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The role of motor processes in three-dimensional mental rotation: Shaping cognitive processing via sensorimotor experience

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ABSTRACT

An extensive body of literature has explored the involvement of motor processes in mental rotation, yet underlying individual differences are less documented and remain to be fully understood. We propose that sensorimotor experience shapes spatial abilities such as assessed in mental rotation tasks. Elite wrestlers' and non-athletes' mental rotation accuracy and response times were measured in three different conditions: mental rotation (a), mental rotation with visual (b) and movement (c) interference. Results showed that both groups were equally affected by the visual interference task, as hypothesized from previous literature. However, the movement interference task impacted tremendously more wrestlers' mental rotation performance. These findings suggest that experts in motor activities rely heavily on motor processes in three-dimensional mental rotation problems solving, thus performing more poorly when simultaneously holding movements. The implications of this work in providing further evidence for the close tie between perceptive, motor and cognitive processes are discussed.

1. Introduction

How does sensorimotor experience influence the involvement of motor processes in mental rotation? In the last few decades, a consistent body of research using experimental, neuropsychological or brain imaging paradigms has focused on the role of motor processes and strategies in performing two and three-dimensional mental rotation tasks such as those presented in Shepard and colleagues seminal work (Cooper & Shepard, 1975; Shepard & Metzler, 1971). A pioneer experiment by Sekiyama (1982) showed that reaction time on a left–right judgment task of two-dimensional hand drawings presented in different orientations was deeply affected by anatomical constraints, underlining the close relationship tying mental rotation of body parts and motor processes. These results were subsequently confirmed by Parsons (1987) using hands and feet stimuli, and via complementary behavioral findings (Georgopoulos & Massey, 1987; Pellizzer & Georgopoulos, 1993), providing solid foundations for subsequent work in the field. Neuroimaging studies have since comforted these findings, emphasizing the activation of cortical areas involved in the control of hand movement in mental rotation and implicit movements of hands (Bonda, Petrides, Ostry, & Evans, 1995; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; Lang, Cheyne, Hollinger, Gerschkager, & Lindinger, 1996, Lang et al., 1994; Parsons & Fox, 1998; Porro et al., 1996).

However, all that trend of research has concerned exclusively mental rotation of body parts. A critical step toward a comprehensive understanding of the relationship between mental rotation and motor processes was taken by Wohlschäger and Wohlschläger (1998). Using the Shepard–Metzler type of stimuli, they found that hand movements facilitated simultaneous mental rotation when the direction matched the rotation, whereas performance decreased when actual and mental rotations were incompatible. Thus, they concluded that motor processes were not solely involved in body parts rotation, but also in the manipulation of abstract objects. Similar work by Wexler, Kosslyn, and Berthoz (1998) found that reaction time was shorter and error rate lower in a two-dimensional mental rotation task when a simultaneous manual rotation was congruent. Nevertheless, the facilitating movement does not necessarily have to be a rotation to increase congruent mental rotation performance. Schwartz and Holton (2000) found that three-dimensional mental rotation can also be facilitated with a straightforward pulling movement resulting in the rotation of an object. From these results, they concluded that motor facilitation in mental rotation involves a cognitive model including spatial and non-spatial features.

Although the link between mental rotation and motor processes has received a lot of corroborating work and is not to be disputed, the studies reported above found significant differences in the use of motor strategies, both between subjects as well as within subjects throughout trials. Individuals seem not to apprehend mental rotation tasks uniformly. What could be the underlying factors responsible for such differences? Could previous motor experience be decisive in the way mental rotation tasks are perceived, and particularly in the

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recruitment of motor processes? Individual differences can—among other factors—explain some of the discrepancies found between studies concerning the involvement of primary motor cortex in mental rotation (Hodge, Dubroff, Huckins, & Szeverinyi, 1996; Kosslyn et al., 1998; Roth et al., 1996; Sabbah, Simond, Levrier, & Habib, 1995; Schnitzler, Salenius, Salmelin, Jousmaki, & Hari, 1997). In an elegant experiment, Wraga et al. found that performing a prior mental rotation task involving hands led to activation of motor cortical areas (BA 6 and M1) in a subsequent mental rotation task of abstract (non-body) items, whereas prior mental rotation task on abstract objects did not (Wraga, Thompson, Alpert, & Kosslyn, 2003). They concluded that motor strategies were covertly transferred to the mental rotation of non-body objects. This finding is truly enlightening; as it means that differential experience has immediate consequences on the use of motor processes in mental rotation. Could that phenomenon be extended to a less immediate or less direct set of actions? Could previous motor experience be of significant influence on mental rotation ability?

The starting point of the present experiment is based on the idea that covert transfer of motor strategies shown by Wraga et al. from a body-based task immediately prior to mental rotation (Wraga et al., 2003) could be permanent in individuals whose motor practice has been consistent over a long period of time. In order to address this issue, elite athletes appear to be a suitable population, for two main reasons. First, elites have spent many years—typically more than ten—practicing, rehearsing and correcting motor skills, reaching a high degree of expertise in order to be able to adapt to any given situation that may arise in a competitive environment. This has contributed to develop elites' motor system to a point that meets no match among non-athletes. Second, for most athletes, the time dedicated over the years to practicing motor skills has prevented them from allocating a substantial amount of time to other activities that could improve significantly mental rotation ability. This last point allows considering more comprehensively important confounding variables. Thereby, the participants of this study included non-athletes and elite athletes practicing Olympic wrestling, an activity that has proven to stimulate mental rotation ability enhancement in previous studies (Moreau, Clerc, Mansy-Dannay, & Guerrien, 2012; Moreau, Mansy-Dannay, Clerc, & Guerrien, 2011).

Mental rotation tasks typically involve the manipulation and the retention of abstract figures, in order to compare pairs of stimuli. In that process, the involvement of motor components allows converting abstract allocentric figures, defined relative to the location of other objects, into body-based egocentric objects, defined relative to body axes, thus facilitating the treatment of information required by the task. Consistent motor experience, such as induced from wrestling practice, could prime the transformation of stimuli from abstract to motor objects, leading to noise reduction and higher overall performance.

Therefore, assuming that sensorimotor experience shape the subsequent pattern of motor processes recruited in mental rotation tasks, elite wrestlers should be more likely than non-athletes to engage motor resources in this type of tasks. Thus, a concurrent task that requires holding movement patterns simultaneously should lead to a greater decrease in mental rotation performance for elite wrestlers—who supposedly rely heavily on motor processes while performing mental rotation—than for non-athletes. Moreover, Hyun and Luck (2007) found that mental rotation tasks rely greatly on object working memory (including visual features such as color and form), but not on spatial working memory (encompassing elements such as positions in space). Following their findings, holding objects in working memory via a concurrent task that focuses on visual content should disrupt a simultaneous mental rotation task and decrease performance. However, the visual span task is not expected to affect the two groups differently, since previous neuroimaging studies found no decrease in cortical parietal activations even for individuals that rely heavily on motor areas in mental rotation (Abbruzzese, Trompetto, & Schieppati, 1996; Ersland et al., 1996).

2. Method

2.1. Participants

A total of 44 participants with normal or corrected-to-normal vision took part in the study (11 female; 36 right-handed; $M = 24.5$ years; range 18–38 years; $SD = 6.45$). None of them had prior exposure to mental rotation or interference tasks such as those used in the present study, or played videogames on a regular basis, since this activity has been linked to higher mental rotation ability (Boot, Kramer, Simons, Fabiani, & Gratton, 2008; De Lisi & Wolford, 2002; Feng, Spence, & Pratt, 2007). They were not paid for their participation. The study was conducted in accordance with the American Psychological Association Ethical Guidelines and with the Helsinki Declaration of 1975.

The expert group consisted of 18 athletes (4 female, $M = 24.3$; $SD = 4.22$), who were elites in Olympic wrestling. The inclusion criterion for this group was to hold at least one selection in an international event at the time of the experiment. The control group consisted of 26 participants (7 female, $M = 24.6$; $SD = 7.14$), who were not practicing any sport or physical activity on a regular basis. They had various athletic backgrounds, none of which could be qualified as regular practice in any physical activity (sustained at least over a few months).

2.2. Design and procedure

Participants performed a computerized three-dimensional mental rotation task in three different experimental conditions: (a) Without concurrent task; (b) While performing a visual interference task; (c) While performing a movement interference task. Thus, conditions (b) and (c) used dual-task paradigms. In order to avoid differences rising from unequal sensitivity to the tasks, the order of each condition (a, b, c) was counterbalanced using a randomized presentation, for a total of six different versions of the whole block.

The experimental procedure was designed using E-Prime software and Java script editors. Participants sat approximately 70 cm away from a 17 in. computer screen. Each trial began with a two-second presentation of paired three-dimensional figures. To ensure that participants attended adequately to the interference items in conditions (b) and (c), the mental rotation response was gathered in each trial only in the case of a correct interference task response. Mental rotation accuracy was subsequently quantified as percent correct.

2.2.1. Mental rotation task

The three-dimensional rotation task used in all conditions (a, b, c) was based on Shepard and Metzler original stimuli (Shepard & Metzler, 1971). Participants had to distinguish between rotated and mirror-reversed images of three-dimensional geometric shapes presented by pairs ($N = 25$). The target figure, on the left of the screen, was presented at a randomly-generated orientation, whereas the figure on the right was either a match or a mirror-image rotated by 45°, 90°, 135°, or 180°. For each trial, both stimuli were visible until participants responded. Participants responded by pressing a key with the index (response: 'same') or middle finger (response: 'different') of their dominant hand. Accuracy and response time were recorded for each trial. In condition (a), mental rotation was the only task presented. No interference task was used (Fig. 1a).

2.2.2. Visual span interference task

In condition (b), participants were asked to perform the previously described mental rotation task while carrying out a visual simple task (Fig. 1b). The latter consisted of a pattern of gray-shaded cells

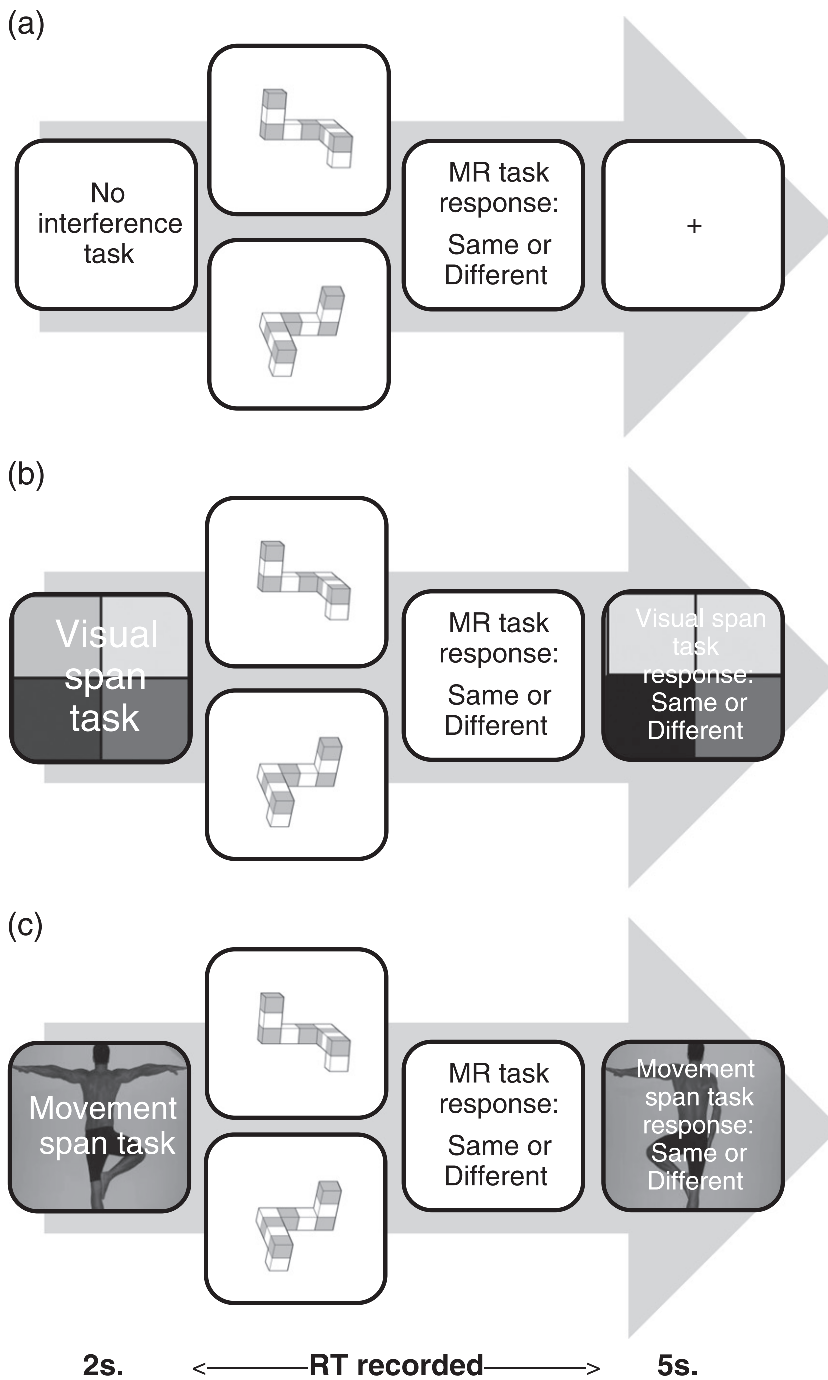

Fig. 1. Example stimuli and procedures used in conditions (a): no interference task, (b): visual span interference task, and (c): movement span interference task.

in a 2 × 2 grid with four different hues to memorize, generated from a palette of six possibilities. A new target pattern was presented for 2 s. before each pair of mental rotation stimuli, which matched (50%) or did not match (50%) a subsequent pattern presented for 5 s. after the mental rotation response. Thus, new visual material had to be held over each mental rotation trial in this condition. Participants responded first to the mental rotation task by pressing a key with the index (response: 'same') or middle finger (response: 'different') of their dominant hand, and then to the visual interference task using the same key combination. Accuracy (in both tasks) and response time (in the mental rotation task) were recorded for each trial.

2.2.3. Movement span interference task

In condition (c), participants were asked to perform the mental rotation task while carrying out a movement simple span task (Fig. 1c). The latter consisted of picture-presented material involving body configurations with four cues (limb positions) to memorize. A new target item was presented for 2 s. before each pair of mental rotation stimuli, which matched (50%) or did not match (50%) a subsequent pattern presented for 5 s. after the mental rotation response. Thus, new movement material had to be held over each mental rotation trial in this condition. Participants responded first to the mental rotation task by pressing a key with the index (response: 'same') or middle finger (response: 'different') of their dominant hand, and then to the movement interference task using the same key combination. Accuracy (in both tasks) and response time (in the mental rotation task) were recorded for each trial.

3. Results

A 2 (motor expertise) × 3 (conditions) factorial ANOVA with repeated measures on the last factor showed significant main effects of motor expertise (wrestlers, controls) and condition (MR, MR + visual, MR + movement) on accuracy ($F(1,42) = 8.49$, $p < .01$, $\eta^2 = 0.17$; and $F(2,84) = 131.31$, $p < .001$, $\eta^2 = 0.76$, respectively, see Fig. 2). The same analysis performed on response time showed a similar trend with significant main effects of motor expertise ($F(1,42) = 9.86$, $p < .001$, $\eta^2 = 0.19$) and condition ($F(2,84) = 79.16$, $p < .001$, $\eta^2 = 0.45$), after wrong answers were partialled out (Fig. 2).

The interaction between expertise and conditions was also significant ($F(2,84) = 59.72$, $p < .001$, $\eta^2 = 0.59$), pointing out differential effects of expertise on the three conditions. Simple effects showed a significant effect of expertise for MR and MR + visual conditions ($F(1,40) = 22.15$, $p < .001$, $\eta^2 = 0.36$ and $F(1,40) = 22.10$, $p < .001$, $\eta^2 = 0.35$, respectively) but not for MR + movement ($F(1,40) = 2.77$, $p = .104$, n.s., $\eta^2 = 0.06$). Further details concerning the pattern of means that contributes to the significant interaction are provided below.

Post hoc analyses (Newman–Keuls) indicated that average accuracy and response time were significantly poorer in the visual (wrestlers: 65.8%, 1204 ms; control: 52.8%, 1462 ms) and the movement (wrestlers: 55.1%, 1375 ms; control: 59.7%, 1298 ms) interference conditions than in the MR-alone condition (wrestlers: 76.9%, 979 ms; control: 64.9%, 1124 ms), for both wrestlers and non-athletes ($p < .001$, in each case), which shows that holding visual or movement items had a negative effect on MR problems solving. When compared across groups of motor expertise, however, results indicated that both groups were equally affected by the MR + visual condition, whereas the MR + movement condition had a different impact on one group or the other ($p < .001$). That is, wrestlers performed more poorly and slowly in the MR + movement condition than in the MR + visual condition, whereas the converse was true for non-athletes ($p < .001$, in all cases). This result points out the differential interference effect of holding movement items in memory while performing a MR task, namely, substantial for wrestlers and weaker for non-athletes.

To discard discrepancies in interference task difficulties or in levels of processing, we isolated retrieval of interference items in the MR + visual and the MR + movement conditions. When comparing the average number of correct discriminations for the visual ($M = 22.57$, $SD = 1.68$) and the movement ($M = 22.25$, $SD = 1.53$) tasks alone within the visual interference and the movement interference conditions, we found no significant differences ($t(43) = 1.40$; $p = .17$). Thus, the differential effect of motor experience observed on the two interference tasks can not be attributed to disparities in condition difficulty or in individual processing levels. Moreover, a one-way ANOVA on the correct responses in the visual and the movement interference tasks with Motor Expertise as a factor showed that wrestlers and controls yielded no significant differences in interference retention ($F(2,41) = 2.33$, $p = .110$, n.s., $\eta^2 = 0.10$).

In order to further understand the role of motor processes in MR, we analyzed mental rotation differences within the control group. When high and low MR performers were separated in a 2 (High MR, Low MR) × 2 (MR + visual, MR + movement) factorial ANOVA with repeated measures on the last factor, we found a significant main effect of MR performance on interference conditions ($F(1,24) = 18.69$, $p < .001$, $\eta^2 = 0.44$), but no significant interaction, in contrast with the pattern observed initially between wrestlers and controls. Thus, as opposed to the prior distinction between wrestlers and controls, high and low MR performers within the control group were not affected differently by a movement interference task.

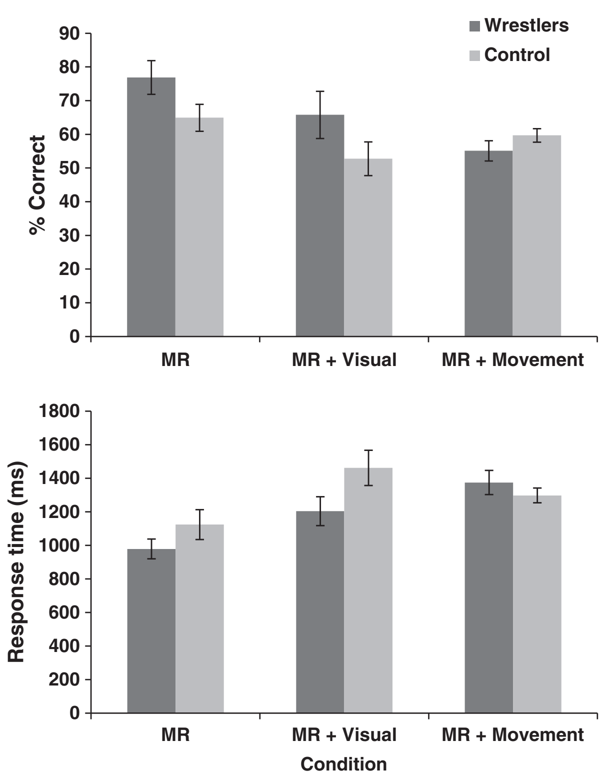

Fig. 2. Mean mental rotation (MR) accuracy and response time data for each condition (MR alone, MR and visual interference task, MR and movement interference task). Error bars represent 95% confidence intervals.

4. Discussion

The aim of this study was to better understand how sensorimotor experience shape subsequent processing in a spatial ability task. To that purpose, athletes and non-athletes (controls) took a mental rotation computerized task, with different conditions including two Working Memory (WM) span interference tasks (object- and movement-based). Previous findings showing an effect of expertise in wrestling on mental rotation performance were confirmed (Moreau et al., 2011). Wrestlers showed higher performance than controls in the mental rotation task when no concurrent task was present. These data add to a growing amount of literature linking motor expertise and mental rotation ability (Jansen, Titze, & Heil, 2009) or perspective-taking (Steggemann, Engbert, & Weigelt, 2011), and are consistent with work showing the activation of cortical motor areas in mental rotation of abstract objects (Hodge et al., 1996; Kosslyn et al., 1998; Roth et al., 1996; Sabbah et al., 1995; Schnitzler et al., 1997).

A potential explanation for such differences lies within individual differences in motor strategies. PET studies by Kosslyn et al. (1998) and Wraga et al. (2003) showed that motor strategies—resulting in activation of motor and premotor cortices—tend to be transferred implicitly to perform mental rotations of abstract objects when a previous task has presented body parts. Engaging motor processes seems not to be automatic in mental rotation but rather triggered by previous tasks motor-related. We proposed that elite wrestlers, because of the daily manipulation of motor representations based on rotations, rely on motor processes more systematically than novices when performing mental rotation tasks. This would be coherent with recent work by Chu and Kita (2011) which showed that strategies in solving mental rotation problems can be divided in three stages. The authors argue that these levels are attained through expertise and internalization of spontaneous gestures. Thus, it is possible that elite wrestlers, due to an extensive motor background, did not start at the first or the second level and could rapidly reach third-stage strategies that normally require internalization through mental rotation practice.

The data gathered in the three conditions confirm the initial hypothesis. Performance in mental rotation decreased dramatically when a visual span task was carried simultaneously. The concurrent task affected equally wrestlers and controls, confirming the hypothesis that both groups rely greatly on visual (object-based) processes to carry out mental rotation of abstract shapes. Visual WM seems to be decisive in maintaining figures properties while performing rotation, in order to distinguish between matching or not-matching responses. This finding provides further evidence for a decisive role of visual WM in mental rotation task (Hyun & Luck, 2007).

However, performing simultaneously a movement-based WM task had different consequences depending on the group considered. As such, mental rotation performance was negatively altered by the movement interference task in both groups, but this effect was much stronger in wrestlers. In fact, this effect was so large that mental rotation performance did not differ significantly from one group to the other only in the movement interference condition. Thus, elite wrestlers tended to rely more heavily on motor processes when performing mental rotation of abstract objects. When the interference weakened the possibility to rely on motor processes effectively, performance in mental rotation decreased. Non-athletes performance did not suffer from the interference task to the same extent, because they relied mainly on visual storage to carry out mental rotation. This finding also means that WM span for movements did not increase with practice in athletes. If it did, they would have been able to maintain their performance above control's level. Thus, the span itself seems to remain constant, which is consistent with WM capacity literature for various types of items (see Cowan, 2005, for a review).

Interestingly, our results are also consistent with Logie's differentiation between the visual cache, passive store holding information about color and form, and the inner scribe, an active rehearsal component dealing with spatial relations and movement (Logie, 2011; Logie & Pearson, 1997). Thus, it is possible that both the mental rotation and the visual interference tasks tap into the same component (i.e. visual cache), whereas the mental rotation and the movement interference tasks involve mainly the visual cache and the inner scribe, respectively. However, motor experience might have let to a gain in efficiency within the inner scribe, allowing this component to handle tasks that are normally dealt with by the visual cache. In short, the use of motor strategies in mental rotation could have increased wrestlers processing efficiency, to the detriment of parallel movement processing. This could explain the larger movement interference effect in wrestlers than in controls.

We should note, however, that our results contrast with Steggemann et al. findings, which showed facilitation from motor expertise in perspective but not object-based transformations (Steggemann et al., 2011). More specifically, these authors found a significant motor expertise effect in left–right but not same–different judgment tasks. However, two important aspects of Steggemann et al. research make it hardly comparable with the present experiment. First, they assessed mental rotation via two-dimensional items, which has been shown to differ significantly from three-dimensional mental rotation (Elman et al., 2008; Kawamichi, Kikuchi, Noriuchi, Senoo, & Ueno, 2007). Second, various motor activities involving different skills and abilities were aggregated into a single group to be compared with non-athletes, procedure which allowed comparing larger samples but might raise ecological concerns. These remarks undermine by no means the excellent work they conducted, but help understand the discrepancies between their results and the present experiment.

Within the control group, further distinction between high and low MR performers showed a more classic pattern of results, highlighting the comparable effect of initial MR performance on both interference conditions. High MR performers displayed a large superiority in all conditions, and a constant difference from low MR performers regardless of the interference condition considered. Thus, discrepancies in performance seem not related to the involvement of motor strategies. This finding emphasizes the diversity of potential strategies in MR, the differences within the general population being influenced by many competing factors. Motor experience in wrestling influence MR problem-solving, yet diverse activities may impact performance in such complex spatial ability tasks (see Hegarty & Waller, 2005, for a review).

It should be acknowledged, though, that one could propose an alternative explanation to this set of data. Elite wrestlers, because of their expertise in coding movements, could have processed and stored more details about the motor actions that were presented in the movement interference task, thus leading to saturation of WM span for movements and a decrease in MR performance. This is different from the explanation provided above in a sense that wrestlers would be more largely affected by the movement interference task because of a more sophisticated level of processing—instead of competitive resources— resulting in an increased difficulty of the task. However, this alternative is unlikely for two main reasons.

First, the movements presented a limited degree of complexity, in a sense that understanding the body segmentations displayed in the task did not require prior motor skill acquisition. Thus, the idea of major individual differences in the levels of processing this kind of task is rather improbable. In fact, converse effects could be argued as well, as a higher level of motor expertise could lead to more efficient chunking strategies, due to movements' expertise, which in turn would allow better subsequent discrimination. These alternatives are likely to be confirmed in domain-specific settings, that is, in a wrestling-related environment in the present case, rather than in general situations pictured in the body configurations of the present interference task.

A second observation, backed up by the data, support this view. Wrestler and control groups did not display any significant differences in visual and movement interference accuracy, which shows that the detrimental effect of the movement interference on MR performance in wrestlers did not come from more sophisticated encoding of movements, as this would result in a more accurate movement discrimination. Consequently, wrestlers would have performed better on the interference component of the MR + movement condition. Furthermore, similarities in visual content discrimination comforted the previous assumption stating that holding visual content in WM should disrupt both groups equally due to comparable processing.

With this in mind, it also seems necessary to point out that the movement interference task requires visual processing, since the presentation modality is via picture media. One could argue that the movement WM task is visual, and that the dissociation between visual and movement WM is not clear-cut. However, the pattern of results obtained showing similar interference for both groups in the visual interference task, but not in the movement interference task, indicates that the two systems seem significantly dissociable from each other, in line with a substantial amount of literature in the field (see Logie, 2011, for a comprehensive review). Besides, the choice to present movements visually in this experiment comes from ecological considerations about motor activity in sports and everyday life. In most situations outside the laboratory, information concerning movements is mainly conveyed through the visual system. Further work should complement these findings using passive movement modality, for example, in order to compare results and refine the present discussion.

In conclusion, three-dimensional mental rotation appears to rely differently on motor processes depending on individual sensorimotor experience. This finding complements the idea that motor processes are involved in mental rotation, showing the importance of prior experience in the study of differences across individuals. Altogether, these results provide further evidence to underline the influence of body interactions on cognitive functioning, and emphasize the interrelation between perceptive, motor, and cognitive processes.

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