et al., 2020). Our results show that it seems promising to reduce gender differences in affective and cognitive spatial dimensions to reduce gender differences in math anxiety. As this seems more necessary in older than in younger adolescents, training females should take place in elementary school and continue during adolescence.

Training spatial abilities and enhancing adolescents' perception of their abilities should not only concentrate on girls and young females. Individual differences in cognitive and affective dimensions of spatial abilities illustrate that better performances and higher perceptions lead to less math anxiety. Reducing boys' math anxiety as well as girls' seems advisable to interest more young people in the STEM field. As many studies show that males report higher confidence in their spatial abilities than females (e.g., Cooke-Simpson & Voyer, 2007), the most beneficial approach could be to strengthen boys' and girls' experience with spatial tasks and especially girls' affective perception of their abilities.

Because our focus was the affective component of math, we did not collect data about participants' math abilities. We found that mental-rotation performance was a predictor of math anxiety. Hence, the cognitive component of a spatial task is related to the affective component of mathematics. It would be interesting to investigate whether the perceived mental-rotation performance could affect actual math performance. The affective component would then affect the cognitive component of mathematics. Further studies could concentrate on cognitive and affective components of mathematics and investigate gender differences in math ability and perceived math abilities as well as math anxiety.

The aim of the current study was to determine changes of gender differences in (perceived) mental-rotation performance and math anxiety during adolescence. Consequently, we concentrated only on two age groups in early adolescence and young adulthood. Future studies should investigate gender differences in a more diverse age group.

Conclusions

In the present study, males outperformed females in mental-rotation performance and rated their performance in a mental-rotation test higher than females. Additionally, females estimated their math anxiety higher than males. All these gender differences were more pronounced in the older than the younger age group. Mental-rotation performance, as well as perceived mental-rotation performance, could mediate the gender differences in math anxiety. Perceived mental-rotation performance was the strongest unique mediator of the relation between gender and math anxiety. To reduce gender differences in adolescents' math anxiety, girls' spatial skills, as well as their perception of their spatial skills, could be improved by training, extra-curricular workshops, or a less gender-stereotyped education. More positive thoughts towards mathematics and spatial subjects could then lead to more engagement in advanced STEM subjects.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability Data will be made available.

Declarations

Ethics approval The experiment was conducted according to the ethical guidelines of the Helsinki declaration. Ethical approval for this study was not required in accordance with the conditions outlined by the German Research Foundation, where research that carries no additional risk beyond daily activities does not require Research Ethics Board Approval.

Consent to participate All participants and parents of all minor participants gave their informed consent.

Conflict of interest The authors declare no competing interests.

References

Ahmed, W., Minnaert, A., Kuyper, H., & van der Werf, G. (2012). Reciprocal relationships between math self-concept and math anxiety. *Learning and Individual Differences, 22*(3), 385–389. https://doi.org/10.1016/j.lindif.2011.12.004

Alexander, G. M., & Son, T. (2007). Androgens and eye movements in women and men during a test of mental rotation ability. *Hormones and Behavior, 52*(2), 197–204. https://doi.org/10.1016/j.yhbeh.2007.01.011

Ariel, R., Lembeck, N. A., Moffat, S., & Hertzog, C. (2018). Are there sex differences in confidence and metacognitive monitoring accuracy for everyday, academic, and psychometrically measured spatial ability? *Intelligence, 70*, 42–51. https://doi.org/10.1016/j.intell.2018.08.001

Ashcraft, M. H. (2002). Math anxiety: Personal, educational, and cognitive consequences. *Current Directions in Psychological Science, 11*(5), 181–185. https://doi.org/10.1111/2F1467-8721.00196

Ashcraft, M. H., & Moore, A. M. (2009). Mathematics anxiety and the affective drop in performance. *Journal of Psychoeducational Assessment, 27*(3), 197–205. https://doi.org/10.1177/2F0734282908330580

Barroso, C., Ganley, C. M., McGraw, A. L., Geer, E. A., Hart, S. A., & Daucourt, M. C. (2021). A meta-analysis of the relation between math anxiety and math achievement. *Psychological Bulletin, 147*(2), 134–168. https://doi.org/10.1037/bul0000307

Battista, M. T. (1990). Spatial visualization and gender differences in high school geometry. *Journal for Research in Mathematics Education, 21*(1), 47–60. https://doi.org/10.2307/749456

Berk, L. E. (2008). Child development. Pearson Education Inc.

Bieg, M., Goetz, T., Wolter, I., & Hall, N. C. (2015). Gender stereotype endorsement differentially predicts girls' and boys' trait-state discrepancy in math anxiety. *Frontiers in Psychology, 6*, 1404. https://doi.org/10.3389/fpsyg.2015.01404

Blajenkova, O., Kozhevnikov, M., & Motes, M. A. (2006). Object-spatial imagery: A new self-report imagery questionnaire. *Applied Cognitive Psychology: the Official Journal of the Society for Applied Research in Memory and Cognition, 20*(2), 239–263. https://doi.org/10.1002/acp.1182

Boone, A. P., & Hegarty, M. (2017). Sex differences in mental rotation tasks: Not just in the mental rotation process! *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*(7), 1005–1019. https://doi.org/10.1037/xlm0000370

Borgonovi, F. (2016). Video gaming and gender differences in digital and printed reading performance among 15-year-olds students in 26 countries. *Journal of Adolescence, 48*, 45–61. https://doi.org/10.1016/j.adolescence.2016.01.004

Casey, M. B., Nuttall, R. L., & Pezaris, E. (1997). Mediators of gender differences in mathematics college entrance test scores: A comparison of spatial skills with internalized beliefs and anxieties. *Developmental Psychology, 33*(4), 669–680. https://doi.org/10.1037/0012-1649.33.4.669

Casey, M. B., Nuttall, R., Pezaris, E., & Benbow, C. P. (1995). The influence of spatial ability on gender differences in mathematics college entrance test scores across diverse samples. *Developmental Psychology, 31*(4), 697–705. https://doi.org/10.1037/0012-1649.31.4.697

Cattell, R. B. (1987). *Intelligence: Its structure, growth and action*. Elsevier.

Chang, H., & Beilock, S. L. (2016). The math anxiety-math performance link and its relation to individual and environmental factors: A review of current behavioral and psychophysiological research. *Current Opinion in Behavioral Sciences, 10*, 33–38. https://doi.org/10.1016/j.cobeha.2016.04.011

Chatterjee, A. (2008). The neural organization of spatial thought and language. *Seminars in Speech and Language, 29*(3), 226–238. https://doi.org/10.1055/s-0028-1082886

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

Cherney, I. D. (2008). Mom, let me play more computer games: They improve my mental rotation skills. *Sex Roles, 59*(11–12), 776–786. https://doi.org/10.1007/s11199-008-9498-z

Cooke-Simpson, A., & Voyer, D. (2007). Confidence and gender differences on the Mental Rotations Test. *Learning and Individual Differences, 17*(2), 181–186. https://doi.org/10.1016/j.lindif.2007.03.009

Douglas, A. F. (2000). *Math anxiety, math self-concept, and performance in math* (Doctoral dissertation Lakehead university). http://knowledgecommons.lakeheadu.ca/handle/2453/3140

Ebisch, S. J., Perrucci, M. G., Mercuri, P., Romanelli, R., Mantini, D., Romani, G. L., & Saggino, A. (2012). Common and unique neuro-functional basis of induction, visualization, and spatial relationships as cognitive components of fluid intelligence. *NeuroImage, 62*(1), 331–342. https://doi.org/10.1016/j.neuroimage.2012.04.053

Estes, Z., & Felker, S. (2012). Confidence mediates the sex difference in mental rotation performance. *Archives of Sexual Behavior, 41*(3), 557–570. https://doi.org/10.1007/s10508-011-9875-5

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science, 18*(10), 850–855. https://doi.org/10.1111/j.1467-9280.2007.01990.x

Ferguson, A. M., Maloney, E. A., Fugelsang, J., & Risko, E. F. (2015). On the relation between math and spatial ability: The case of math anxiety. *Learning and Individual Differences, 39*, 1–12. https://doi.org/10.1016/j.lindif.2015.02.007

Geiser, C., Lehmann, W., & Eid, M. (2006). Separating "rotators" from "nonrotators" in the mental rotations test: A multigroup latent class analysis. *Multivariate Behavioral Research, 41*(3), 261–293. https://doi.org/10.1207/s15327906mbr4103_2

Grabner, R. H., Ischebeck, A., Reishofer, G., Koschutnig, K., Delazer, M., Ebner, F., & Neuper, C. (2009). Fact learning in complex arithmetic and figural-spatial tasks: The role of the angular gyrus and its relation to mathematical competence. *Human Brain Mapping, 30*(9), 2936–2952. https://doi.org/10.1002/hbm.20720

Halpern, D. F., Straight, C. A., & Stephenson, C. L. (2011). Beliefs about cognitive gender differences: Accurate for direction, underestimated for size. *Sex Roles, 64*(5–6), 336–347. https://doi.org/10.1007/s11199-010-9891-2

Hegarty, M. (2018). Ability and sex differences in spatial thinking: What does the mental rotation test really measure? *Psychonomic Bulletin & Review, 25*(3), 1212–1219. https://doi.org/10.3758/s13423-017-1347-z

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence, 32*(2), 175–191. https://doi.org/10.1016/j.intell.2003.12.001

Heil, M., & Jansen-Osmann, P. (2008). Sex differences in mental rotation with polygons of different complexity: Do men utilize holistic processes whereas women prefer piecemeal ones? *Quarterly Journal of Experimental Psychology, 61*(5), 683–689. https://doi.org/10.1080/17470210701822967

Hembree, R. (1990). The nature, effects, and relief of mathematics anxiety. *Journal for Research in Mathematics Education, 21*(1), 33–46. https://doi.org/10.2307/749455

Hopko, D. R., Mahadevan, R., Bare, R. L., & Hunt, M. K. (2003). The abbreviated math anxiety scale (AMAS) construction, validity, and reliability. *Assessment, 10*(2), 178–182. https://doi.org/10.1177/1073191103010002008

Jameson, M. M. (2014). Contextual factors related to math anxiety in second-grade children. *The Journal of Experimental Education, 82*(4), 518–536.

Kail, R. (1985). Development of mental rotation: A speed-accuracy study. *Journal of Experimental Child Psychology, 40*(1), 181–192. https://doi.org/10.1016/0022-0965(85)90071-2

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition, 29*(5), 745–756. https://doi.org/10.3758/BF03200477

Kozhevnikov, M., Kosslyn, S., & Shephard, J. (2005). Spatial versus object visualizers: A new characterization of visual cognitive style. *Memory & Cognition, 33*(4), 710–726. https://doi.org/10.3758/BF03195337

Kyttälä, M., & Lehto, J. E. (2008). Some factors underlying mathematical performance: The role of visuospatial working memory and non-verbal intelligence. *European Journal of Psychology of Education, 23*(1), 77–94. https://doi.org/10.1007/BF03173141

Lauer, J. E., Esposito, A. G., & Bauer, P. J. (2018). Domain-specific anxiety relates to children's math and spatial performance. *Developmental Psychology, 54*(11), 2126–2138. https://doi.org/10.1037/dev0000605

Lauer, J. E., Yhang, E., & Lourenco, S. F. (2019). The development of gender differences in spatial reasoning: A meta-analytic review. *Psychological Bulletin, 145*(6), 537–565. https://doi.org/10.1037/bul0000191

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

Lowrie, T., Resnick, I., Harris, D., & Logan, T. (2020). In search of the mechanisms that enable transfer from spatial reasoning to mathematics understanding. *Mathematics Education Research Journal, 32*, 175–188. https://doi.org/10.1007/s13394-020-00336-9

Ma, X. (1999). A meta-analysis of the relationship between anxiety toward mathematics and achievement in mathematics. *Journal for Research in Mathematics Education, 30*(5), 520–540. https://doi.org/10.2307/749772

Maloney, E. A., Waechter, S., Risko, E. F., & Fugelsang, J. A. (2012). Reducing the sex difference in math anxiety: The role of spatial processing ability. *Learning and Individual Differences, 22*(3), 380–384. https://doi.org/10.1016/j.lindif.2012.01.001

Meneghetti, C., Borella, E., & Pazzaglia, F. (2016). Mental rotation training: Transfer and maintenance effects on spatial abilities. *Psychological Research Psychologische Forschung, 80*(1), 113–127. https://doi.org/10.1007/s00426-014-0644-7

Mix, K. S., & Cheng, Y. L. (2012). The relation between space and math: Developmental and educational implications. *Advances in Child Development and Behavior, 42*, 197–243. https://doi.org/10.1016/B978-0-12-394388-0.00006-X

Mix, K. S., Levine, S. C., Cheng, Y. L., Young, C., Hambrick, D. Z., 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

Moè, A., Hausmann, M., Hirnstein, M. (2020) Gender stereotypes and incremental beliefs in STEM and non-STEM students in three countries: Relationships with performance in cognitive tasks Psychological Research Psychologische Forschung 1–14 https://doi.org/10.1007/s00426-019-01285-0

Moè, A., & Pazzaglia, F. (2006). Following the instructions!: Effects of gender beliefs in mental rotation. *Learning and Individual Differences, 16*(4), 369–377. https://doi.org/10.1016/j.lindif.2007.01.002

Muenks, K., Peterson, E. G., Green, A. E., Kolvoord, R. A., & Uttal, D. H. (2019). Parents' beliefs about high school students' spatial abilities: Gender differences and associations with parent encouragement to pursue a STEM career and students' STEM career intentions. *Sex Roles, 82*, 570–583. https://doi.org/10.1007/s11199-019-01072-6

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In *Studying visual and spatial reasoning for design creativity* (pp. 179–192). Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9297-4_10

Nosek, B. A., Banaji, M. R., & Greenwald, A. G. (2002). Math = male, me = female, therefore math ≠ me. *Journal of Personality and Social Psychology, 83*(1), 44–59. https://doi.org/10.1037//0022-3514.83.1.44

Prescott, J., Gavrilescu, M., Cunnington, R., O'Boyle, M. W., & Egan, G. F. (2010). Enhanced brain connectivity in math-gifted adolescents: An fMRI study using mental rotation. *Cognitive Neuroscience, 1*(4), 277–288. https://doi.org/10.1080/17588928.2010.506951

Quinn, P. C., & Liben, L. S. (2014). A sex difference in mental rotation in infants: Convergent evidence. *Infancy, 19*(1), 103–116. https://doi.org/10.1111/infa.12033

Rahe, M., & Quaiser-Pohl, C. (2019). Mental-rotation performance in middle and high-school age: Influence of stimulus material, gender stereotype beliefs, and perceived ability of gendered activities. *Journal of Cognitive Psychology, 31*(5–6), 594–604. https://doi.org/10.1080/20445911.2019.1649265

Rahe, M., & Quaiser-Pohl, C. (2020). Cubes or pellets in mental-rotation tests: Effects on gender differences and on the performance in a subsequent math test. *Behavioral Sciences, 10*(1), 12. https://doi.org/10.3390/bs10010012

Rahe, M., Ruthsatz, V., Jansen, P., & Quaiser-Pohl, C. (2019a). Different practice effects for males and females by psychometric and chronometric mental-rotation tests. *Journal of Cognitive Psychology, 31*(1), 92–103. https://doi.org/10.1080/20445911.2018.1561702

Rahe, M., Ruthsatz, V., Schürmann, L., & Quaiser-Pohl, C. (2019b). The effects of feedback on the gender differences in the performance in a chronometric mental-rotation test. *Journal of Cognitive Psychology, 31*(4), 467–475. https://doi.org/10.1080/20445911.2019.1621872

Ramirez, G., Gunderson, E. A., Levine, S. C., & Beilock, S. L. (2013). Math anxiety, working memory, and math achievement in early elementary school. *Journal of Cognition and Development, 14*(2), 187–202.

Reilly D., Neumann D.L., & Andrews G. (2017) Gender differences in spatial ability: Implications for STEM education and approaches to reducing the gender gap for parents and educators. In: Khine M. (eds) *Visual-spatial ability in STEM education.* Springer, Cham. https://doi.org/10.1007/978-3-319-44385-0_10

Reinhold, F., Hofer, S., Berkowitz, M., Strohmaier, A., Scheuerer, S., Loch, F., & Reiss, K. (2020). The role of spatial, verbal, numerical, and general reasoning abilities in complex word problem solving for young female and male adults. *Mathematics Education Research Journal, 32*, 189–211. https://doi.org/10.1007/s13394-020-00331-0

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*(171), 701–703. https://doi.org/10.1126/science.171.3972.701

Sisman, B., Kucuk, S., Yaman, Y. (2020). The effects of robotics training on children's spatial ability and attitude toward STEM International Journal of Social Robotics 1–11 https://doi.org/10.1007/s12369-020-00646-9

Sokolowski, H. M., Hawes, Z., & Lyons, I. M. (2019). What explains sex differences in math anxiety? A closer look at the role of spatial processing. *Cognition, 182*, 193–212. https://doi.org/10.1016/j.cognition.2018.10.005

Sorby, S. A., & Panther, G. C. (2020). Is the key to better PISA math scores improving spatial skills? *Mathematics Education Research Journal, 32*, 213–233. https://doi.org/10.1007/s13394-020-00328-9

Steele, C. M., & Aronson, J. (1995). Stereotype threat and the intellectual test performance of African Americans. *Journal of Personality and Social Psychology, 69*(5), 797–811. https://doi.org/10.1037/0022-3514.69.5.797

Steinmayr, R., Weidinger, A. F., Heyder, A., & Bergold, S. (2020). Warum schätzen Mädchen ihre mathematischen Kompetenzen geringer ein als Jungen? (Why do girls rate their mathematical competencies lower than boys? Considering grades, competency tests, teacher- and parent-ratings as potentially explaining factors) *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, 51(2), 71–83. https://doi.org/10.1026/0049-8637/a000213

Stieff, M., & Uttal, D. (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review, 27*(4), 607–615. https://doi.org/10.1007/s10648-015-9304-8

Tarampi, M. R., Heydari, N., & Hegarty, M. (2016). A tale of two types of perspective taking: Sex differences in spatial ability. *Psychological Science, 27*(11), 1507–1516. https://doi.org/10.1177/0956797616667459

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

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*(2), 599–604. https://doi.org/10.2466/pms.1978.47.2.599

Varriale, V., van der Molen, M. W., & De Pascalis, V. (2018). Mental rotation and fluid intelligence: A brain potential analysis. *Intelligence, 69*, 146–157. https://doi.org/10.1016/j.intell.2018.05.007

Voyer, D. (2011). Time limits and gender differences on paper-and-pencil tests of mental rotation: A meta-analysis. *Psychonomic Bulletin & Review, 18*(2), 267–277. https://doi.org/10.3758/s13423-010-0042-0

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin, 117*(2), 250–270. https://doi.org/10.1037/0033-2909.117.2.250

Wang, L. (2020). Mediation relationships among gender, spatial ability, math anxiety, and math achievement. *Educational Psychology Review, 32*(1), 1–15. https://doi.org/10.1007/s10648-019-09487-z

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817–835. https://doi.org/10.1037/a0016127

Weckbacher, L. M., & Okamoto, Y. (2014). Mental rotation ability in relation to self-perceptions of high school geometry. *Learning and Individual Differences, 30*, 58–63. https://doi.org/10.1016/j.lindif.2013.10.007

Wiedenbauer, G., & Jansen-Osmann, P. (2008). Manual training of mental rotation in children. *Learning and Instruction, 18*(1), 30–41. https://doi.org/10.1016/j.learninstruc.2006.09.009

Xie, F., Zhang, L., Chen, X., & Xin, Z. (2020). Is spatial ability related to mathematical ability: A meta-analysis. *Educational Psychology Review, 32*, 113–155. https://doi.org/10.1007/s10648-019-09496-y

Young, C. J., Levine, S. C., & Mix, K. S. (2018). The connection between spatial and mathematical ability across development. *Frontiers in Psychology, 9*, 755. https://doi.org/10.3389/fpsyg.2018.00755

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.