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RESEARCH ARTICLE

An evaluation of visuospatial skills using hands-on tasks

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Abstract

Several tests of mental rotation ability have been used to investigate its development and the origins of sex differences. One of the most used tests is the mental rotation test (MRT) by Vandenberg and Kuse. A limitation of the MRT is that it is a pen-and-paper test with 2D images of 3D objects. This is a challenge to the ecological validity of the MRT because mental rotation typically involves physical 3D objects that are also physically manipulated. The purpose of the present study was to compare mental rotation ability as evaluated by the MRT to three new tasks with physical objects (toy bricks) that were physically manipulated. The different tasks allowed us to vary the processing demands on mental rotation while standardizing other aspects of the tasks. Fifty-nine females and twenty-eight males completed the LMR and HMR conditions (low- and high-mental rotation demands, respectively) of the brick building task (BBT), a visual search task, and the MRT. As demands on mental rotation for the BBT increased, performance decreased and a sex difference, with males outperforming females, increased. There were correlations between all tasks, but they were larger between the versions of the BBT with the MRT. The results suggest that spatial skill is an assembly of interrelated subskills and that the sex difference is sensitive to the demands on mental rotation and dimensionality crossing. The benefits of the BBT are that it is ecologically valid, avoids dimensionality crossing, and the demands on mental rotation can be manipulated.

Keywords Spatial skills · Mental rotation ability · Spatial tasks · Sex difference

Introduction

Spatial ability "refers to the skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information" (Linn and Petersen 1985, p. 1482). Spatial skill is not a solitary function but rather an assemblage of specific skills (Voyer, Voyer and Bryden 1995). These skills have been classified across the literature into three main constructs: spatial visualization, spatial perception, and mental rotation. Spatial visualization is defined as the ability to mentally manipulate spatial information that requires a multistep, analytical process (Linn and Petersen 1985). This ability, for example, allows us to meticulously pack the trunk of a car or a suitcase; by analyzing the object's properties (i.e. size and shape), we can determine whether the object will fit in a particular space. Spatial perception is described as the ability to navigate our environment and orient our bodies accordingly, regardless of the variety of distractors situated around us (Linn and Petersen 1985; Voyer et al. 1995). This ability is important when reaching for objects in the visual field and to adjust our gaze accordingly (Kolb and Wishaw 1985). When picking up a glass of wine, for example, spatial perception helps us locate the glass and stay on target regardless of other objects around it. Lastly, mental rotation is the ability to imagine what a two- or three-dimensional figure would look like when rotated (Kolb and Wishaw 2000). This ability is used when seeing vehicles in a rear-view mirror to understand where they are with respect to the driver. Mental rotation has been extensively assessed by the Shepard and Metzler test (Shepard and Metzler 1971; Peters and Battista 2008). This paper-based test (which by nature is two dimensional) uses perspective views of two three-dimensional figures and measures the time to determine whether the two simultaneously presented figures with different orientations are of the same three-dimensional

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shape (Shepard and Metzler 1988). Figure 1 shows the mental rotation task (MRT) by Vandenberg and Kuse (1978) (Peters, Laeng, Latham, Jackson, Zaiyouna and Richardson 1995), a variant of the Shepard and Metzler test. The MRT is the most widely used test to assess mental rotation skill.

A challenge with the MRT is its ecological validity; it is a pen-and-paper task, whereas most mental rotation activities of daily living are combined with physical interactions of three-dimensional (3D) objects. Thus, it may be beneficial to evaluate mental rotation skill using familiar 3D objects, and even more beneficial if these objects are manipulated.

Some researchers have adapted the images from the paper-based mental rotation task to look more like 3D objects using virtual reality (Parsons, Larson, Kratz, Thiebaux, Bluestein, Buckwalter et al. 2004) or augmented reality (Neubauer, Bergner and Schatz 2010; Arendasy, Sommer, Hergovich, Feldhammer 2011). Moreover, a few studies have compared paper-based mental rotation tasks to their 3D analogs (e.g., McWilliams et al. 1997; Robert and Chevrier 2003, Felix et al. 2011; Hawes, LeFevre, Xu and Bruce 2015). For the MRT, the paper-based task was compared to a version of the task where all the stimuli were transformed into 3D by gluing wood cubes together. The common finding from the virtual/augmented reality and 3D object studies is that performance improves when the stimuli are 3D. The mechanism behind this improvement with 3D requires further exploration. The dimensionality-crossing hypothesis (Horan and Rosser 1984) is one explanation for the improvement when using 3D objects instead of paper-based tests.

The dimensionality-crossing hypothesis (Horan and Rosser 1984) assumes that the representation of an object with a depth component must be formed as a 3D mental image before it can be mentally rotated. In the MRT, this implies that the paper-based representation of the figures must be transformed from a 2D representation to a 3D mental image. In other words, additional perceptual processing is required to cross dimensions. Performance is improved when 3D objects with real depth cues are used because the additional processing to cross dimensions is obviated (McWilliams et al. 1997; Parsons et al. 2004; Neubauer et al. 2010; Felix et al. 2011). This may also be the case with the more salient depth cues with virtual or augmented reality (Parsons et al. 2004; Neubauer et al. 2010).

The aforementioned studies showed improved mental rotation performance when the ecological validity of the task was increased with 3D objects. In the current study, we hypothesized that assessment of mental rotation ability would improve by further increasing the ecological validity by introducing 3D objects that require manipulation (see Figs. 2 and 3). To our knowledge, our lab has developed the only mental rotation task that involves manipulation of 3D objects (de Bruin et al. 2016); specifically, Lego® bricks. We refer to this task as the Brick Building Task (BBT). This task required the participant to duplicate a brick model from an assortment of bricks. Spatial visualization is used to identify the matching bricks (i.e., shape and size), spatial perception is used when searching and reaching for the correct brick among a multitude of distractors, and mental rotation is used to determine how each brick should be placed. All these skills work simultaneously to accurately duplicate the model. The models from the test vary in spatial complexity, with a low-mental rotation demand condition (LMR; their configuration allows for an understanding of the model from a front view) and a high-mental rotation demand condition (HMR; their configuration can only be understood

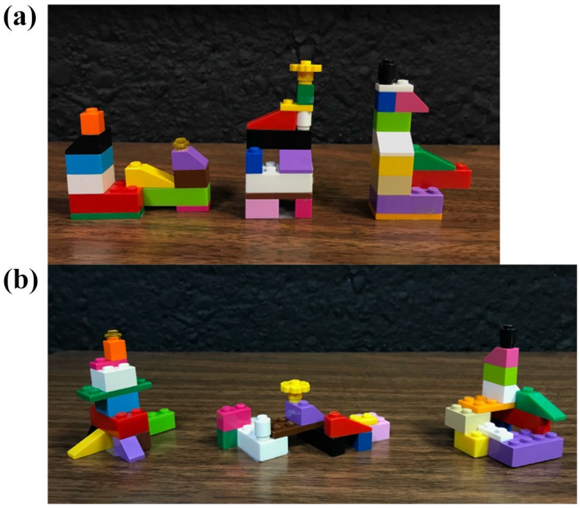

Fig. 2 **a** LMR condition of the brick building task models (low-mental rotation requirements). **b** HMR conditions of the brick building task models (high-mental rotation requirements). Note that both sets of models contained the same number of identical bricks

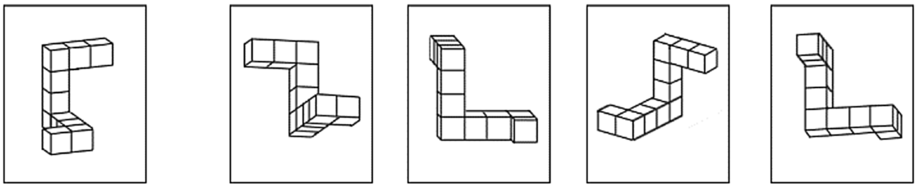

Fig. 1 The mental rotation task (MRT; Vandenberg and Kuse 1978). A target figure on the left is compared to four figures on the right. The participant attempts to identify the two figures that match the target. The second and third figures match the target figure in this example

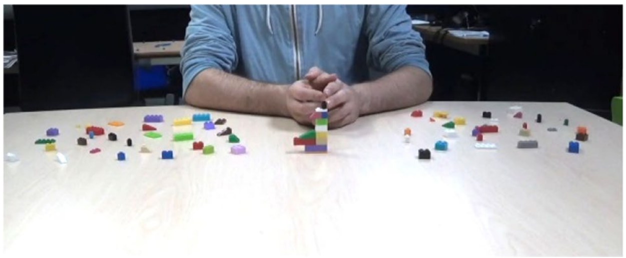

Fig. 3 Set-up of the bricks at the start of the first trial. Sixty unique bricks were pseudo-randomly placed on the table with thirty to the left of the participant and thirty to the right. A model is placed in front of the participant and they are asked to replicate it (LMR or HMR model), or to find the bricks in the model (visual search task) as quickly and accurately as possible. One of the LMR models is shown in front of the participant. Consent was obtained from the participant for use of this image for publication

when viewed from different angles). All participants from that study took longer to replicate the HMR models, even though the models were built with exactly the same number and type of bricks as the LMR models (de Bruin et al. 2016). This finding indicates that the increase in time when building the HMR models was related to the higher level of spatial complexity (higher demands on mental rotation) featured in those models. Another finding of de Bruin et al. (2016) was the presence of sex differences with males outperforming females, although this was in a small sample of participants ($n = 24$ young adults).

The finding of sex differences by de Bruin et al. was not surprising given that the largest sex difference in cognitive function has been found in visuospatial abilities (Linn and Petersen 1985), with mental rotation skill showing the largest sex effect. Using the MRT, researchers have consistently found sex differences in humans (Vandenberg and Kuse 1978; Peters 2005). A meta-analysis supported that males are better than females at mental rotation tests (mean weighted Cohen's $d = 0.56$; Voyer et al. 1995). Although, various theories have emerged to explain the origin and development of sex differences, one well-investigated hypothesis is related to the differential exposure to sex hormones by males and females.

It has been shown that sex hormones affect brain cell structure and function (Kolb and Whishaw 2003; Kolb and Gibb 2011; Wierenga et al. 2018), including cells in regions that support visuospatial cognition (e.g., Kolb and Whishaw 2003; Becker et al. 2008; Gurvich, Hoy, Thomas and Kulkarni 2018). Natural occurring hormonal disorders (e.g. Congenital Adrenal Hyperplasia-CAH [Puts, McDaniel, Jordan and Breedlove 2008] and Hypogonadotropic Hypogonadism- IHH [Hier and Crowley 1982]), natural hormonal changes (e.g., puberty [Waber 1976; Beltz and Berenbaum 2013], menstrual cycle [Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis and Gunturkun 2000; Hampson, Levy-Cooperman and Korman 2014], older adulthood [Janowsky 2006]) and induced hormonal changes (i.e., hormonal medications [Beltz, Hampson and Berenbaum 2015]) show strong evidence to support this hypothesis. High levels of testosterone often lead to better performance on spatial tasks and vice versa; high levels of estrogen often lead to worse performance on spatial tasks and vice versa.

Sex differences in spatial abilities, however, have been widely assessed using paper-based tasks. The results of the few studies that have used 3D tests to investigate sex differences in mental rotation are mixed. Some have found that males are better than females (de Bruin et al. 2016 young adults; Felix et al. 2011; Hawes et al. 2015), whereas others have not found sex differences (Robert and Chevrier 2003; Mc.Williams et al. 1997). Although both males and females have shown improvements in performance in 3D tasks compared to paper-based tasks (McWilliams et al. 1997; Robert and Chevrier 2003; Felix et al. 2011), the disappearance of sex differences in some studies using 3D tasks could suggest that females may benefit the most from being assessed with 3D tasks. Likewise, females may also benefit the most from assessment with 3D objects that require manipulation.

The purpose of the present study was to investigate spatial abilities using 3D tasks in female and male participants. For this, participants completed the two versions of the brick building task (LMR and HMR) and a visual search task. Performance in these 3D visuospatial tasks was compared to that of the commonly used paper-based MRT. This is important as it is yet not clear to what extent 3D mental rotation tasks are measuring similar cognitive processes as paper-based mental rotation tests. The comparison would be relevant to researchers, as the 3D tasks would offer unique advantages over the paper-based tests. The 3D tasks used in this study, require real-world manipulation of objects, making it more comparable to our everyday environment where we are not only mentally rotating objects but also physically manipulating them to position them appropriately in our environment.

Materials and methods

Participants

Eighty-seven university students participated in the study (28 males and 59 females). Female participants were further divided into two groups, those using hormonal medication (females-ON, $n = 29$) and those without it (females-OFF, $n = 30$). This was done because previous literature has argued that sex differences are driven by hormonal levels (Hausmann et al. 2000; Hampson et al. 2014; Hampson 2018). Participants were healthy students from the University of Lethbridge, who received course credits for participating.

They were recruited through the Psychology Department, using participant management software (Sona Systems). The experiment was approved by the University of Lethbridge Human Subject Research Committee and participants were asked to read and sign an informed consent form.

Tasks

Participants completed four tasks: the LMR and HMR conditions (low- and high-mental rotation demands, respectively; Fig. 2a, b) of the brick building task, a visuospatial search task, and the MRT (Fig. 1). The LMR and HMR conditions consisted of three trials each. Each trial involved duplicating a 12-brick model. At the beginning of the task, sixty unique bricks were pseudo-randomly placed in front of the participant with thirty bricks on the left side and thirty bricks on the right side of the participant (Fig. 3). The LMR and HMR models consisted of identical number and type of bricks, the only difference was in the configuration of the model (Fig. 2a, b). The configuration of the models in the LMR condition allowed for an understanding of the entire model from a front view (i.e., a "flat" configuration), removing the need to physically manipulate them. Conversely, the configuration of the models on the HMR condition could only be understood when viewed from different angles, necessitating physical manipulation of the models. The visual search task used the same set up and models as those used for the LMR. The difference was that participants looked on the table for the 12 bricks that composed the model and placed those pieces into a bowl [without duplicating (i.e., building) the model]. The MRT consisted of two sets of 12 problems each. Each problem had five stimuli (Fig. 1). Within each problem, there was a target stimulus and the participant's job was to find the *two* of the four stimuli that matched the target. The order of the four tasks was counterbalanced for each participant, and the order of the trials within each task was randomized.

Procedure

For the brick building task, participants were seated in front of a table facing the middle of the brick display (Fig. 3). The participants were instructed to build an exact replica of the model (LMR or HMR) located in front of them using the bricks placed on the table; they were told the time to complete each model was going to be recorded, so to build the models as quickly and also as accurately as possible. They were told they could move or rotate the model as needed to investigate it. Additionally, they were told to start at the "go" signal and to say "done" when they were finished. For the visual search task, the participants were instructed to look for the bricks that made up the LMR model and place them in the container located in front of them as quickly and accurately as possible. For the paper-based MRT, participants were instructed to choose (by circling or crossing) the two out of the four options that matched the target stimuli. They were given a three-minute time limit for each set (each set had 12 problems, Fig. 1 shows an example of one of the problems) with a three-minute rest in between the two sets. At the end of the tasks, participants were asked to fill out two questionnaires. The first questionnaire asked participants about their experience with Lego: Q1) first age at which they had begun playing with Lego ("To the best of your memory, what is the earliest age you remember playing with Lego?"), Q2) frequency using bricks for building (e.g., "how many times do you manipulate Lego (or similar) in a week") on a scale from 1–10 (1 being no manipulation, and 10 being daily manipulation), Q3) comfort using bricks for building (e.g., "how comfortable are you at manipulating Lego (or similar)" on a scale of 1–10 (1 being not comfortable and 10 being completely comfortable). The second questionnaire asked the participants' handedness, a modified version of the Waterloo and Edinburgh was used (Stone, Bryant and Gonzalez 2013). In addition, the consent form included a question regarding the participant's use of hormonal medication: "Are you on any medication that affects your sex hormones (estrogen, progesterone, testosterone); for example, oral or injection birth control, hormonal intrauterine device (hormonal IUD), hormonal replacement therapy"?

Data analysis

For the LMR-, HMR models, and visual search task, the total amount of time taken to build or collect the bricks for each trial was registered from the "go" signal of the experimenter to the "done" signal of the participant. The mean time for the three trials was calculated for each task (LMR, HMR, visual search). Additionally, we explored the relative increase in difficulty from the LMR to the HMR condition across groups (HMR/LMR × 100). To do this, the percent increase in the mean time to build the models in the HMR condition compared to the LMR condition was calculated. Specifically, mean time in the HMR condition was divided by the mean time of the LMR condition and then multiplied by 100 (to be expressed in percentage). Exploring this is useful when discriminating between demand for mental rotation from that of motor speed or visual search. The number of correct responses for the MR score was calculated as a percent: the sum of only the problems in which the two answers were correct across the two sets of 12 problems were divided by the maximum score of 24 points (Vandenberg and Kuse 1978; Peters et al. 1995) and then multiplied by 100. The relationship among all tasks was examined with correlations (Pearson's r); specifically, the participants' performance (time and/or score) on each task were correlated with all the other tasks. Sex differences were investigated with a one-way ANOVA for each task. Significant main effects were analyzed with post-hoc comparisons, and the familywise error rate was controlled with the Bonferroni correction. The alpha level for all comparisons was 0.05.

Results

As the intake of hormonal medication is known to affect sex hormone levels and spatial ability, we initially divided females into two groups (females-ON and females-OFF). There were no significant differences between the two groups in any of the tasks. Therefore, all females were collapsed into a single group ($n = 59$) for the rest of the analyses.

Correlation analysis

Significant correlations were found between all dependent variables (Table 1). The largest correlation, unsurprisingly, was between the LMR times and HMR times ($r = 0.64$). The smallest correlation had a medium effect size and was between the visual search times and MRT scores ($r = -0.26$). Noteworthy, the correlation between HMR times and MRT scores ($r = -0.48$) was higher than between LMR times and MRT scores ($r = -0.37$).

Sex differences

The grand mean scores and group mean scores are shown in Table 2. There was a significant main effect of sex for LMR times ($F_{(1,86)} = 7.4$, $p < 0.001$, $\eta^2 = 0.08$), HMR times ($F_{(1,86)} = 14.9$, $p < 0.001$, $\eta^2 = 0.15$), and MRT score ($F_{(1,86)} = 14.7$, $p < 0.001$, $\eta^2 = 0.15$). Males had shorter LMR and HMR times than females, they also scored significantly higher on the MRT. There was no main effect of sex in the ratio (HMR/LMR × 100) measurement ($F_{(1,86)} = 2.3$, $p > 0.1$, $\eta^2 = 0.03$), and no main effect of sex in visual search time ($F_{(1,86)} = 2.7$, $p > 0.1$, $\eta^2 = 0.03$).

Table 1 Correlation table for all the dependent variables

	Visual Search	LMR time	HMR time	MRT
Visual Search	1.00	0.54**	0.52**	− 0.26*
R^2		0.29	0.27	0.07
LMR time		1.00	0.64**	− 0.37**
R^2			0.41	0.14
HMR time			1.00	− 0.48**
R^2				0.23
MRT				1.00

*$p < 0.05$, **$p < 0.01$

Table 2 Means and standard errors for the dependent variables

Dependent variable	Grand mean	Males	Females
Visual search time (s)	24.8 ± 0.6	23.4 ± 1.3	25.5 ± 0.7
LMR time (s)	39.5 ± 1.1	35.5 ± 1.8	41.3 ± 1.2
HMR time (s)	69.3 ± 1.9	59.3 ± 2.9	74.0 ± 2.2
Ratio (%)	178.3 ± 3.8	170.0 ± 6.0	182.2 ± 4.8
MRT (%)	41.1 ± 2.3	53.2 ± 4.1	35.4 ± 2.5

Differences in spatial demand between tasks

A 2 Sex by 3 Task repeated-measures ANOVA was conducted to explore the difference in demands between the 3D tasks (visual search, LMR, HMR). A main effect was found ($F_{(1,86)} = 458.65$, $p < 0.001$, $\eta^2 = 0.9$): participants took less time when completing the visual search task, followed by the LMR, and then followed by the HMR (all comparisons were significantly different from each other $p < 0.001$; see Table 2 for means and SEs). There was a significant Sex by Task (Visual Search, LMR, HMR) interaction ($F_{(1,86)} = 13.19$, $p < 0.001$, $\eta^2 = 0.9$). This interaction (see Fig. 4) was because there was no significant difference between males and females in the visual search task ($p > 0.1$) but there were significant sex differences in the LMR ($p < 0.01$) and HMR tasks ($p < 0.001$). Closer inspection of the data revealed that the interaction between Sex and Task was also significant ($p < 0.001$) when task had two levels: LRM and HRM. This interaction was likely caused by a larger male advantage in the HMR task than the LMR task.

Questionnaires

For the questionnaire documenting Lego experience, there was not a significant correlation between the age at which the participant begun playing with Lego and their time on any of the 3D tasks ($p > 0.05$). The frequency of manipulating bricks (Lego or similar) showed that males and females

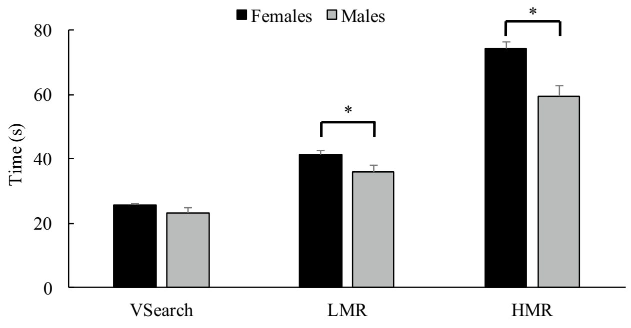

Fig. 4 Performance on the timed tasks (visual search, low mental rotation [LMR], and high mental rotation [HMR]) for female and male participants. *$p < 0.05$

had low continuous manipulations (1.4 ± 0.1) that were not significantly different, ($F_{(1,86)} = 2.7$, $p > 0.1$, $\eta^2 = 0.03$). However, there was a main effect of sex regarding the level of comfort using bricks ($F_{(1,86)} = 8.6$, $p < 0.05$, $\eta^2 = 0.09$). Males (8.4 ± 0.19) reported that they were more comfortable using bricks than females (7.2 ± 0.25). Given this result, additional correlations between comfort using bricks and the spatial tasks were conducted. There was a significant correlation with comfort and performance on the HMR task ($r = -0.24$, $p < 0.05$), the visual search task ($r = -0.23$, $p < 0.05$), and the MRT ($p < 0.05$), but there was not a significant correlation between comfort playing with bricks and the LMR task ($p > 0.05$). Interestingly, the significant correlations between comfort and the other tasks were only present when all participants were analyzed together; no significant correlations were found when participants were split into male and female groups.

The Waterloo–Edinburgh handedness questionnaire was used to determine whether participants were right-handed ($n = 75$), left-handed ($n = 8$), or ambidextrous ($n = 4$). All results remained similar with or without the left-handed or ambidextrous participants, so everyone was included in the analyses.

Discussion

This study used 3D tasks to assess spatial skills in female and male participants. The tasks required participants to use the three main spatial skills; specifically, spatial visualization, spatial perception, and mental rotation. Importantly, the processing demands on mental rotation ability differed in the visual search, LMR, and HMR tasks. In the visual search task, participants were simply required to search for, locate, pick up a brick, and place it into a container. The same elements were necessary to complete the LMR, but participants assembled the bricks to replicate a model. The models were relatively easy to replicate as all the pieces were visible from a front view (see Fig. 2a), which placed low demands on physical and mental rotation abilities. The HMR built upon those previous elements by using models with challenging configurations (see Fig. 2b). This placed high demands on physical and mental rotation abilities. The different demands of the three tasks were captured by the results in that even though the same number and type of bricks were used in all three tasks, participants were fastest in the visual search task, slower in the LMR task, and slowest in the HMR task.

To investigate if there was a relationship between 3D and paper-based mental rotation tasks, participants were also asked to complete a version of the Vandenberg and Kuse mental rotation task (MRT). All 3D tasks were significantly correlated with the paper-based MRT. Participants who completed the visual search task quickly were also quick at solving the LMR and HMR tasks and scored higher on the MRT. Thus, participants who had good performance on one of the tasks also showed good performance on the others. These relationships between all the different tasks demonstrate the interdependence among the various spatial skills. One conclusion from this interdependence could be that spatial skill is one function. However, the correlations between the 3D tasks and the MRT explained only 7–41% of the variability ($r = -0.26$, $R^2 = 0.07$; $r = 0.64$, $R^2 = 0.41$). Furthermore, some of the correlations were higher than others. Of note was the low correlation between the visual search task and the MRT score ($r = -0.26$), which suggest these tasks require somewhat different spatial skills. Stronger correlations were found between the time to complete the LMR task and the MRT scores ($r = -0.37$), which suggests more commonalties between these two tasks. Finally, the HMR task showed the most overlap with the MRT ($r = -0.48$), likely because both tasks feature high-mental rotation demands. Together, these results suggest that spatial skill is not a monolithic construct, but rather it is an association of interrelated subskills that contribute to its proper functioning.

Another finding of the present study relates to sex differences. Previous studies have used paper-based tasks to study spatial skill, particularly mental rotation (Linn and Petersen 1985; Voyer et al. 1995; Peters 2005). These studies have shown sex differences, with males tending to outperform females. The present study supports these findings using 3D tasks, but importantly, emphasizes that this sex difference is linked to the mental rotation demand of the task. The significant interaction between sex and task demonstrated that the higher the demand for mental rotation, the greater the sex difference. The demands on mental rotation increased from visual search, to the LMR task, and then to the HMR task. Likewise, the gap between males and females increased from no sex differences in visual search, to males outperforming females in the LMR task ($\eta^2 = 0.08$) and in the HMR task ($\eta^2 = 0.15$), with this last task having the largest sex difference.

There were two unexpected results from the current study. First, that performance of females taking hormonal medication was similar to those without medication. Previous studies have shown that performance in visuospatial tasks varies according to the levels of circulating hormones (Hausmann et al. 2000; Hampson et al. 2014; Hampson 2018). Furthermore, it has been shown that female users of oral birth control outperform non-users in mental rotation tasks, including the paper-based MRT used in our study (Beltz et al. 2015). The absence of differences in performance between female groups could be because we did not control for the type of contraceptive, pill/device constituents, or the phase of the menstrual cycle. Studies have shown, for example, that during the luteal phase (high estrogen and progesterone levels), women are worse at mental rotation when compared to when they are in the ovulatory phase (low levels of estrogen and high levels of testosterone; Hampson 1995; Hausmann et al. 2000; Hampson et al. 2014). However, some studies have challenged this notion, and, just as we did, have not found a difference between naturally cycling women and those on birth control (Rosenberg and Park 2002; Gogos 2013; Wharton et al. 2008). Gogos (2013) did not find sex differences in a paper-based visuospatial/constructional ability test (this included figure copying and line orientation tasks), and other researchers have not found sex differences when using the paper-based MRT (Griksiene and Ruksenas 2011; Wharton et al. 2008). It has been argued that the active ingredients of the different contraceptive oral medications differentially influence mental rotation skill and, thus, the mixed findings in the literature (Griksiene and Ruksenas 2011; Wharton et al. 2008; Beltz et al. 2015). Future research should account for these factors when focusing their investigation on sex differences in visuospatial abilities. It is important to note that this is the first study to investigate the effects of hormonal medication on 3D mental rotation tasks. 3D mental rotation tasks place greater demands on mental rotation ability and they have higher ecological validity than paper-based tasks. Future research on sex differences that wish to use 3D tasks should also account for the type of oral contraceptive, active ingredients, and menstrual cycle phase.

The second unexpected result was the absence of a sex difference when the ratio between the HMR and LMR tasks was calculated. The relative increase in difficulty from the LMR to the HMR condition was examined by expressing the time that it took participants to complete the HMR as a percentage of the LMR. We reasoned that investigating this relative increase would be useful when discriminating between demand for mental rotation from that of motor speed or visual search efficient. This is an interesting finding that deserves attention and further exploration. de Bruin et al. (2016) also found no sex difference when looking at the relative increase in difficulty from LMR to HMR in a small sample of young (12 males and 12 females) and older (10 males and 10 females) adults. In the present study, the relative increase in time was comparable across sexes; both groups took about 1.8 times longer to complete the HMR with respect to the LMR. One possibility for the absence of sex differences when looking at the ration, is that sex differences in mental rotation using 3D tasks are less pronounced than those found when using paper-based tasks. For example, some studies have found that females perform similarly to males when a 3D version of the paper-based MRT is used (Robert and Chevrier 2003; Hawes et al. 2015) or when the test is presented through virtual or augmented reality (Larson et al. 1999; Parsons et al. 2004; Neubauer et al. 2010). It is important to note that females use a more effective strategy when solving augmented reality tasks (Arendasy et al. 2011) and are more sensitive to differences in the mode of presentation of the stimuli (Neubauer et al. 2010). In general, these researchers have suggested that the sex differences found in paper-based tasks may be caused by a greater difficulty for females to transform a 2D flat figure into a 3D mental representation. For example, females have shown greater difficulty at solving paper-based tasks in which the stimuli have part of their configuration occluded (Voyer and Doyle 2010) as is the case with the MRT. The dimensionality-crossing hypothesis suggest that it may be easier for males compared to females to cross from 2D to 3D. This second unexpected result from the present experience supports the dimensionality-crossing hypothesis. The disappearance of the sex differences in 3D tasks could be because females benefit the most from real depth cues to properly understand the configuration of the stimuli, even when parts of it are occluded. It is possible that the manipulation of real objects and the haptic feedback facilitated the understanding of the model configuration in the current study. Future research should investigate if females have difficulty with 3D objects if some of their features are occluded; for example, by not allowing participants to physically manipulate the 3D objects particularly during the HMR condition.

Evidence has shown that performance in 3D tasks is better than in paper-based tasks. The MRT variant of the Shepard and Metzler [based on Vandenberg and Kuse 1978; Peters et al. 1995)] used in this study is considered too difficult for young children (Hoyek, Collet, Fargier and Guillot 2012; Jansen, Schmelter, Quaiser-Pohl, Neuburger and Heil 2013), for seniors [as mental rotation performance decreases with age (Jansen and Heil 2009), and for people with brain disorders [i.e., dyslexic children (Winner et al. 2001)]. Therefore, we believe the 3D tasks offer several advantages over other spatial tests. The 3D tasks have real depth components, which in turn, decrease the processing load needed for dimensionality crossing in paper-based tasks. Lastly, manipulating the object might improve its mental representation and, thus, the ability to mentally rotate it. Importantly, the 3D tasks used in this study, unlike in other studies using 3D objects, required real-world manipulation and involved a "game" structure. These exclusive attributes may make these tasks more inclusive, appealing, and suitable for more populations (e.g., children, teens, and seniors).

We have started using the brick building test in a group of 5- to 8-year-old children, not only as an evaluating tool, but as well as a tool to enhance visuospatial abilities. There is evidence suggesting that having good visuospatial skills can strongly influence achievement in science, technology, engineering, and mathematics (i.e., STEM programs; Wai, Lubinski and Benbow 2009; Lubinski 2010; Uttal et al. 2012). Additionally, studies have shown that children's early performance on visuospatial tasks is related to later aptitude on spatial and mathematical concepts along with a stronger arithmetical development (Lauer and Lourenco 2016; Zhang et al. 2014). Certainly, the development of visuospatial skills has proven to be important for an individual's general intelligence (Wai et al. 2009). As a consequence, we consider it of great importance to enhance, detect and, if difficulties exist, remediate the progress of spatial skills at an early stage, as this will affect the overall development of the person. Implementation of 3D tasks (like the ones used here) at home or in school settings would be an easy and engaging means to enrich visuospatial function in children.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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