# MENTAL ROTATION AND MOTOR EXPERTISE: STORAGE DOES NOT ACCOUNT FOR BETTER PROCESSING

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*Abstract:* Whether visuospatial memory span accounts for part of the differences in three-dimensional mental rotation performance is currently debated in the field of spatial cognition. In order to further explore this issue, we assessed mental rotation, visual and spatial memory spans in a sample of elite and novice athletes in combat sports, an activity that has been linked to higher spatial ability. Although results yielded significant differences in mental rotation ability favoring elite athletes, there was no effect of sport expertise on either the visual or the spatial memory span task. In addition, correlations between the visuospatial memory span tasks and the Mental Rotations Test were not significant, whereas there was a strong correlation between the visual and the spatial memory tasks. We further discuss these findings and their implication in explaining mental rotation differences, as well as toward a comprehensive understanding of the cognitive processes specifically involved in motor performance.

*Key words:* mental rotation, spatial ability, working memory, visuospatial span, motor expertise

Spatial ability, the ability to represent and manipulate spatial relationships among objects, is a critical process in human intelligence (Johnson, Bouchard, 2005). Within the psychometric literature, a large number of studies have underlined the idea that spatial ability is not a unitary concept, but rather divided into several categories of abilities (McGee, 1979; Lohman, 1988; Caroll, 1993). As such, two meta-analytic studies (Linn, Petersen, 1985; Voyer, Voyer, Bryden, 1995) have distinguished three categories of spatial abilities: spatial perception, spatial visualization and mental rotation, based on differences in the psychometric rationale and in cognitive processing involved. One of these categories, mental rotation, has been studied extensively throughout different kind of tasks, often based on three-dimensional Shepard-Metzler figures (Shepard, Metzler, 1971), as in the Mental Rotations Test (MRT, Vandenberg, Kuse, 1978), the test most commonly used in the literature for several reasons such as its validity and reliability (Peters et al., 1995) and its format favoring large-scale studies. Moreover, MRT studies usually yield recurrent gender differences favoring males over females (Linn, Petersen, 1985; Voyer, Voyer, Bryden, 1995) regardless of cultural aspects (Oosthuizen, 1991; Jahoda,

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1980; Stumpf, Klieme, 1989), and show a large effect of prior exposition and appropriate training on performance (Lohman, Nichols, 1990; Leone, Taine, Droulez, 1993), which can sometimes reduce partially or completely gender differences (Vasta, Knott, Gaze, 1996; Ackerman, Kanfer, Goff, 1995; Devon, Engel, Turner, 1998).

Beyond these theoretical considerations, spatial ability is critical for success in many professional fields. Thus, individual difference studies have straightforward practical applications in many different fields. Following that idea, mental rotation ability has been used to select and recruit various professionals such as surgeons, airline pilots, dentists, and engineers (see Halpern, Collaer, 2005, for a review). Spatial ability has also proved to be important for academic achievement, particularly in fields such as mathematics and mechanical reasoning (Hegarty, Waller, 2005). With this in mind, many studies have focused on establishing individual differences based on several factors such as gender (Voyer, Voyer, Bryden, 1995), academic program, age, or strategies (see Peters et al., 1995, for a review). Within this line of applied research, others have looked at the experiential factors that could be responsible for spatial ability enhancement. This has led to the identification of specific activities that can influence performance in mental rotation laboratory tasks. Playing videogames (De Lisi, Wolford, 2002; Feng, Spence, Pratt, 2007; Boot et al., 2008), studying science (Moreau et al., 2010; Peters et al., 2006) and practicing specific sports or experiencing different tasks (Moreau et al., 2011; Voyer, Nolan, Voyer, 2000) are just a few examples of such activities. However, very little has been done so far to understand the underlying causes yielding such individual differences. What kinds of processes do spatial ability tests, such as mental rotation tasks for instance, precisely tap into?

In an attempt to explain the well-established individual differences in spatial cognition, a quite consequent body of research (see Miyake et al., 2001, for a review) has been published showing a relation between spatial visualization ability and Visuospatial Working Memory (VSWM). Hence, empirical measures of the spatial visualization factor (using Paper folding and DAT Space relations tests) have proved to be an excellent predictor of VSWM processing-and-storage tasks (Dot Matrix and Letter rotation tasks), better than other factors such as spatial relations and perceptual speed (Miyake et al., 2001; see also Kane et al., 2004). Other studies have also shown that increasing the load of the storage component on a VSWM task results in larger individual differences in visualization ability performance (see Hegarty, Waller, 2005), consistent with a prior study showing that loading the storage component on a VSWM task implies greater individual differences in visualization ability performance (Salthouse et al., 1990). Storage is one of the important functions involved in VSWM, and can include visual patterns and sequences of successive locations in a given referential frame. When only patterns are stored, tasks are named visual (sometimes labeled as spatial-simultaneous in the literature) since only the shape of the pattern has to be memorized; when sequences have to be recalled in order, tasks are labeled spatial (or spatial-sequential). These are two different aspects of VSWM storage, both neurologically and functionally (Logie et al., 2005; Pickering, 2001; Pickering et al., 2001; Vecchi, Girelli, 1998; see also Logie, Della Sala, 2005, for a review), and have shown to be clearly separated (Park et al., 2002), despite a factor analysis by Miyake et al. (2001) questioning the distinction between short-term and working memory tasks. Taken together, these studies suggest a close tie between memory storage and spatial ability.

Although they underlined the relationship between the broad category of spatial visualization and VSWM, these studies, however, did not try to relate specifically three-dimensional mental rotation and VSWM. This is a critical point as mental rotation tasks are known to systematically produce larger individual differences than spatial visualization tasks (Voyer, Voyer, Bryden, 1995). Only recently, a few experiments have yielded a relationship between mental rotation performance and VSWM span tasks (Colom et al., 2005; Kaufman, 2007), providing an updated view of past research in the field (Stríženec, Droppová, 1979). Interestingly, Kaufman (2007) showed that part of the variance in performance on the MRT can be explained by individual differences in a simple block VSWM span task (sequential). This author argues that it is not surprising to find a relationship between three-dimensional mental rotation tasks such as the MRT and VSWM span tasks, since both involve storage components. In the case of the MRT, it consists of maintaining the target figure intermediate results to be compared with the initial figure. Furthermore, Just and Carpenter (1985) found that a poor performance on a Shepard-Metzler mental rotation task can be related to a slower speed of rotation, and that low spatial individuals showed difficulty maintaining mentally spatial properties of a figure. These studies suggest that individual differences in mental rotation performance might be - at least partly - yielded by differences in VSWM capacity.

We intended to replicate these findings within a population of athletes which has shown higher mental rotation performance in prior studies (Moreau, 2012; Moreau et al., 2012). To that purpose, we assessed three-dimensional mental rotation ability, visual and spatial memory spans, in elite and novice athletes practicing combat sports. We hypothesized higher mental rotation ability in elite athletes compared with novices, along with a more efficient storage of both visual and spatial material.

## METHOD

### *Participants*

Sixty athletes took part in this study (30 males and 30 females, mean age = 22.8 years; range: 18-29, SD = 3.35). They practiced fencing (N = 20, 10 males and 10 females), judo (N = 20, 10 males and 10 females), or wrestling (N = 20, 10 males and 10 females), and were either novice athletes in these activities (N = 30, 15 males and 15 females; mean age = 23.3 years, SD = 4.04), which means that they never participated in any competition, or elite athletes (N = 30, 15 males and 15 females; mean age = 22.3 years, SD = 2.98), which means that they were selected at least once for an international championship. Novices were recruited in local clubs and elites were drawn from high-level federal facilities. There was no intermediate level. The elite group had an average of 13.25 years of practice in their sport at the time of the experiment (SD = 4.85), whereas the novice group had practiced for less than a year (0.80 year, SD = .55), from data gathered via questionnaires at the onset of the experiment. None of the participants had prior exposition to any of the tasks of this experiment, and none of them were involved in any personal or professional occupations known to be strongly related to high spatial abilities, such as the particular jobs or activities detailed in this introduction, with the exception of sport practice.

## MATERIAL AND PROCEDURE

### *Mental Rotations Test*

We used a printed version of the MRT (Vandenberg, Kuse, 1978) including two sets of ten problems based on Shepard and Metzler original stimuli (Shepard, Metzler, 1971). Each problem includes a target figure on the left of the line and four potential matches on the right, including rotated or mirror images. Two of these stimuli match the target after a 3D rotation is mentally performed (right answers), whereas two do not match (wrong answers).

Three minutes were given for each set of 10 problems, separated by a five-minute break. Scoring for each problem was as follows: two points for two right answers, one point if only half of the item was answered and the answer was correct, and zero point if there were one or two mistakes. This was meant to provide a correction for guessing, as advised by Albaret and Aubert (1996).

### *Visual Simple Span Task*

The visual task presented a computerized 5x5 matrix. Participants were asked to memorize a pattern of filled cells (Figure 1) presented for three seconds followed by a blank

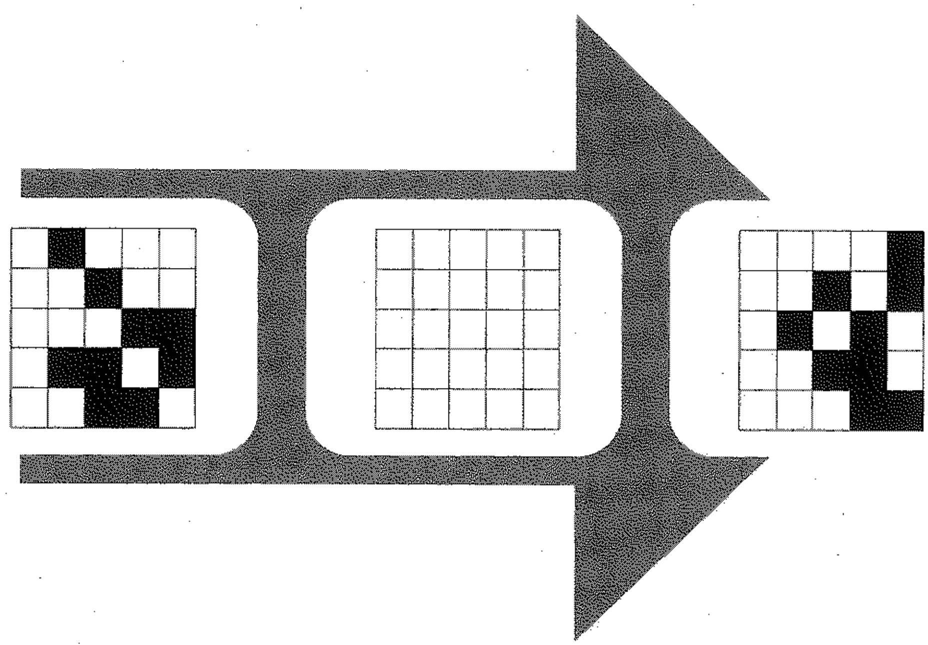

Figure 1. Visual simple span task, levels 9a and 9b (9 grid cells to recall)

matrix on which the participants had to point previously filled cells.

The session started with five cells filled (level five). None of the participants failed at this level. Every level was divided in two parts including patterns of equivalent difficulty to recall (5a, recall, 5b, recall, 6a, recall, 6b, recall, ..., 12a, recall, 12b, recall). The test stopped after level 12 was completed. If participants failed the two parts of a previous level, the test was stopped. We scored the test giving one point for every part completed. Therefore, the maximum possible score was 16.

*Spatial Simple Span Task*

The spatial task presented a computerized 5x5 matrix. As opposed to the visual task, the presentation modality was dynamic, with the matrix visible throughout the entire test. Participants were asked to memorize a pattern of successive filled cells (Figure 2). Every cell was filled for two seconds, followed by a blank matrix for one second before the next cell was filled.

The session started with level five (five locations to recall in order). None of the participants failed at this level. Every level was divided in two parts including patterns of equivalent difficulty to recall (5a, recall, 5b, recall, 6a, recall, 6b, recall, ..., 12a, recall, 12b, recall). The test stopped after level 12 was completed. If participants failed the two parts of a previous level, the test was stopped. Participants had to recall the successive positions of the filled cell by pointing out, at the end of every part, the locations on the blank matrix. Recalling the right cells with the wrong order was not taken into account, since this would provide a measure of visual memory span. We scored the spatial task

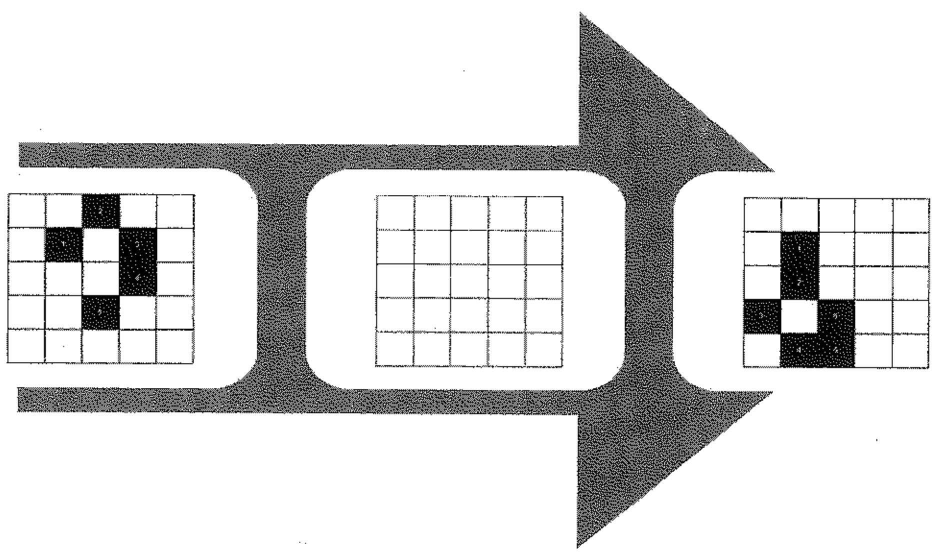

Figure 2. Spatial simple span task, levels 5b to 6a (successively five and six grid cells to recall in order, separated by a blank matrix)

following the procedure described above concerning the visual task. Therefore, the maximum possible score was 16.

## RESULTS

Descriptive statistics for each task, including means, standard deviations, range, skewness and kurtosis, are presented in Table 1. MRT scores are out of 40, whereas both span tasks performances are out of 16. The whole sample represents the sum of both elites and novices groups.

A one-way ANOVA with expertise [elite, novice] as a single factor was performed on the MRT data. It yielded a main effect in favor of elite athletes ($F(1,58) = 44.20$, $p < .001$, $\eta^2 = .43$), consistent with previous work described above. Similar one-way ANOVAs were conducted on visual and spatial memory spans with contrasting results. No significant expertise effect was found, either on the visual or the spatial tasks ($F(1,58) = 0.03$, $p = .87$, $\eta^2 < .001$ and ($F(1,58) = 0.13$, $p = .72$, $\eta^2 = .002$, respectively).

Further analyses based on correlations matrices revealed a positive relation between visual and spatial tasks values in both groups (elites: $r = .88$; $p < .001$; novices: $r = .70$; $p < .001$), pointing out the close relationship between both memory span tasks. However, correlation analyses did not yield any relationship between the MRT and the visual task (elites: $r = .32$; $p > .05$; novices: $r = .18$; $p > .05$), or between the MRT and the spatial task (elites: $r = .27$; $p > .05$; novices: $r = -.15$; $p > .05$). This means that although the MRT and the memory span tasks were not correlated, the memory span tasks shared common variance. Similar results were found when elite and novice groups were merged into a single group. Correlation matrices were further refined via regression analyses which, as expected, did not show any of the two

Table 1. Summary of descriptive statistics for the whole sample, the elites group and the novices group

| *Whole sample* | | | | | | |
|---|---|---|---|---|---|---|
| Task | Mean | SD | Min. | Max. | Skew. | Kurtosis |
| MRT | 17.5 | 8.94 | 5 | 38 | 0.90 | -0.37 |
| Visual span | 10.7 | 1.52 | 8 | 14 | 0.26 | -0.33 |
| Spatial span | 10.3 | 1.42 | 8 | 13 | 0.26 | -0.89 |
| *Elites group* | | | | | | |
| Task | Mean | SD | Min. | Max. | Skew. | Kurtosis |
| MRT | 23.4 | 8.97 | 12 | 38 | 0.10 | -1.52 |
| Visual span | 10.8 | 1.52 | 8 | 14 | 0.36 | -0.73 |
| Spatial span | 10.4 | 1.56 | 8 | 13 | 0.21 | -1.14 |
| *Novices group* | | | | | | |
| Task | Mean | SD | Min. | Max. | Skew. | Kurtosis |
| MRT | 11.7 | 3.44 | 5 | 18 | -0.05 | -0.52 |
| Visual span | 10.7 | 1.53 | 8 | 14 | 0.17 | 0.20 |
| Spatial span | 10.2 | 1.28 | 8 | 13 | 0.27 | -0.55 |

Table 2. Summary of regression analyses for variables predicting MRT performance

| Variable | β | SE β | $R^2$ | F | p |
|---|---|---|---|---|---|
| *Whole sample* | | | | | |
| Visual span | .207 | .128 | .042 | 2.59 | .113 |
| Spatial span | .153 | .130 | .023 | 1.39 | .243 |
| *Experts* | | | | | |
| Visual span | .319 | .179 | .102 | 3.17 | .086 |
| Spatial span | .270 | .182 | .073 | 2.20 | .149 |
| *Novices* | | | | | |
| Visual span | .178 | .186 | .032 | .92 | .347 |
| Spatial span | .148 | .187 | .022 | .63 | .435 |

visuospatial memory span tasks to predict the MRT scores. This was found when the whole sample was considered, but also within the experts group or the novices group alone. Complete results are presented in Table 2.

## DISCUSSION

The data reported herein yielded a strong relation between sport expertise and MRT performance, which confirms previous findings showing that sport practice alters spatial ability (Moreau et al., 2012). From our particular design, we can make two opposite assumptions: a) special abilities are needed to access high performance in sport (self-selection effect: athletes have become elites because they had special abilities); b) intense sport practice, inherent to high performance, helped develop particular spatial abilities. Although the two assumptions are not exclusive, recent work has validated the second hypothesis (Moreau et al., 2012). Beyond this particular result, there is a need to understand what particular processes favor experts in sports compared with the general population.

To date, very little research has been conducted to identify precisely the cognitive processes involved in mental rotation tasks. As Kaufman (2007) showed a correlation between MRT performance and visuospatial memory span tasks, we proposed visuospatial memory span as a possible factor explaining individual differences among athletes. Although we found particularly high correlations between the visual and the spatial measures of memory span, probably due to the similarities in design and modalities of the two tasks, the present study showed no relationship between MRT performance and visuospatial memory span within a population displaying important variance in overall MRT scores. Correlations between the MRT and the visual task, or between the MRT and the spatial task, were systematically non-significant regardless of the group considered. Elites performed better than novices on the MRT, yet this cannot be related to the ability to hold more items in memory. This particular point is confirmed by the non-significance of the effect of expertise on either of the two visuospatial memory span tasks. In that sense, our findings highlight the fact that better mental rotation performance in athletes might not lie within storage capacity. This finding contrasts with previous work (Kaufman, 2007), but is in line with a consequent body of literature in cognitive psychology and neuropsychology. We discuss below previous evidence that corroborates our results and provides further explanation within the larger context of human cognitive differences.

First, our findings are consistent with classical research on gender differences. As such, Cornoldi and Vecchi recently acknowledged that differences between males and females are non-significant on passive visuospatial span tasks (Cornoldi, Vecchi, 2003). MRT performance, on the other hand, is systematically affected by gender, favoring males in almost every design (Peters et al., 1995; Voyer, Voyer, Bryden, 1995). From this perspective, the MRT and the passive visuospatial memory span tasks described in this study were unlikely to show correlations in performance. Interestingly, this idea is also in line with Kosslyn's view of a distinction between storage and manipulation in visuospatial processes (Kosslyn, 1991), as well as with a neuropsychological study by Morton and Morris (1995) describing a patient, M.G., with altered mental rotation ability but intact object recognition after a cerebrovascular accident affecting her left hemisphere. Therefore, our results are consistent with a strong body of literature bridging cognitive sciences and neuropsychology.

Second, our data yield an interesting perspective to understand cognitive processes specifically involved in mental rotation. Elite athletes performed better on the MRT not because they can store more items at any given time, but because they process or manipulate the information more efficiently. A possible explanation might lie within the differences in strategic choices made by elites and novices. This factor has been quite popular among gender difference studies to explain variations in mental rotation performance, or in the study of individual differences in visuospatial abilities based on cognitive styles (Guisande et al., 2012). Within the field of research on expertise, previous studies have shown that experts are more likely to switch between different strategies (such as rotation, verbal-analytic, and others), whereas novices tend to stick to a comfortable procedure throughout the entire test (Coyle, Bjorklund, 1997; Moreau et al., 2011; Schwenck, Bjorklund, Schneider, 2007). Considering that strategies are adaptable and improvable, this idea also helps to understand studies showing a rapid increase in performance with appropriate practice (Vasta, Knott, Gaze, 1996; Ackerman, Kanfer, Goff, 1995; Devon, Engel, Turner, 1998). Further, strategic choices are critical in a sophisticated mental rotation test such as the MRT, but are of less significance in the two visuospatial memory tasks used in this study. This clearly shows the difference between the cognitive resources involved when performing a mental rotation task as opposed to a simple span task (visual or spatial). Visuospatial memory span does not influence mental rotation performance, probably because the latter is too sophisticated in a sense that it brings on many different factors that can potentially affect performance, which are not involved in memory span tasks, more stable measurements of a single ability.

Following that idea, discrepancies in executive functions could explain the impressive performance of the elite group. It should be noted that this paper deals exclusively with visuospatial memory span, and did not assess more complex storage-and-processing WM tasks. As opposed to passive memory tasks, active measures, combining storage and processing, have yielded consistent gender differences favoring males (see Cornoldi, Vecchi, 2003, for a review). Hence, they are more likely to show significant correlations with MRT performance. However, considering that storage-and-processing WM tasks involve executive functioning and visuospatial modalities, their use instead of visuospatial memory span tasks would make any interpretation about the source of individual differences more difficult. Therefore, assessing visuospatial memory span in athletes was a necessary first step, but subsequent research should bring more definite answers to that matter.

Moreover, comparing visual and spatial span tasks data gives us further information to interpret our results. These two tasks were correlated to each other, but not identical. Such a comparison is possible due to the equivalent design in the tasks, which only differ in presentation modalities and recall instructions. Although they do not assess the exact same components, our results showed that these two tasks are strongly correlated with one another. This finding leads to the conclusion that the different presentation modalities (static or dynamic) and recall instructions (free or serial) either tap into the same visuospatial storage component or are influenced by a third common factor, executive functioning, as recent asymmetrical models of WM point out (Shah, Miyake, 1996; Baddeley, Logie, 1999). From that point of view, potential involvement of executive functioning in our spatial task might be considered. As such, since there is an additional information that has to be recalled when the task is dynamic (the presentation order), we could consider that each new item presented works both as a concurrent factor for previously stored items and as a part of the whole sequence to be recalled after presentation. The role of executive functioning in this case is not equivalent to its central position in storage-and-processing WM tasks, but its slight involvement in both memory tasks could be sufficient to explain common variance.

Beyond the scope of this discussion, there are additional factors that need to be assessed in order to explain individual differences in the MRT. Outside the VSWM framework, there is evidence that individuals do not apprehend two-dimensional and three-dimensional objects similarly (Elman et al., 2008), the neural correlates underlying manipulation of such objects being distinct (Kawamichi et al., 2007). Considering that the MRT displays three-dimensional figures[1], adding a third dimension to visuospatial memory span tasks could be relevant before concluding that storage does not account for part of individual differences in mental rotation. To that purpose, prospective research should assess individual differences in three-dimensional visuospatial memory span tasks, involving storage or storage-and-processing. This approach would also be relevant in terms of ecological validity, as individuals do not apprehend their real life environment in two-dimensions but rather in a three-dimensional frame, which points out the questionable relevancy of assessing two-dimensional 'spatial' memory spans.

[1] A more appropriate term would be 'quasi-three-dimensional' figures, since the presentation modality (either paper-and-pencil or computerized test) is, in fact, a two-dimensional projection of a three-dimensional figure.

Furthermore, this idea follows current research on VSWM pointing toward further distinctions within the spatial component (Mammarella et al., 2006).

In conclusion, one should bear in mind that the sample we used in this experiment is specific and thus might not be representative of a general, non-sportive population. Elite athletes perform better than novices on the MRT, but this does not necessarily mean that they showed the same features found in non-sportive individuals performing well. Athletes might use sport-specific strategies, such as recoding non-motor figures in motor-like representations, which are perhaps not relevant to other individuals performing similarly. Related research on mental rotation in a motor context has found that this ability might be closely related to motor processes (Kosslyn et al., 2001; Wraga et al., 2003; Wexler, Kosslyn, Berthoz, 1998). Following that trend of research, athletes might show a completely original pattern of results in the MRT and more generally in mental rotation ability. Although they might not apply in a more general frame of study, the findings presented in this paper are important to understand which processes do and do not benefit from motor expertise in particular activities. Moreover, there is a possibility that our findings could be replicated in different fields of expertise - such as other sports, but also different professional activities commonly identified for their influence on mental rotation processes. To that extent, these results shed new light on cognitive processes involved in mental rotation and should contribute to refine human differences in spatial abilities.

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