Journal of Cognition and Development
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/hjcd20

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Accepted author version posted online: 25 Feb 2013.Published online: 28 Mar 2014.

JOURNAL OF COGNITION AND DEVELOPMENT, 15(3):495–505

ISSN: 1524-8372 print/1532-7647 online
DOI: 10.1080/15248372.2012.760158

Routledge
Taylor & Francis Group

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Previous studies provided evidence of a relationship between mental rotation (MR) and motor processes in children and adults. However, there is no direct evidence that MR ability is a reliable predictor of success for motor performance. After completion of a MR test, the motor performance of 7- to 8-year-old and 11- to 12-year-old children was measured along a steeple chase and an equivalent straight distance sprint. The chase involved several motor actions requiring, among different competencies, spatial abilities such as performing a forward roll, jumping, crawling, turning, and changing directions. Data revealed that the time taken to complete the chase was influenced by speed and sex, but also by the individual MR ability. Based on these findings, we assume that MR and motor performance may share similar subprocesses.

A great amount of research has examined the relationship between mental rotation (MR) and motor processes. However, little is known in regards to the correlation between MR ability and a motor task performance. Parsons (1994) studied the MR of schematic body segments such as hand pictures. He showed that participants frequently reported imagining their own hand moving up to the stimulus orientation. Kosslyn, Digirolamo, Thompson, and Alpert (1998) later distinguished two distinct types of MR: The internal strategy requires imagining oneself physically manipulating and rotating the stimuli, while the external strategy is based on visualizing the consequences of an external force moving the stimuli. Practically, the internal strategy would be more easily performed when mentally rotating body parts, while the external strategy would be preferred when performing object-related MR. However, several studies have shown that the internal strategy could even be used during MR of abstract objects if participants are explicitly instructed to imagine physically rotating the stimuli (Cohen et al., 1996; Kosslyn, Thompson, Wraga, & Alpert, 2001; Richter, Somorjai, Summers, & Jarmasz, 2000). Other behavioral experiments provided evidence that MR and manual rotations share common processes, in particular that motor processes are activated during MR (Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger,

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1998). MR may even share common processes with some motor skills, as demonstrated in studies where athletes had greater MR ability than did nonathletes (Naito, 1994; Ozel, Larue, & Molinaro, 2004). Finally, several neuroimaging studies provided evidence that motor areas, including the lateral and medial premotor cortex and the supplementary motor area, are involved during MR (e.g., Lamm, Windischberger, Moser, & Bauer, 2007; Richter et al.; Seurinck, Vingerhoets, de Lange, & Achten, 2004; Vingerhoets, de Lange, Vandemaele, Deblaere, & Achten, 2002).

The involvement of motor processes during MR has also been reported in children. Spatial abilities are constructed during the course of child development, and early training on physical and sporting activities is likely to impact spatial abilities. Wiedenbauer and Jansen-Osmann (2008) showed that manual rotation training resulted in enhanced MR performance. During hand MR, children were found to rely on virtually rotating their own hand (Funk, Brugger, & Wilkening, 2005). In a more recent study, Caeyenberghs, Tsoupas, Wilson, and Smits-Engelsman (2009) found that between 9 and 12 years of age, children were able to simulate the movement of their own hand to compare it to the stimulus. In contrast, 7- and 8-year-old children encountered greater difficulty in performing egocentric transformations and thus relied on a less efficient external strategy. Taken together, these data support the hypothesis that motor processes are involved in children's MR, especially for hand stimuli.

The literature mentioned here tends to suggest that motor processes are involved in MR both in children and adults and that engaging in sports and spatial activities during the lifespan contributes to enhanced MR ability. Hand MR was frequently used to recall motor processes in these experiments, and MR of body segments is more generally considered as a reliable procedure to investigate motor imagery (Caeyenberghs et al., 2009). To date, however, little is known in regards to the possible relationship between an object-related MR task and motor task performance, especially in 7- to 12-year-old-children. The aim of the present study was therefore to investigate how MR ability as measured by the Vandenberg and Kuse Mental Rotation Test (VMRT; Vandenberg & Kuse, 1978) can be related to performance on a complex motor task (obstacle chase) in two independent groups of 7- to 8-year-old and 11- to 12-year-old children. The VMRT is a well-known paper-and-pencil test that evaluates a visual MR ability that is considered a general competence that requires an external strategy (Kosslyn et al., 1998). On the other hand, the chase we used involved several motor actions requiring, among different competencies, spatial abilities such as performing a forward roll, jumping, crawling, turning, and changing directions. At first glance, our two tasks are not directly related and do not call upon the same motor processes. It was, however, hypothesized that participants with low MR ability would have more difficulties in performing the obstacle chase. Furthermore, as individual differences in MR scores are supposed to influence motor performance, sex differences were also expected. Accordingly, previous studies revealed that adult men outperform women widely in MR tests (e.g., Peters, 2005; Voyer, Voyer, & Bryden, 1995). These sex differences were also observed in children (Levine, Huttenlocher, Taylor, & Langrock, 1999; Vederhus & Krekling, 1996). To date, however, sex differences have not been investigated while studying the relationship between MR and a motor task.

Three main results are expected: i) a correlation between MR ability and motor performance on an obstacle chase; ii) an effect of age on MR and motor performance; and iii) a sex difference in MR ability and in its interaction with the obstacle chase.

METHOD

Participants

To investigate the effects of age, both primary school children (7 to 8 years old) and middle-school children (11 to 12 years old) took part in the experiment. We chose to investigate 7- to 8-year-old and 11- to 12-year-old children, because around the age of 9 and 10 a change in spatial ability development occurs—specifically the content of gender beliefs begins to resemble the content of adults' stereotypes (Titze, Jansen, & Heil, 2010a). The experimental design was first presented to two schools to recruit a large and balanced number of children for age and sex. Only 2 teachers from the primary school compared with 3 from the middle school volunteered to participate in the experiment. Hence, 28 primary school children (11 girls and 17 boys from second grade, $M_{\text{age}} = 7;8$, $SD = 9.6$ months) and 66 middle school children (33 girls and 33 boys from sixth grade, $M_{\text{age}} = 11;4$, $SD = 6$ months) were recruited. Before the experiment, they were told they would have a particular sequence of physical activity but were not aware of the main objectives of the research or the variables of interest. Experimental procedures were approved by the research ethics board of the university, by the schools' head teachers, and by the parents, who signed individual informed consent forms.

Procedure

Three different tests were administered in a randomized order: an MR pen-and-paper test, an obstacle chase, and a 22-m sprint race.

MR test. MR ability was assessed using the well-established VMRT, which consists of 24 items of three-dimensional objects (Vandenberg & Kuse, 1978). Each item presents one reference figure on the left and four target figures on the right. The participants had to find the two correct items matching the reference. A scoring method that discouraged guessing was used, credit for an item was given only if both correct test figures were identified (Vandenberg & Kuse). The score thus ranged from 0 to 24 for each participant. The test was completed within a 6-min period. All participants were requested to use an external MR strategy.

Obstacle chase. Children were requested to perform the ''Harre's Steeple Chase,'' which includes different motor tasks (Harre, 1976) and has been successfully used in children (Hoyek, Champely, Collet, Fargier & Guillot, 2009). They first started with a forward roll, and then ran toward a medicine ball right in the middle of the course. They passed around the ball by a 90° right turn and ran in the direction of a first bench. They were then requested to jump over the bench, turn back to pass under the same obstacle, and run again toward the medicine ball. They were told to use the same rule to achieve the chase completely (i.e., turning around it [90°] and running in the direction of the next bench; Figure 1).

Three benches were placed around the medicine ball with the exception of the first part of the course, where a gymnastic mattress was placed to prevent any injury while rolling forward. In other words, the course was made of four goal-oriented running sequences with a 90° right turn around the medicine ball, stepping over the bench, passing under it, and then doing the sequence

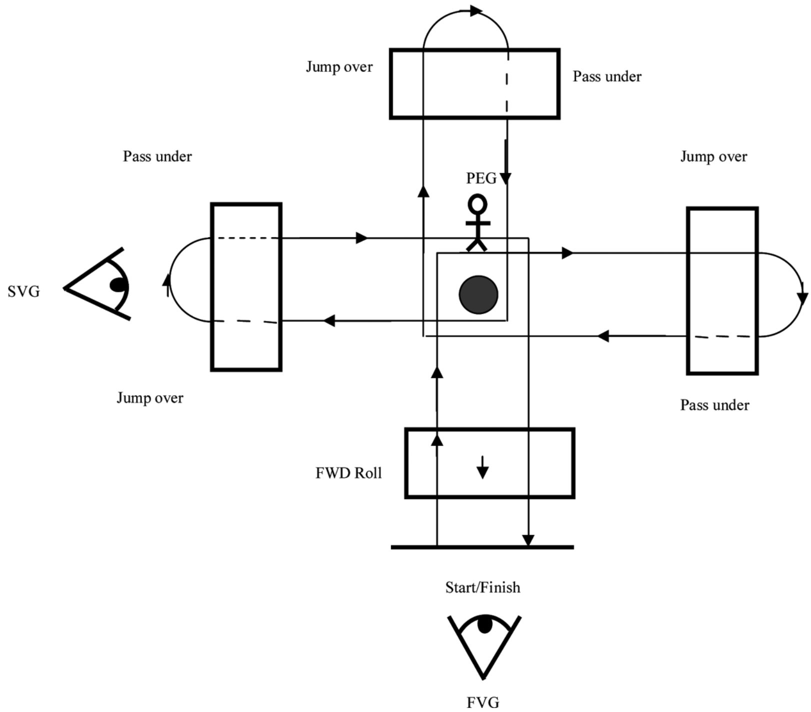

FIGURE 1 Description of the Harre's chase test. The different stages and orientation inside the chase are indicated with arrows. Starting with a forward (FWD) roll, children had to run up to the medicine ball and turn right in the direction of the first bench, where they had to jump and turn back to pass under the same obstacle. Then, they were requested to run as fast as possible up to the medicine ball again and then had to repeat the same motor sequence for the second (top) and third (left) bench. Finally, they were asked to run back toward the ''start/finish line'' as fast as possible. All children received the same instructions describing what to do precisely, and then they were randomly assigned into one of three different groups. The front-view group (FVG) and side-view group (SVG) conditions are represented by an eye symbol and describe the position from which instructions were given—in front of the chase and behind the left bench, respectively. The physical execution group (PEG) condition corresponds to the actual location of each sequence of the chase, associated with specific instructions.

again in another direction. The start and finish lines were at the same point. Actual duration to complete the steeple chase was the main dependent variable.

All children received the same verbal instructions but were randomly assigned into one of three different groups according to the position taken while receiving instructions (group variable). In the ''front-view group'' (FVG), children received the instructions while standing in front of the starting line. In the ''side-view group'' (SVG), children stood motionless behind the left bench during oral instructions, so that they needed to perform a 90° MR to correctly visualize the motor sequence to be performed. The aim was to add an additional constraint involving MR and spatial processes before performing the chase. Finally, the children of the ''physical execution group'' (PEG) received the same instructions while walking across the chase (but without performing it), so that they could associate the instructions to specific motor skills required by the chase (Figure 1).

Before the pretest, children were asked to provide an explicit description of the task to prevent any misunderstanding. The SVG children gave their description while standing behind the left bench, while the FVG and the PEG children were standing behind the starting line. None failed, and all were able to explain in detail the entire chase by providing the correct sequence of movement to be performed.

Sprint race. Sprint performance was measured during a 22-m test (i.e., a straight-line distance that matched that of the Harre's Chase). Photoelectric cells were used to record sprint times with standardized starting procedures. The mean time of two trials was taken as the final result.

Data Analysis

Exploratory data analysis (Hoaglin, Mosteller, & Tukey, 1983) showed that a squared root transformation provided a more symmetric data distribution for the VMRT rotation test. To check the well-known effects of age and sex on the sprint race, VMRT, and Harre's chase performances, we first used two-way analyses of variance (ANOVAs) with interaction.

The main statistical analysis is a multiple regression to explain the dependent variable, Harre's time, by the five independent variables: VMRT, speed, age, sex, and group. Starting from a complete model including all order-one interactions, a backward automatic selection algorithm was used to reduce the regression model (F test at the 5% level). Obeying marginality restrictions (Venables & Ripley, 2002), main effects were considered only when corresponding interactions were first removed as being nonsignificant. The final model was interpreted with the help of an effect plot (Fox, 2003). The response variable was plotted against each interaction or main effect averaging over all the other explanatory variables included in the reduced regression model. Despite the fact that group is the only controlled and randomized variable in this experiment and the other four independent variables are observational measurements, we will broadly talk about the effect of an independent variable on Harre's time in the following discussion.

RESULTS

Mean sprint times were 4.98 s ($SD = 0.38$) and 4.20 s ($SD = 0.25$) for the primary and middle school children, respectively. Boys performed the 22 m in 4.38 s ($SD = 0.43$), girls performed the 22 m in 4.49 s ($SD = 0.50$). The ANOVA revealed no interaction, $F(1, 90) = 0.56$, $p = .46$, but a significant effect of sex, $F(1, 90) = 9.43$, $p = .003$, and age, $F(1, 90) = 155.48$, $p < .001$.

Looking at individual MR ability revealed that middle school children outperformed primary school children, with respective mean scores of 7.74 ($SD = 4.04$) and 4.25 ($SD = 2.78$). Similarly, boys performed better than girls, with mean scores of 7.54 ($SD = 4.28$) and 5.75 ($SD = 3.53$), respectively. Both age and sex effects reached significance, $F(1, 90) = 21.32$, $p < .001$, and $F(1, 90) = 7.17$, $p = .009$, respectively, without any interaction, $F(1, 90) = 0.99$, $p = .32$.

All children were able to correctly perform all parts of the Harre's chase. Primary school children took an average of 23.26 s ($SD = 3.90$), while middle school children's time was 20.97 s ($SD = 4.84$). Similarly, boys performed faster than girls, with respective mean times of 20.33 s ($SD = 3.90$) and 23.14 s ($SD = 5.08$). The ANOVA revealed no interaction, $F(1, 90) = 0.65$, $p = .42$, but both age and sex effects reached the significant threshold, $F(1, 90) = 6.95$, $p = .01$, and $F(1, 90) = 11.25$, $p = .001$, respectively.

Finally, we performed a multiple regression analysis to explain Harre's time by the five independent variables (i.e., VMRT, speed, age, sex, and group). Starting from a general model including all order-one interactions (10 order-one interactions and 5 main effects), the automatic selection process resulted in a final model including the squared-root transformation of VMRT main effect, $F(1, 83) = 5.13$, $p = .03$, the sprint × age interaction, $F(1, 83) = 4.86$, $p = .03$, and the group × sex interaction, $F(2, 83) = 3.76$, $p = .03$. The percentage of variance explained by this model is $R^2 = .46$, $F(9, 83) = 8.02$, $p < .001$. These effects are shown in Figure 2.

Interestingly, children with high MR ability took less time to complete the chase than did those with poor MR abilities; hence, this correlation suggests that performing the chase required MR abilities. No interaction was found between the VMRT scores and the sprint race time.

The fastest sprint race times were strongly correlated with the best Harre's chase performances, but separate regression lines were needed for primary and middle school children.

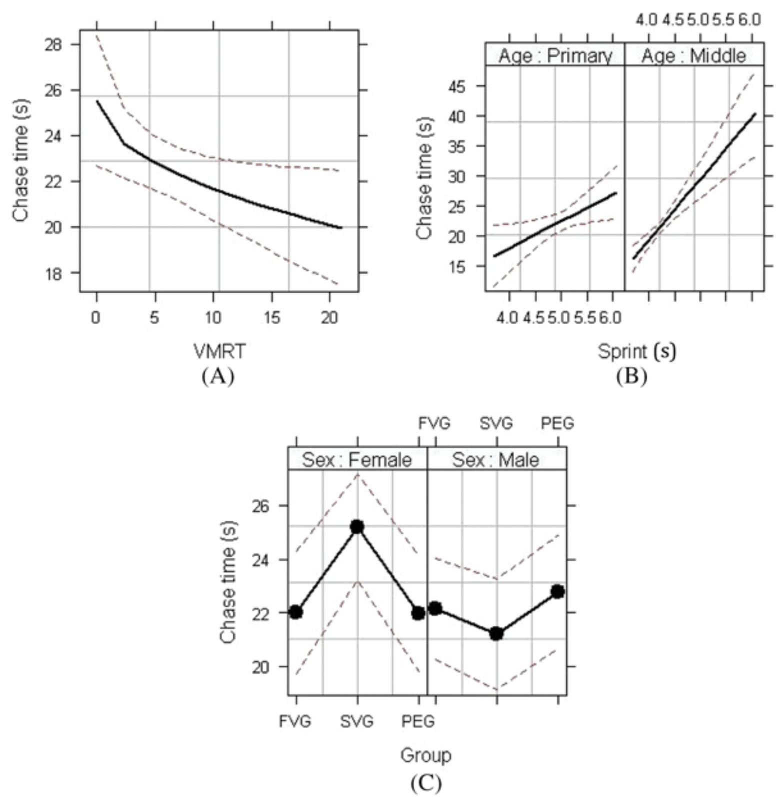

FIGURE 2 Effect plot of the final multiple regression model. (A) Main effect of MR ability as measured by the VMRT on Harre's chase time. (B) Interaction effect of speed and age on Harre's chase time. (C) Interaction effect of sex and group on Harre's chase time.

Though middle school children performed the chase faster than did primary school children (previous ANOVA result), the model with corrected effects including all covariates revealed that primary school children were, relatively speaking and especially when sprint time was growing, more efficient than were middle school children.

As far as the group × sex interaction effect is concerned, the plot revealed that performance was quite similar in all groups, except in girls from the SVG, who received the instructions while standing at a 90° position in the left direction as compared with the starting line.

DISCUSSION

The present study was designed to investigate the relationships between age, sex, VMRT performance, and motor skill performance. It was notably expected that children with high MR ability would also take less time to complete the motor chase. The main results supported this hypothesis and provided further evidence of a complex relationship between age, sex, MR ability, and motor skill performance.

First, our data confirmed the well-known age- and sex-related effects reported in the MR literature. Accordingly, boys had higher MR abilities than girls, as measured by the VMRT (e.g., Peters et al., 1995). Such dissimilarity has been partially explained with regards to differences in cortical activation (Jordan, Wüstenberg, Heinze, Peters, & Jancke, 2002), concentration of sexual hormones (Hampson, 1990), or prior experience with spatial tasks (Baenninger & Newcombe, 1989; Quaiser-Pohl, Geiser, & Lehmann, 2006). As expected, middle school children outperformed primary school children, probably due to their brain maturity (in particular, frontal-lobe maturation) and life experience. School programs may also explain such differences as they include mathematics courses and most especially specific knowledge in geometry, which is thought to substantially contribute to improve spatial abilities. Such a finding is consistent with greater processing capacities observed across motor and cognitive tasks (Caeyenberghs et al., 2009; Casey, Colon, & Goris, 1992; Kail, 1997). Providing evidence that middle school children ran faster than primary school children during the sprint race, while boys were faster than girls, was quite expected and logical and therefore does not need to be discussed in greater detail. This was mainly due to age difference (height and weight) and to sex difference in muscle development.

The innovative aspect of the present study is investigating the relationship between MR ability and motor performance on the Harre's chase. By examining motor skill as a function of VMRT scores, speed, age, and sex, the multiple regression model provided evidence of a complex relationship among these variables. Interestingly, and for the first time, present data revealed a positive correlation between the VMRT performance that does not intuitively require an internal strategy and the Harre's chase performance. It is noteworthy that the VMRT scores were not related to the sprint race times. This supposes that MR ability may be needed for the chase performance but not for the sprint. At first glance, this latter result attests that MR ability serves motor performance during which changing direction and coordinating movements are required. However, caution should be taken before generalizing such findings. Actually, the rationale behind our interpretation is that there was no interaction between VMRT scores and sprint race speed; thus, we are dealing with two distinct abilities that contribute to the effectiveness in the Harre's chase, even though each task requires independent individual competencies. According to Rey (1995), each problem (e.g., the Harre's chase) requires a complex and specific set of competencies integrating different ''small'' competencies (e.g., velocity, spatial ability, etc.). We thus assume that performing the Harre's chase requires the children to mentally imagine their bodies turning in space, at least during the encoding phase. Therefore, the VMRT and the Harre's chase share several common competencies that have been determined experimentally using a multiple regression model. The factors we integrated into this model were shown to represent a major part of the whole variance. In an attempt to point out these common competencies, we may hypothesize that MR abilities were primarily required for the following motor skill components: i) memorizing and encoding the different sections of the chase (including the integration of the general rule of changing direction); ii) rolling forward; iii) dealing with obstacles; and iv) spatial orientation. Accordingly, rolling forward requires an egocentric rotation of the body in the sagittal plane, which may call upon MR during the preparation phase. Turning 90° to the right around the medicine ball also requires some egocentric rotation in the transverse plane and spatial orientation.

An expected effect was found between the time taken to complete the chase and the sprint race speed, hence demonstrating that Harre's chase relies heavily on individual velocity. Even though the chase has several obstacles, it requires pure velocity to run between the medicine ball and the bench. Though middle school children took less time to perform the chase than did primary school children, the sprint $\times$ age interaction of the multiple regression model indicated that primary school children were actually, for a given speed, more efficient than were middle school children. This result might be partially explained by the effect of prepuberty. Accordingly, due to the early growth in long bones (arms and legs) as compared with flat bones (shoulder blade), body schemata of children might be disrupted in middle school children. This led to time loss when confronted with events requiring general coordination. Also, the height of the middle school children may have influenced their efficiency, notably while passing under the bench (i.e., 11- and 12-year-old children took a longer time to pass under the bench, as they are taller than 8-year-old children). Altogether, this may have led 11- and 12-year-old children to spend more time on dealing with obstacles. These explanations remain working hypotheses, however, still waiting for experimental investigations before drawing general conclusions.

Finally, a second interaction was related to the group variable (i.e., to the position in which the children received the instructions to perform the motor sequence). Data revealed that all groups equally performed the Harre's chase, with the exception of the girls assigned into the SVG, who took significantly more time to complete the chase. We assume that girls in this group took more time to start the chase and to move throughout the course. The participants from this group received the instructions while standing at a 90° position in the left direction from the starting line. Hence, they needed to perform an MR to efficiently encode and correctly imagine the directions of the movement to be performed. Although MR tasks reveal ample evidence of sex differences in favor of boys (e.g., Hoyek, Collet, et al., 2009; Peters et al., 1995; Vandenberg & Kuse, 1978), the present findings demonstrate that a low MR ability may also result in poorer motor skill performance. This finding is important as it shows for the first time that sex differences in spatial ability are likely to influence girls' motor performance. Two main causes explain these differences: the ''psychosocial'' variety (e.g., stereotype threat, sex-role identification, or differential experience and socialization) and the ''biological'' variety (e.g., genetic complement, sex hormone level, or cerebral lateralization). Titze, Jansen, and Heil (2010b) recently studied more deeply the psychosocial theory by investigating the influence of gender beliefs in children. Three different instructions were given: Boys are better in this task; girls are better in this task; or performance is independent of gender. Surprisingly, they did not find any changes in performance as a function of the instruction: Boys always outperformed girls. On the other hand, Hahn, Jansen, and Heil (2010a, 2010b) examined this gender difference in children from a biological point of view. In their two studies, they found a hemispheric asymmetry as a function of gender. In sum, whether this gender difference in children's MR is caused by biological factors (brain lateralization, hormonal) or psychosocial factors (spatial activities, socialization, gender beliefs) remains to be answered. Our study was not meant to validate one of these theories, but our findings strongly lean toward the psychosocial explanation. Accordingly, prior experience with spatial tasks has been constantly used to explain boys' outperformance (Baenninger & Newcombe, 1989; Quaiser-Pohl et al., 2006). In fact, Harre's chase may be considered a new and more complex spatial task including additional spatial constraints in the SVG. Facing these new constraints, girls—probably with less spatial experience—encountered more difficulties to complete the chase. We can thus assume that girls' performance can be increased after practice. Thus, future investigation should focus more on the effects of an early exposure to spatial-related activities in girls to observe whether this gender difference would always exist.

To summarize, present data indicated the MR ability (assessed with the VMRT) may contribute to achieve peak performance in a motor chase. Therefore, MR ability could impact subsequent motor performance in children. Practically, children engaging in MR and spatial training might reinvest some common competencies in motor tasks. On the other hand, the opposite relationship (the motor tasks contributing to the success on MR) can hold true. However, the common subprocesses between MR and motor performance should be clearly identified. The main concern in our study is that the experimental design did not aim to identify which processes might underlie the relation between motor skill and MR ability. Thus, we cannot rule out the influence of some other confounding variable (e.g., IQ, health status, participation in sports, number of hours playing video games, etc.) that may have affected performance on both MR and physical tasks such as running. Future investigations should thus attempt to define these competencies in greater detail. For example, we could use different kinds of motor tasks that are hypothesized to involve MR ability to different degrees (e.g., fine-motor hand skills). As part of this strategy, other cognitive tasks that do not involve MR ability would also have to be administered to pinpoint the source of any ability shared by motor and MR tasks. This would allow for making more precise statements about the processes that are common across motor and MR tasks and would contribute to develop mental training programs to enhance motor performance. Finally, regarding sex differences, we may conclude and confirm previous studies that training on spatial abilities can reduce sex differences (Hoyek, Collet, et al., 2009; Roberts & Bell, 2000; Samsudin & Ismail, 2004), and this may in return enhance motor performance requiring spatial orientation.

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