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Spatial ability and motor performance: Assessing mental rotation processes in elite and novice athletes.

DAVID MOREAU* ANNIE MANSY-DANNAY**, JÉRÔME CLERC**, ALAIN GUERRIÉN**

(*) Departement of Psychology, Princeton University, USA
(**) EA 4072 PSITEC, University of Lille-North, France

Experimental and brain imaging studies provide strong evidence for the involvement of motor processes in spatial ability problems, such as mental rotation tasks. This study was designed to assess the relationship between motor performance in sport and mental rotation problems solving. Elite and novice athletes in various sports completed two spatial ability tasks the Mental Rotation Test (MRT Vandenberg & Kuse, 1978) and the Movement Imagery Specific Test (MIST), sport specific training and MRT results (experiments 1 & 2 Moreau, Clerc, Mansy-Dannay, Guerrien, 2010). If motor processes are decisive in spatial ability tasks, we should find differences favoring individuals involved in activities that require complex motor skills. Interestingly, we found a significant relationship between sports performance, activity, sport-specific training and MRT results (experiment 1 & 2). In addition, the well-documented gender effect on the MRT was confirmed (experiments 1 & 2). Results also underlined that elite athletes gained efficiency by using flexible strategies, which can be adjusted to the particular problems encountered (experiment 2). These results help fostering our understanding of the relationship between motor representations, spatial abilities and performance in sports. They are discussed in terms of their implications to general spatial ability models and to training procedures or sports advertising.

KEYWORDS.: Mental rotation, Motor representation, Spatial ability, Sport performance, Strategies.

Introduction

Catching a ball, performing a dance routine, swimming from one point to another, or reacting to an opponent's move are just a few examples of motor actions that require some form of spatial coding and representation to be executed. In order to precise what cognitive mechanisms are involved in

Correspondence to: David Moreau, EA 4072 PSITEC, University of Lille - Nord de France, Dom. Univ. Pont de Bois, BP 60149, F-59653, Villeneuve d'Ascq Cedex, France (david.moreau@fulbrightmail.org)

such actions, researchers have made further distinctions within spatial reasoning processes, which have turned out to be decisive in providing new insights into the cognitive demands required by human motor actions.

Psychometric and neuropsychological studies have led to identify several spatial ability factors (Carroll, 1993; Eliot & Smith, 1983; Kozhevnikov, Kosslyn, & Shepard, 2005; Lohman, 1979, 1988; Mc Gee, 1979; Miyake et al., 2001). Reviewing over 90 data sets from the factor-analytic literature, Carroll (1993) differentiated six of them, namely Spatial Visualization, Spatial Relations, Perceptual Speed, Closure Speed, Flexibility of Closure and Visual Memory. However, he found no distinction between Spatial Visualization (SV), the ability to apprehend, encode and manipulate objects or spatial forms, and Spatial Orientation (SO), the ability to imagine changes in perspectives (Carroll, 1993), confirming previous work in the psychometric literature that questioned the relevance to distinguish SV from SO (Borich, & Bauman, 1972; Goldberg & Meredith, 1975; Price & Eliot, 1975; Roff, 1952).

Interestingly though, cognitive experiments found a strong dissociation between these two factors (Guilford & Zimmerman, 1948; Lohman, 1988; McGee, 1979, Simons & Wang, 1998; Wraga, Creem, & Proffitt, 2000), confirmed by neuropsychological studies (Creem et al., 2001; Kosslyn, DiGirolamo, Thompson, Alpert, 1998; Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999). These rather equivocal results and the confusion that followed mainly arose from the lack of control over the strategic factor. As early as in the middle of the twentieth century, Barratt showed that participants interviewed after taking the Guilford-Zimmerman test of spatial orientation (Guilford & Zimmerman, 1948), commonly considered a strong marker for SO, reported using object-based transformations supposedly related to SV ability (Barratt, 1953). Several authors have also found that participants performing on tasks commonly falling into the SV or the SO categories actually displayed various strategies – mainly object-based mental rotation, perspective-taking and analytic ones (Just & Carpenter, 1985; Lohman, 1988; Schultz, 1991). Thus, none of these tests seem to provide an actual measure of a single ability. Furthermore, not only do different participants use different strategies from one another, but one often adapts strategies to each particular problem of a complete set (Barratt, 1953; Just & Carpenter, 1985; Lohman, 1988). Regardless of task categorization, this lack of experimental control over different potential strategies might have confused the distinction between SV and SO in the scientific literature. The former appears to be the most broadly studied, particularly since typical markers for this factor include 3D mental rotation tests, used extensively in cognitive psychology studies.

The Mental Rotation Test (MRT, Vandenber & Kuse, 1978) is the task measuring SV that has been used in the most extensive number of studies. Peters et al. (1995) identified three different practical reasons for that: the fact that the MRT is undoubtedly a spatial abilities test, the tendency to favor males in all studies, and the appreciable effect sizes. Besides, and as with any other paper and pencil test, large studies with an important number of participants are facilitated. On a more theoretical point of view, mental rotation tasks are commonly utilized on both spatial ability differential studies as well as mental imagery experimental paradigms, which might help explain their popularity among researchers. Even though mental imagery can be defined as the conscious access to one's mental representation whereas spatial ability refers to spatial features of images (Hegarty & Waller, 2005), the two concepts are strongly interrelated, some imagery ability processes being related to what spatial abilities tests actually measure (Hegarty & Waller, 2005), therefore being responsible for the shared variance in these tasks (Pellegrino & Kail, 1982).

One of the most common and well-documented findings concerning the MRT is a recurrent gender difference (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995). Historically, the underlying causes put forward have opposed biological and experiential factors, although current theories agree for a combination of both (see Halpern & Collaer, 2005, for a comprehensive review). MRT studies favor males in almost every design experiment, regardless of cultural aspects (Jahoda, 1980; Oosthuizen, 1991; Stumpf & Klieme, 1989), the gender factor accounting for as much as 17.7% of the variance in scores (Peters et al., 1995). However, these particular results are not immutable, individual differences being malleable with practice. To illustrate this particular point, several studies have shown that an appropriate training on spatial ability tasks leads to significant improvements in performance (Leone, Taine, & Droulez, 1993; Lohman & Nichols, 1990). More importantly, specific practice on these tasks seems to attenuate gender differences, sometimes even erasing them (Ackerman, Kanfer, & Goff, 1995; Devon, Engel, & Turner, 1998; Vasta, Knott, & Gaze, 1996).

These results have paved the way to diverse applied research paradigms. Some particular activities, such as playing videogames (Boot, Kramer, Simons, Fabiani, & Gratton, 2008; De Lisi & Wolford, 2002; Feng, Spence, & Pratt, 2007), studying science (Moreau, Mansy-Dannay, Clerc, & Guerrien, 2010; Peters, Lehmann, Takahira, Takeuchi, & Jordan, 2006), or specific professions (e.g. surgeons, pilots, dentists, or engineers) have thus shown positive correlations with mental rotation performance. Whether a prerequisite or a consequence of their occupation, these professionals score higher on mental rotation tasks than the average population. Following this idea, spatial ability tests have been used to select and recruit participants or professionals in different fields, such as pilots in the United States Army, for instance (Humphreys & Lubinski, 1996). However, Halpern and Collaer (2005) emphasized that spatial abilities have not been considered as they should have, especially for training and educational purposes, considering their importance in order to be successful in a broad range of professional areas.

Strengthening these findings, other studies highlighted the relationship between motor processes and the manipulation of mental images (Olivier & De Mendoza, 2000), as required in mental rotation tasks. Thus, Wexler and colleagues showed that when a mental rotation task is incompatible with a concurrent motor task, error rate and reaction time increase. Both of these decreased, however, when directions of motor actions and mental rotations were similar (Wexler, Kosslyn, & Berthoz, 1998). Further experiments on the manipulation of human hands confirmed these results, Parsons (1994) pointing out that mental rotation performance increase when biomechanically coherent. Consistent with these results, Olivier and colleagues argued that performance in mental rotation of left versus right hands depends on the hand used to respond (Olivier, Velay, Labiale, Celse, & Faure, 2004).

This line of work was confirmed by neuropsychological data underlining impaired mental rotation ability in subjects displaying motor deficits (Lee, Harris, & Calvert, 1997), and corroborates studies in the field of developmental psychology, indicating a relationship between motor processes and mental rotation in children (Courbois, 2005; Zabalia, 2002). Taken together, these findings reassert the notion of functional equivalence between motor and mental rotation processes, with common neural structures dedicated to both motor actions and mental rotation tasks.

Following this idea, recent work (Jansen, Titze, & Heil, 2009) has shown that motor practice can improve reaction time in a mental rotation task. These results are also consistent with Wraga and colleagues findings which emphasized that motor strategies (i.e. strategies based on the use of whole bodies or body parts) are often used to perform rotations of non-body objects when a previous task has concerned body parts (Wraga, Thompson, Alpert, & Kosslyn, 2003). Other related work showed consistent activation of motor cortical areas when performing 3D mental rotation tasks (Cohen et al., 1996; Williams, Rippon, Stone, & Annett, 1995), independently from the response movement following decision-making (Richter et al., 2000). In addition, mental rotation performance was impaired in pathological subjects showing motor deficits (Lee, Harris, & Calvert, 1997).

One might think that these results had direct implications in sports sciences research paradigms. However, in a sport context, spatial abilities have not been extensively studied as opposed to mental imagery. Both frameworks show similarities and partly overlap in mental rotation tasks, although traditionally spatial abilities have been studied assessing individual differences through performance tests whereas mental imagery paradigms used experimental designs mostly based on tools such as self-reports and vividness scales (Hegarty & Waller, 2005). Indeed, imagery ability is known to be closely related to spatial abilities (Kosslyn, 1995) and to be determinant in learning, memory and motor processes (Denis, 1985; Hall and Buckolz, 1981). Besides, the use of some kind of imagery practice is commonly reported in elite performance (see for reviews Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983; Grouios, 1992; Hinshaw, 1991; and Orlick & Partington, 1986), with positive outcomes. Murphy (1990) remarked, however, that it is difficult to draw any general conclusion from the varied techniques and paradigms that have appeared in the literature under the heading of mental practice. Moreover, the use and understanding of mental practice and the mental-based training procedures vary tremendously from one athlete to another, leading to relative vagueness of terms and practices which has contributed to make difficult any rigorous scientific assessment.

The efficiency of mental practice in sports is based on the functional equivalence between performing and visualizing a movement, both sharing common representations (Decety, 2002; Grèzes & Decety, 2001; Jeannerod, 1995, 1999). According to this notion, motor imagery is the result of conscious access to the intention of a motor action, usually non-conscious during execution. Thus, imagery allows rehearsing and correcting motor representation without actual movement. Moreover, two different perspectives of imagery have been identified among elite athletes. In the first-person perspective, athletes see themselves performing from an internal point of reference. Conversely, in the third-person perspective, athletes visualize themselves from an external point of reference – similar to a video film. The former is known to be more likely to activate the primary motor cortex (Lotze et al., 1999), also activated in actual motion. Two different modalities can also be distinguished (visual and kinesthetic), which should not be confused with perspectives, although often used for one another (Moran, 2009).

Considering the involvement of mental imagery processes in mental rotation tasks and the shared mental representations underlying motor practice and mental imagery, one could expect that motor practice influences mental rotation. However, the results detailed previously were obtained in specific and restricted conditions. In fact, most studies in the significant body of research showing similarities between imagined and executed movements have concerned fingers, hands and feet motion, with almost none of these being really representative of complex coordination involving larger muscle groups (Dietrich, 2008). Thereby, there is a need to reveal whether they can be duplicated in more ecological areas, with competitive sports being a fully representative and valid form of motor practice. This is not an easy task, however, as the brain imaging techniques used in these kinds of studies require subjects to stay still, at least for the torso and head parts. Unfortunately, this constraint prevents subjects from performing complex coordination patterns in the scanner.

Carefully conducted experimental designs, based on related findings in cognitive psychology and neurosciences, are a suitable answer to that issue. Thus, from the close relationship between mental rotation and motor processes, intense practice in manipulating motor representations should be helpful when solving problems that involve objects movements in space, such as mental rotation tasks. Regardless of the specific paradigm advocated, this idea is in line with research concerning memory and expertise (Gobet & Simon, 1996; Vicente, 2000).

Research question

We hypothesized that elite athletes whose particular activity involves mental manipulation should display better results in mental rotation tasks than novices or than elite and novice athletes practicing activities that do not require particular spatial abilities. Furthermore, if shaping mental representations via sports practice also implies changes in more neutral tasks (*i.e.* tasks that are not sport-specific), it will mean that the particular representations involved in sports practice, or the processes and strategies required to manipulate them, can be transferred to solving other problems.

To confirm that hypothesis, we recruited elite and novice athletes, practicing either one of the combat sports among fencing, judo or wrestling – these three sports involving a constant connection between visuospatial and kinesthetic processes – or running. Comparing performances of elite athletes in sports involving rotations in three-dimensional space (combat sports) and of elites practicing a cardiovascular sport that do not specifically involve rotations (running) was meant to ensure that the potential differences are not solely due to fitness outcomes but genuinely related to particular cognitive demands.

We assessed mental imagery via a sport-specific test and a general mental rotation task, the MRT. These two tests mainly differ in the mental representations they involve, explicitly related to sports practice for the former and displaying neutral objects for the latter. We expect to observe better motor imagery (assessed through the sport-specific task) and better mental rotation performance (assessed through the MRT) in elite athletes, who have trained for a long time and got better results in competition, than in novices. If our hypothesis is true, this should be visible in athletes practicing combats sports but not in runners. According to previous literature, we also expect to find a gender effect favoring males on mental rotation performance.

Experiment 1

This experiment was conducted on two groups: French athletes practicing combat sports (fencing, judo or wrestling) and road runners. It was designed to determine whether sport level in combat sports is related to MRT performance.

METHOD

Participants

A total of 98 participants took part in the study. All were naive to the two tasks presented and had normal or corrected-to-normal vision. The first group was composed of sixty athletes (*M* = 22.8 years; range: 18-29) divided as follows: 20 fencers, 20 judokas and 20 wrestlers. For each sport, half of the athletes were elites (*M* = 22.3 years, 5 males and 5 females), which means that at the time of the study they held at least one selection in an international event among the Olympics, World championship or European championship. The other participants were novices (*M* = 23.3 years, 5 males and 5 females, in each sport), which means that they did not hold any significant result in competition.

Thirty-eight road runners made up the second group (*M* = 23.9 years; range: 19-32). This group included 19 elites who represented their country in an international event (*M* = 22.5 years, 10 males and 9 females) and 19 novices who were not involved in any competition (*M* = 25.4 years, 10 males and 9 females).

We made sure that none of the athletes from the two groups was involved in any personal or professional occupations or activities known to be strongly related to high spatial abilities, such as particular jobs as detailed in this introduction, or the tendency to play videogames on a regular basis (Boot, Kramer, Simons, Fabiani, & Gratton, 2008). We also ensured that novices were not elite athletes in any other sport since this would compromise the significance of the results and the relevance of the experiment.

MATERIALS

Both groups took the MRT. The first group subsequently took the MIST which displays relevant items for combat sports.

Mental Rotation Test (MRT)

We used a printed version of the MRT (Vandenberg & Kuse, 1978). This test contains two sets of ten problems each, based on Shepard and Metzler (1971) stimuli (there are in fact two different versions of this test in the literature, one with 20 and the other with 24 items). Each problem has a target figure on the left of the line. Four other stimuli are shown to the right of this target. Two of these stimuli match the target after a 3D rotation is mentally performed (right answers), whereas two do not match (wrong answers).

Movement Imagery Specific Test (MIST)

We assessed movement imagery in the first group of athletes with the Movement Imagery Specific Test (MIST, Moreau et al., 2010), a test specific to their individual practice. The MIST was standardized, and its validity and reliability were confirmed in a previous study (MIST, Moreau et al., 2010). It presents twenty items for each sport (fencing, judo, and wrestling), verbally describing original situations that involves production and manipulation of spatial representations. There are two possible choices for each item, and only one correct answer (see table I).

PROCEDURE AND SCORING

MRT

We limited the testing time to three minutes for each set of 10 problems, separated by a five-minute break. Scoring for each item was as follows: two points for two right answers, one point if the athlete answered just half of the item 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). As opposed to other studies, we did not use the reac-

TABLE I

Example of Items For Each Version Of The MIST (Fencing, Judo and Wrestling).

MIST $_{Fencing}$

Starting from an engagement in sixte with my opponent whose left hand is armed. If I am performing a lunge, am I in his/her parry of quarte or sixte?

☐ Quarte
☐ Sixte

MIST $_{Judo}$

I am performing *juji-gatame* on my opponent's right arm. Which of my legs is holding his head down?

☐ Right
☐ Left

MIST $_{Wrestling}$

I am performing an *ankle lace* to my opponent's left. Which of his ankles is on the top of the other?

☐ Right
☐ Left

tion time variable, because the time constraint was considerable, thus supposedly yielding differences in performance.

MIST

We limited the testing time to three minutes for the whole test. We scored the MIST giving one point for each correct answer and zero point when the answer was blank or wrong. Consequently, the maximum possible score was 20.

Results and discussion

Due to the limited sample in each sport ($N = 20$) we first ran a Mann-Whitney U test to ensure that there was no effect of sport type within the combat sports group on the MRT performance ($U > 8$; $p > .21$, in all cases). From this results, we aggregated the data into a larger single group ($N = 60$). This preliminary result underlined the fact that the type of sport does not influence MRT performance, at least for the three combat sports considered in the present study. ANOVA assumptions on normality and on the homogeneity of variances were verified for each sample (Kolmogorov-Smirnov and Levene's tests n.s., in all cases).

Analyses of variance on MRT performance

We first performed a two-way factorial ANOVA with sport [combat, running] and expertise [elite, novice] factors on MRT performance. We found a significant effect of both sport and expertise factors on performance ($F(1,94) = 6.99$, $p = .01$, $\eta^2 = 0.07$, and $F(1,94) = 24.57$, $p < .001$, $\eta^2 = 0.21$, respectively), as well as a significant interaction of the two ($F(1,94) = 18.07$, $p < .001$, $\eta^2 = 0.16$). Having stated these relationships, we carried out further analyses within each group of activities.

Combat sports

A two-way factorial ANOVA with level of expertise [elite, novice] and gender factors was performed on the MRT data. It yielded a main effect of level on the combat sports group ($F(1,48) = 134.54$, $p < .0001$, $\eta^2 = 0.74$). Elite athletes performance was strongly better than novice performance ($M =$

23.37; $SD = 8.97$ and $M = 11.70$; $SD = 3.45$, respectively). There was a strong relationship between sport level and MRT performance, although the MRT does not include any item directly relevant to sport practice. This confirmed our main hypothesis, that is, sport level and MRT performance are strongly related. Thus, sport practice and non-motor items rotations (which includes maintaining and manipulating representations) are connected, which means that elite athletes make connections between processes involved in both sport practice and the MRT. The analysis also revealed a main effect of gender ($F(1,48) = 77.71$, $p < .0001$, $\eta^2 = 0.62$), with better results for males than females ($M = 21.97$; $SD = 10.29$ and $M = 13.10$; $SD = 4.04$, respectively), following subsequent research on gender differences in mental rotation. Males performed better than females on the MRT, which confirms our second hypothesis.

The results of additional analyses buttressed these findings. In fact, the interaction effect between level in sport and gender revealed that the effect of level in combat sport is stronger for males than females ($F(1,48) = 49.36$, $p < .0001$, $\eta^2 = 0.51$, see fig. 1). Elite males scored higher on the MRT ($M = 31.34$; $SD = 4.27$) than elite females ($M = 15.40$, $SD = 3.54$; Tukey's HSD significant, $p < .001$). Accordingly, the influence of sport level was stronger on MRT performance for males than females. However, gender difference was non-significant within the novice group, with novice females performance ($M = 10.80$; SD=3.14) being comparable to that of novice males ($M = 12.6$;

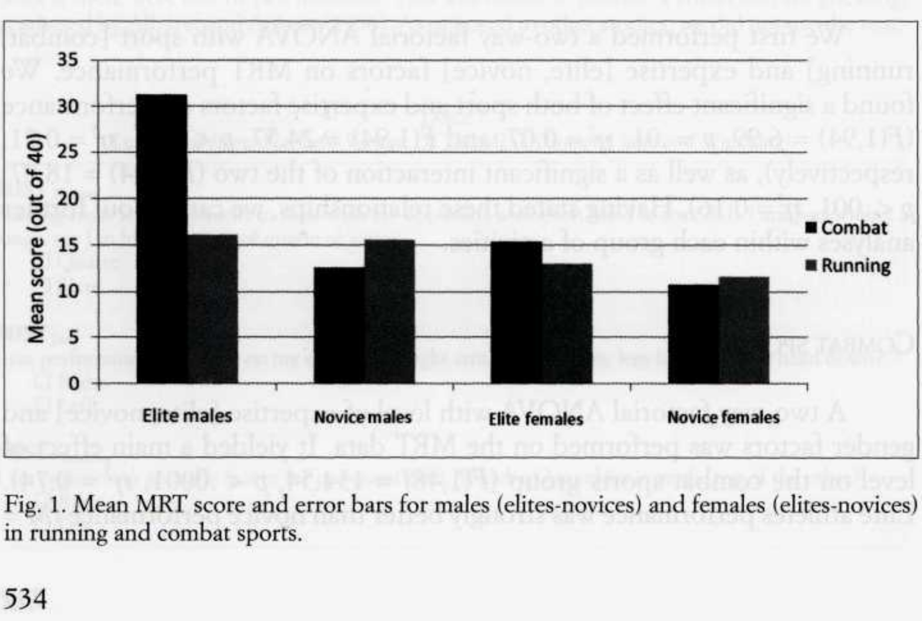

Fig. 1. Mean MRT score and error bars for males (elites-novices) and females (elites-novices) in running and combat sports.

$SD = 3.60$; Tukey's HSD n.s.). This result might be surprising, but it has to be nuanced because there was thirty athletes in the novice group, reducing this to a comparison between fifteen men and fifteen women and thus making this observation quite weak as a result taken out alone. This will be discussed more broadly in the general discussion part.

ROAD RUNNING

Composed of elite and novice road runners, our control group did not yield similar results. In fact, the two-way factorial ANOVA with level of expertise [elite, novice] and gender factors performed on the MRT data revealed no effect of sport level in the running group ($F(1,34) = .38, p =$ n.s.). Elite athletes performance ($M = 14.63$; $SD = 5.32$) was comparable to novice performance ($M = 13.74$; $SD = 4.23$). Thus, level in running seems to be unrelated to MRT performance. As opposed to combat sports, road running does not require retention and manipulation of complex mental representations, which would influence spatial ability factors. Rather, the features of road running – elementary coordination coupled with a predictable environment – are likely to explain the results displayed above. This is in line with our initial hypothesis, stating that level in combat sports might be related to MRT performance, because of the particular representations that are involved.

The analysis showed a significant effect of gender ($F(1,34) = 5.58$, $p = .02$, $\eta^2 = 0.14$), with better results for males ($M = 15.85$; $SD = 5.30$) than females ($M = 12.33$; $SD = 3.32$), in line with research previously discussed. This confirms our second hypothesis, that is, males performed better than females on the MRT.

ANALYSES OF VARIANCE ON MIST PERFORMANCE

A two-way factorial ANOVA with level of expertise [elite, novice] and gender factors showed a significant effect of level on MIST performance, regardless of gender ($F(1,48) = 309{,}03$, p < .001, $\eta^2 = 0{,}87$). The difference males–females was also significant ($F(1,48) = 19{,}88$, p < .001, $\eta^2 = 0{,}29$), as was the interaction between level and gender ($F(1,48) = 9{,}35$, $p < .05$, $\eta^2 = 0{,}16$). Thus, elite males ($M = 18.2$; $SD = 1.70$) performed constantly higher than elite females ($M = 14.3$; $SD = 2.71$), regardless of sport (Tukey's HSD significant, $p < .001$).

Correlation analyses between MRT and MIST performances

We ran correlation analyses between MRT performance and MIST performance, for both elites and novices groups. Both were significant ($r(30) = .79, p < .001$; and $r(30) = .79, p < .001$, respectively for elites and novices). These results mean that some cognitive processes are shared by both tests, which is consistent with the hypothesis of motor strategies use in the MRT to explain elite athlete better performances. This idea will be more broadly explained and discussed in the General discussion section.

This experiment underlined an interesting relationship between sport level and mental rotation processes, both on a sport-specific task (MIST) and on a general test (MRT). It also provided interesting insights into the associations bonding mental rotation and motor imagery, and outlined differences between motor demands and representations in combat sports as opposed to road running. However, our particular design did not allow us to determine precisely what mechanisms and processes caused this relationship. Thus, the direction of the causal relation between sport performance and MRT performance cannot be inferred certainly. Additional factors such as strategies and the amount of sport-specific training could refine our understanding of the results.

The following experiment was conducted to provide additional answers. Since we did not previously find significant differences within the combat sports group, we recruited exclusively athletes practicing wrestling.

Experiment 2

This experiment involved American wrestlers. It was designed to confirm our previous findings – mainly the relationship between level of expertise in sport and MRT results, as well as the gender effect on mental rotation performance – along with providing further hints to some key-questions left unanswered, such as the relation between sport-specific training amount and MRT performance, and the effect of strategies on MRT performance. These variables are relevant in order to understand the direction of the effect tying sport and MRT performance.

METHOD

Participants

A total of 122 participants took part in this experiment. All were naive to the task and had normal or corrected-to-normal vision. Three of them decided not to continue because of personal reasons. The remaining 119 wrestlers (age range: 18-31) composed four groups depending on gender and level of expertise, as follows: 29 elite males (M = 25.6 years, SD = 3.65), 24 elite females (M = 26.3 years, SD = 3.92), 35 novice males (M = 24.2 years, SD = 4.15) and 31 novice females (M = 27.6 years, SD = 4.06). Particular precautions were taken, as detailed in the first experiment (age, profession and level of practice in another sport for novices). Furthermore, 'Elite' and 'Novice' groups were recruited and divided exactly as in the first experiment (*i.e.* one selection to an international event required for elites and no significant result in competition for novices).

Materials and procedure

We used a printed version of the MRT (Vandenberg & Kuse, 1978). Testing and scoring procedures were identical to those detailed previously. However, we also gathered extra information on this sample, such as data concerning the amount of sport-specific training, for each athlete. After taking the test, we also asked the participants to write down a detailed explanation about the strategy they used to solve the MRT. This was meant to provide deeper insight concerning the differences between elites and novices on this task. For statistical readability, we then categorize their answers into four types, which will be detailed in the results section.

RESULTS AND DISCUSSION

MRT and sport level

We performed a factorial two-way ANOVA with level of expertise [elite, novice] and gender factors, after assumptions on normality and on the homogeneity of variances were verified for each sample (Kolmogorov-Smirnov and Levene's tests being non-significant, in all cases). It revealed a strong effect of sport level ($F(1,115) = 240.29, p < .001, \eta^2 = .68$) on MRT results. This means that elites, regardless of gender, performed better on the MRT. Although weaker than the effect of sport level, we also found a strong effect of gender on MRT performance, males performing better than females, which is consistent with prior studies ($F(1,115) = 193.03, p < .001, \eta^2 = .63$).

There was a significant level of expertise x gender interaction as well ($F(1,115) = 27.88, p < .001, \eta^2 = .19$). In other words, the effect of expertise was greater on males MRT performance than on females MRT performance (see fig. 2). As previously found in the first experiment, this result may seem surprising; however, it will be fully explained and discussed below.

MRT and amount of sport-specific training

We studied the relationship between the amount of sport-specific training and MRT performance, by gathering data on training frequency (weekly hours of practice) and years of practice. From this information, we evaluated elite athletes' amount of sport-specific training since they started practicing. On average elite males had undergone 10360 hours of sport-specific training at the time of the experiment, whereas elite females had trained 7220 hours. In

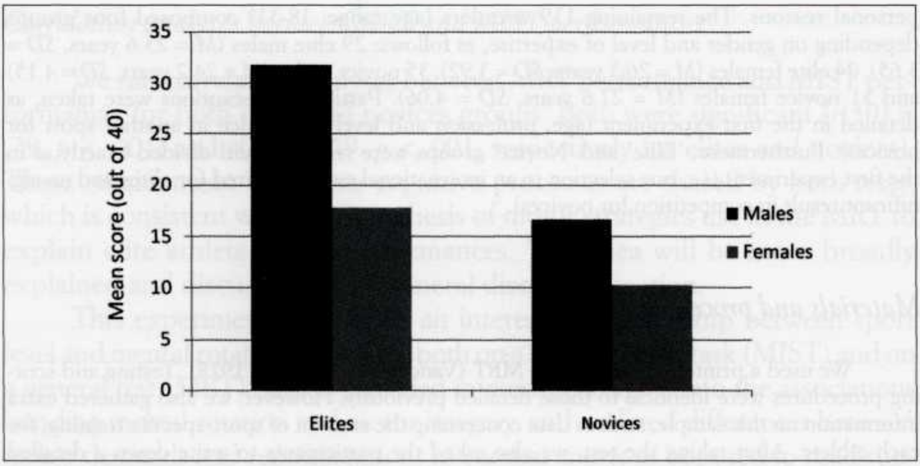

Fig. 2. Mean MRT score and error bars for male and female wrestlers (elites-novices).

fact, elite males started their practice younger ($M = 6.8$, $SD = 2.7$) than elite females ($M = 7.9$, $SD = 3.9$), and they also trained more frequently, especially during teen years. Although this is an estimation, results clearly match MRT performance ($M = 31.9$ and $M = 17.8$, for elite males and elite females, respectively), which means that gender differences in elites are mainly due to differences in training amount rather than to genetic factors. This can be found in fig. 3 by comparing MRT performance and sport-specific training amount variables.

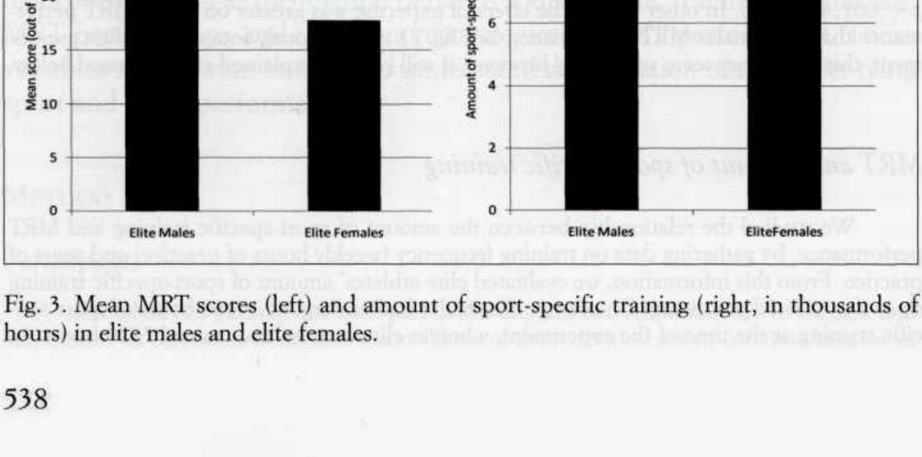

Fig. 3. Mean MRT scores (left) and amount of sport-specific training (right, in thousands of hours) in elite males and elite females.

MRT and strategies

After taking the test, we asked our participants what strategy they used to solve the problems. Based on their answers and on previous work by Peters and colleagues (1995), we yielded four different categories of strategic processes (fig. 4). *Adjustment* (A) means that athletes adapted their strategy to the particular problem with which they had to deal. *Rotation* (R) refers to a strategy based on mentally rotating the presented item (object-based mental rotation), or rotating the environmental frame (perspective-taking strategy), but not a combination of both (which is the *Adjustment* condition). When participants were not clearly aware of their own strategy, we selected the *Unidentified* (U) condition. Otherwise, we labeled it *Other* (O) (consequently, this condition includes analytic strategies, given that participants were aware of them. If they were not aware of them, it appears under the U condition).

There was a strong differenciation between elites and novices self-reported strategies (X^2 (9, N = 119) = 33.5, p <.0001, when considering elite males, elite females, novice males and novice females separately; and X^2 (3, N = 119) = 32.3, p < .0001, when males and females were aggregated as a single group within the elite and novice groups). As we could expect, novices were more often unaware of the process they used to solve the problem (U, males: 34%, females: 32%) than elites (males: 0%, females: 8.5%). More interestingly, efficiency for elites did not apparently come from a quicker and more efficient rotation process alone (R; elite males: 38%; elite females: 29%; novice males: 43%; novice females: 48.5%), but from their possibility to adapt their strategy to the type of problem encountered (A; elite males: 48%; elite females: 54%; novice males: 11.5%; novice females: 6.5%). In fact, they seemed to quickly notify and rule out obvious wrong answers. This was true regardless of gender. The O condition (including analytic strategies) was stable over expertise and gender variables. A simple factor ANOVA on these data confirmed the previous findings.Thus, the strategy choice effect on MRT performance was significant (F(3,115) = 14.45, p < .001, η^2 = .27, see fig. 4), which means that mental rotation performance was affected by the strategies participants used.

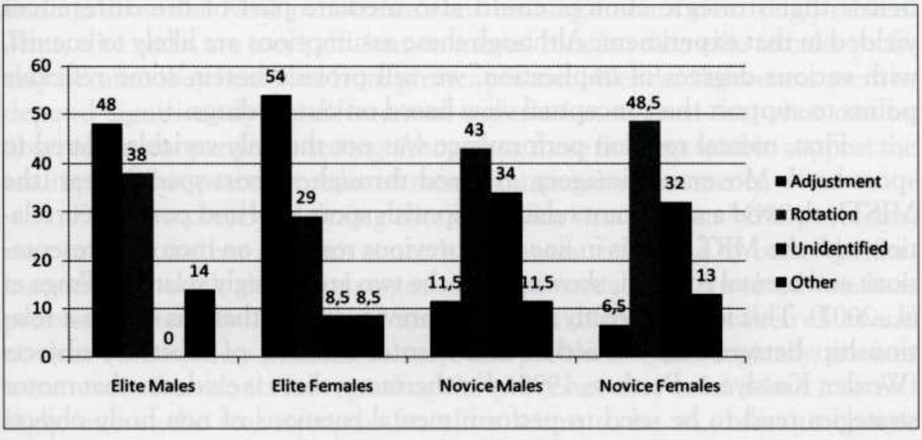

Fig. 4. Athlete strategies for the MRT (in % of each group).

General discussion

The central aim of this paper was to investigate whether level of expertise in particular sports are related to better mental rotation performance. Our main hypothesis is confirmed by the results, with significant effect sizes in both experiments. Elite athletes, practicing daily a combat sport among fencing, judo or wrestling – but not running – showed consistent high performance in the MRT. In itself, this finding is quite interesting because it provides further evidence for a strong tie between motor performance and spatial abilities, such as mental rotation in particular.

However, with this type of cross-sectional study, cause and effect relationships are not certain, and we can thereby make different assumptions. One way to look at this set of data would be to consider that daily motor practice required to achieve high performance in sports helped develop spatial ability. In other words, daily practice inherent to high performance increased spatial ability component and solving strategies. Conversely, one could assume that initial above-average spatial abilities are necessary to access high performance in sport – self-selection effect: athletes have become elites because they had some specific abilities. Moreover, a third assumption that should not be discarded could explain our main finding via one or several common factors, shared by both sport and mental rotation tasks. Potential candidates would be visuospatial working memory or executive functioning, through control and regulation of mental processes, for instance, but because of the effect size we observed, they are not likely to account for the whole variance between elite and novice athletes. More precisely, we will see below that strategic choices could also mediate part of the differences yielded in that experiment. Although these assumptions are likely to coexist, with various degrees of implication, we will provide herein some reflexive points to support the conceptual view based on our findings.

First, mental rotation performance was not the only variable related to sport level. Movement imagery, assessed through a sport-specific test (the MIST), showed a significant relationship with sport level and positive correlation with the MRT. This is in line with previous research on motor representations and mental rotation, showing that the two are strongly related (Wraga et al., 2003). This idea is directly related to previous work that has shown a relationship between motor action and mental rotation of arbitrary objects (Wexler, Kosslyn & Berthoz, 1998). Furthermore, there is evidence that motor strategies tend to be used to perform mental rotations of non-body objects when a previous task has presented body parts, with activation of motor and premotor cortices during mental rotation tasks when motor strategies were implicitly introduced (Wraga, Thompson, Alpert & Kosslyn, 2003; Kosslyn, Thompson, Wraga & Alpert, 2001). Therefore, engaging motor processes is not automatic in mental rotation but rather triggered by previous tasks motor-related. Thus, one can suppose that elite athletes in combat sports, because of their daily manipulation of particular representations based on rotations, relied on motor imagery more systematically than novices when performing the MRT. In fact, relevant literature on expertise shows that elites might have stored a tremendous number of motor representations, to be retrieved when pertinent cues are presented (Ericsson & Kintsch, 1995; Ericsson & Smith, 2002). Thus, MRT shapes could act like such cues to favor motor strategies. Elites would be primed to engage in motor strategies, with better outcomes than novices. This strategy could be in part equivalent to adding human heads on the top of the objects to rotate (Amorim, Isableu, Jarraya, 2006) or using human figures instead of geometric shapes (Alexander & Evardone, 2008), which have been shown to dramatically improve MRT performance for both males and females.

Subsequent findings favor that hypothesis. Indeed, we observed a gender effect on MRT performance, which means that males performed significantly better than females. This is a well-known effect, as described previously, and our results confirmed previous findings in the field. However, this particular study brings up an interesting twist that is worth discussing. The level of expertise effect was stronger for males than for females, which means that elites-novices differences were greater for males. This might seem surprising, considering that gender differences tend to shrink or to remain stable with practice (Peters et al., 1995). However, the reasons for such an atypical result could simply lie within the amount of sport-specific training they received. Following that idea, our findings show that MRT performance and training amount are strongly related. Thus, elite males are more efficient on mental rotation than elite females probably because they benefited from greater practice. Gender differences seem to depend significantly on differential experience, at least for what can be observed in our particular setting. Altogether, these findings tend to support the assumption that practice mediated mental rotation improvements.

Furthermore, by analyzing elite vs. novice strategies on MRT problems, we provided further answers concerning causes to leading to better performances. Although deeper changes might potentially be involved (such as processes efficiency itself), there is a significant difference between elites and novices on how they proceed to solve the problem. Quite logically, novices were more often doubtful regarding the processes they used. More interestingly, one of the real strengths for elites seems to be an ability to choose between different strategies depending on the item, in line with research on expertise outside spatial ability (Abernethy, Neal, & Koning, 1994; Williams

& Ford, 2008). In short, they saved time and were more efficient by selecting the most suitable strategy for each problem. This result is also consistent with a broader point of view on cognitive strategies acquisition. Indeed, a very general trend of strategy acquisition over childhood consists of a transition from mono to multiple strategy use (Coyle & Bjorklund, 1997; DeMarie, Miller, Ferron, & Cunningham, 2004; Schneider, Kron-Sperl, & Hünnerkopf, 2009; Schwenck, Bjorklund, & Schneider, 2007). In the present study, elite participants showed a strong multiple-strategy use, since they displayed constant flexibility over the strategy used, depending on the particular item presented. Conversely, novices turned out to show less versatility, favoring stability in their strategy uses overtime (see fig. 4).

We should also note that there was no effect of the type of combat sport (in this case, fencing, judo or wrestling) or the geographic background (France or USA) on MRT overall differences, which means that practice types in these three sports and those two countries are somehow similar, at least regarding the cognitive processes involved. Thereby, this last point brings more consistency to the results displayed in this paper.

Although the aim of our work was to better understand cognitive processes in a broad sense, independently from any sport practice, the specific frame we have chosen provided us with interesting possibilities because of the intense training in which athletes were involved. In a sense, these findings add to the already extensive literature on expertise in sports (see for example Memmert, Simons, & Grimme, 2009, on attention and expertise; or Williams, Davids, & Williams, 1999 and Williams & Grant, 1999, on perceptual skills in sport). On a more applied paradigm, it is also legitimate to wonder what can be used outside the research field. We think that our results are probative for a few reasons.

Sports practice seems to enhance mental rotation performance, but one might argue that there are other ways to do so. Various activities can lead to similar results, which raise the present question: can mental rotation improvements be helpful and transferable to other activities? From the results presented in this paper, we believe that spatial abilities improved by sport practice could be used for different tasks and activities, such as other sports, but also in independent fields, such as academic and professional ones. Following that idea, this trend of work helps raise sport practice as a determining factor to build up general and transferable abilities. Since sport might help developing spatial abilities – traditionally thought to be mainly improved by academic-related material – it could provide interesting ideas to governments and public institutions for sports advertising or for training programs designs. Indeed, it might be possible to detect potential cognitive weaknesses that could lead to different problems in sport performance, via appropriate testing. Conversely, we could think of spatial ability tasks as an interesting training complement to physical practice. For that particular purpose, the MIST also appears as an interesting complement to the MRT, because of its explicit focus on sports-related movement imagery and the possibility it offers to create new versions in different activities. Spatial abilities needed in particular areas could be developed through an appropriate practice in sports, or, on the contrary, decisive abilities in sports could be sought elsewhere.

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