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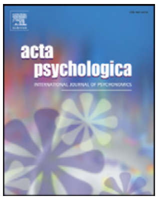

Motor expertise modulates movement processing in working memory

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ABSTRACT

A substantial amount of literature has demonstrated individuals' tendency to code verbally a series of movements for subsequent recall. However, the mechanisms underlying movement encoding remain unclear. In this paper, I argue that sensorimotor expertise influences the involvement of motor processes to store movements in working memory. Experts in motor activities and individuals with limited motor expertise were compared in three experimental conditions assessing movement recall: (a) without suppression task, (b) with verbal suppression, and (c) with motor suppression. Athletes outperformed controls in movement recall, but the suppression tasks affected the two groups differently. Verbal suppression affected controls more than athletes, whereas the effect was reversed with motor suppression. Together, these findings suggest that controls and athletes favor different mechanisms to encode movements, either based on verbal or on motor processes, providing further evidence for a tight relationship between sensorimotor and cognitive processes.

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1. Introduction

In the working memory literature, dual-task paradigms based on interference or suppression tasks have often been used to demonstrate dissociations between processing components. This approach takes advantage of the limited capacity of the working memory system (Cowan, 2001; Miller, 1956), in order to establish distinctions between components tapping into different resources, while providing corroborating evidence for shared processes among tasks involving competing resources. Originally, the separation between verbal and visuospatial domains within the multi-component model of working memory arose from carefully designed dual-task experiments, inspired by neuropsychological observations (see for reviews Logie, 1995; Repovs & Baddeley, 2006). Within the visuospatial domain, myriad of experimental findings (Baddeley, 1996; Klauer & Zhao, 2004; Logie, 1986; Logie, Zucco, & Baddeley, 1990) and neuropsychological findings (Baddeley, Della Sala, & Spinnler, 1991; De Renzi & Nichelli, 1975; Shallice & Warrington, 1970) have established further fractionation into visual and spatial components. For example, Della Sala, Gray, Baddeley, Allamano, and Wilson (1999) showed that spatial interference disrupts performance on the Corsi Block Test (Corsi, 1972), a task that requires memorizing sequences of spatial locations on a board, but not on the Visual Patterns Test (Della Sala, Gray, Baddeley, & Wilson, 1997), which consists of visual displays to remember with no sequencing required. In contrast, visual interference had the opposite effect, disrupting performance on the Visual Patterns Test but not the Corsi Block Test.

Consistent with these findings, Logie has proposed a distinction between the visual cache, a 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). Furthermore, recent evidence has pointed out that the visual–spatial distinction might be better characterized in terms of a distributed network, rather than separated and unitary components (Zimmer, 2008). Additional work using dual-task paradigms has also proposed a distinct system to handle movements, with an additional separation between configured movements and movements to spatial targets (Smyth & Pendleton, 1989, 1990). In an impressive series of experiments designed to further understand action processing in working memory, Wood showed that working memory for observed actions can be distinguished from working memory for object and spatial content (Wood, 2007, 2011). Although research exploring working memory for movements and its relation with other working memory components is growing, caveats remain concerning the underlying theoretical models and their capacity to adequately explain experimental data (Quinn, 2008).

Related research has pointed out the critical role of verbal strategies to store movements in working memory. In a series of experiments involving undergraduate students, Helstrup (2000) found a propensity for using verbal strategies to encode movements serially. After participants were instructed to adopt a verbal, spatial or motor strategy in a within-subject design, they were presented with successive movement patterns to remember. These conditions were compared with a baseline

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recall in which the encoding strategy was not constrained. Results showed that apart from the unconstrained condition, recoding movements verbally was the most efficient strategy. Explicit motor encoding, thought to be based on motor imagery, led to the poorest performance of all conditions. Developing on this idea, a study by Frencham, Fox, & Maybery (2004) explored how verbal labeling affects movement recall. In two experiments, three conditions—baseline, congruent labels and incongruent labels—were compared. The authors found that congruent labeling enhanced recall relative to baseline, whereas incongruent labeling had a negative effect on further recall. They concluded that verbal recoding was the strategy naturally favored by participants, and that it could be enhanced via appropriate labels. Altogether, these findings suggest that individuals spontaneously recode a series of movements verbally, rather than spatially or motorically.

Exploring further the relationship between motor and verbal components, Weigelt and colleagues studied the effect of a reaching movement on verbal recall (Weigelt, Rosenbaum, Huelshorst, & Schack, 2009). Participants had to manually retrieve cups from a column of drawers and memorize the letters written inside the cups. The authors found that the classical recency—but not the primacy—effect was eliminated by motor manipulation inherent to letter retrieval, and concluded for tight links between motor control and higher-order processing. Consistent with these findings, a subsequent study showed that re-planning an intended action reduced letter recall performance, and that the planning stage of a grasping movement, but not execution, shared common cognitive resources with verbal working memory (Spiegel, Koester, Weigelt, & Schack, 2012).

Whether in the verbal or the motor domain, interference effects seem to differ depending on expertise levels. In a study comparing trained interpreters and language teachers, Christoffels and colleagues demonstrated that memory capacity is a critical feature related to high proficiency in language interpreting, suggesting that high verbal span is related to expertise in this field (Christoffels, de Groot, & Kroll, 2006). Similarly, Smyth and Pendleton (1994) showed better recall of a dance routine for professional ballet dancers than for non-dancers. Interestingly, this effect was also found on movements unrelated to dance, indicating that the mechanisms that allow superior encoding of movements were not restricted to the field of expertise. Overall recall of dance movements was not superior to this of unrelated movements in dancers, in contrast with traditional views leaning toward a domain-specific advantage (see for a review Starkes & Allard, 1993). Furthermore, both articulatory and movement suppression tasks interfered with dancers' spans.

One particular issue that was not investigated in the study by Smyth and Pendleton, however, is whether motor experts rely on different resources than novices to encode a set of movements. Using dual-task designs, recent experimental evidence indicated that elite athletes favor motor processes when performing a mental rotation task, whereas non-athletes treat the same stimuli as visual (Moreau, 2012). In this experiment, however, high and low mental rotation performers within the group of non-athletes were not affected differently by a movement interference task, suggesting that motor strategies were not a factor mediating differences among individuals with limited motor expertise. These findings suggest an experience-based embodied mechanism in cognition, potentially varying along a continuum rather than in an all-or-none fashion. Thus, sensorimotor experience can shape the involvement of motor processes in cognitive reasoning, in line with recent research in the field of neuroplasticity emphasizing the structural and functional adaptability of the neural system throughout the lifespan (van Praag, Kempermann, & Gage, 2000).

The above experiment (Moreau, 2012) did not, however, specify how motor expertise modulates the processes and strategies involved in movement recall itself. As motor learning relies on repeated associations between movement control and its outcomes, trained individuals build motor representations that allow sustained performance at a high level (Schack & Mechsner, 2006). In their field of expertise, stored representations lead to efficient identification of one's or others' body configurations (Bläsing & Schack, 2012; Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005), to facilitate appropriate actions integrated within space and time constraints. As a result, does extensive experience dealing with movement configurations lead elite athletes to encode movements motorically, rather than verbally? And if so, is this process restricted to movements related to the field of expertise or does it transfer to unfamiliar motor coordination? In broader terms, does sensorimotor experience influence the way we store and process general motor patterns?

The aim of the present experiment was to provide answers to these questions. To that purpose, motor experts and non-experts were selected to participate in an experiment assessing memory span for movements, including verbal and motor suppression tasks. Because motor expertise has been related to better movement recall in previous studies (Dijkstraa, MacMahon, & Misirlisoy, 2008; see also Bläsing et al., 2012, for a review), experts were expected to recall movements more efficiently than non-experts. Following the hypothesis of predominant motor strategies for elite athletes and verbal strategies for non-athletes, converse effects of expertise were expected on both suppression conditions, namely greater decrease in recall for athletes when exposed to motor suppression, and greater decrease in recall for controls in the verbal suppression condition.

2. Method

2.1. Participants

A total of 36 participants with normal or corrected-to-normal vision consented to the present experiment (18 females; 32 right-handed; $M = 22.5$ years; range 18–27 years; $SD = 2.47$). 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 (9 female, $M = 22.8$; $SD = 2.53$), who practiced wrestling at elite level, as this activity has shown to induce embodied strategies in spatial reasoning tasks (Moreau, Mansy-Dannay, Clerc, & Guerrien, 2011). The inclusion criterion for this group was to hold at least one selection in a national or international event at the time of the experiment. The control group consisted of 18 participants (9 female, $M = 22.3$; $SD = 2.44$), who did not practice any sport or physical activity on a regular basis. Although controls had various athletic backgrounds, none of these qualified as regular practice in a given physical activity, defined as being sustained at least over a month. This lack of commitment prevented them from acquiring substantial expertise in a single physical activity. None of the participants played a musical instrument.

2.2. Material and procedure

Participants performed a movement recall task in three different experimental conditions: (a) without suppression; (b) with verbal suppression; (c) with motor suppression. Thus, conditions (b) and (c) used dual-task paradigms. Condition (a) was performed first for all participants. The presentation order of conditions (b) and (c) was counterbalanced across subjects. Pictures of static bodies were used for all conditions of the experiment, as they have been shown to induce motor processing in previous studies (Güldenpenning, Koester, Kunde, Weigelt, & Schack, 2011; Moreau, 2012).

The experimental procedure was designed using E-Prime 2.0 (©Psychology Software Tools, Inc., 2010) and Java script editors. Participants sat approximately 70 cm away from a 17-inch computer screen. An example-trial for each of the three conditions is presented in Fig. 1.

2.2.1. No-suppression condition

Twenty sequences of six pictures depicting body movements were generated from a pool of 28 stimuli created for the experiment. The

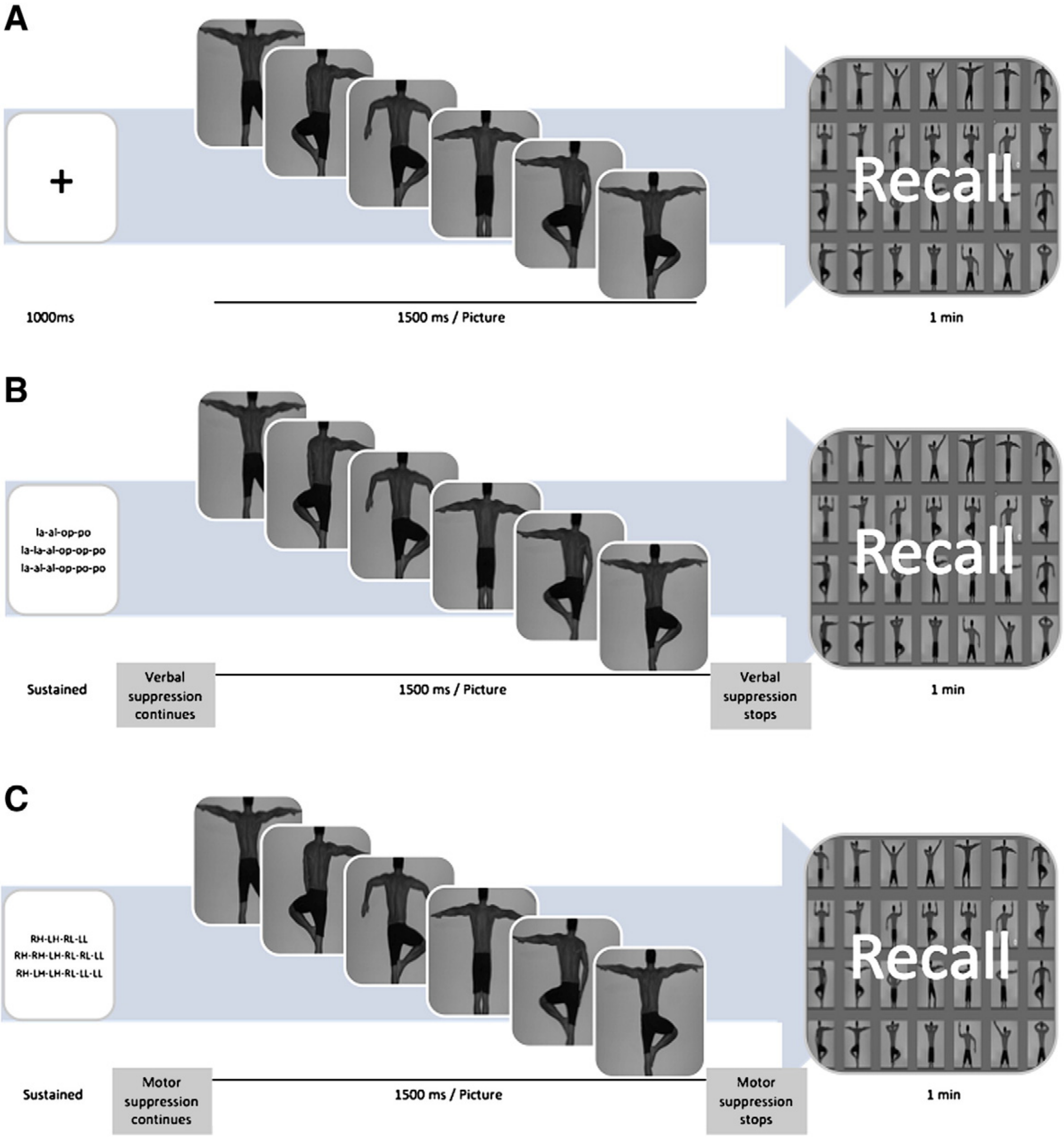

Fig. 1. Example stimuli and procedures for the three experimental conditions: (A) no-suppression condition, (B) verbal suppression condition, and (C) motor suppression condition. Each example depicts one trial. The experiment consisted of 20 trials in each condition.

movements consisted of a combination of arm and leg positions. After a blank screen displaying a fixation cross, each picture appeared on the screen for 1500 ms, in a randomized presentation except for the exclusion of two identical items following each other. After the last item was presented, participants had 1 minute to recall the sequence in order, by pointing the corresponding body movements on a screen displaying the 28 pictures included in the experiment in a randomized order. This condition provided baseline scores for both groups of expertise. Scoring was serial, with one point credited only if both the movement and the order were accurate. Scores were subsequently converted into averages per sequence.

2.2.2. Suppression conditions

The suppression conditions included the movement span task described above, with an additional interference task. Prior to stimuli presentation, participants were asked to either start repeating a verbal pattern (verbal suppression condition) or producing a motor sequence (motor suppression condition), until the entire sequence of six movements had been presented.

The suppression patterns were based on a drumming drill known as the single paradiddle. In the verbal suppression condition, the pattern was the following:

[la-al-op-po]
[la-la-al-op-op-po]
[la-al-al-op-po-po]

In the motor suppression condition, coding right hand (RH), left hand (LH), right leg (RL), and left leg (LL), participants were instructed to tap the tips of their hands and feet alternately in the following sequence:

RH-LH-RL-LL
RH-RH-LH-RL-RL-LL
RH-LH-LH-RL-LL-LL

The suppression patterns were rehearsed before starting each condition to ensure participants understood the design and could perform it accurately. The testing session started when participants could repeat the pattern three times consecutively without errors, at a frequency of one syllable or movement per s., synchronized with a digital metronome. The metronome was present throughout the entire testing session to provide participants with timing referential and to control for accuracy. Participants were instructed to sustain the suppression pattern throughout the series, until the recall display of 28 pictures was presented. From that moment, they could stop concurrent rehearsal and respond by pointing on the screen the movements of the series. The importance of keeping the suppression task accurate at all times throughout the 20 series was emphasized, and non-accurate trials were excluded from the analyses (<5%). Scoring was identical to the no-suppression condition.

3. Results

I report here a 2 (expert, control) × 3 (no suppression, verbal suppression, motor suppression) mixed factorial ANOVA with repeated measures on the last factor. Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(2) = 17.50$, $p < .001$), therefore the initial degrees of freedom were corrected using the Greenhouse–Geisser estimates of sphericity ($\varepsilon = .71$). The p-values reflect these changes.

The analysis revealed a significant interaction between expertise and condition ($F(1.42,48.17) = 21.21$, $p < .001$, $\eta_p^2 = .38$), underlining differential effects of expertise on the three conditions (Fig. 2). Simple effects of expertise at each level of condition showed better recall for athletes without interference and with verbal suppression ($F(1,34) = 10.98$, $p < .01$, $\eta_p^2 = .24$; $F(1,34) = 38.82$, $p < .001$, $\eta_p^2 = .53$, respectively), but no difference in the motor suppression condition.

Additional analyses were subsequently conducted to assess performance decreases from the no-suppression condition to the suppression conditions. A 2 (expert, control) × 2 (no suppression, verbal suppression) mixed factorial ANOVA with repeated measures on the last factor showed a greater decrease for controls than for athletes from no suppression to verbal suppression (respectively 0.63 item/sequence vs. 0.19 item/sequence; $F(1,34) = 20.28$, $p < .001$, $\eta_p^2 = .37$), which suggests that controls rely more extensively on verbal encoding. A simple effects analysis indicated that both controls' and athletes' performance dropped from the no-suppression to the verbal suppression condition ($F(1,17) = 68.71$, $p < .001$, $\eta_p^2 = .80$ and $F(1,17) = 9.31$, $p < .01$, $\eta_p^2 = .35$, respectively). By contrast, a 2 (expert, control) × 2 (no suppression, motor suppression) mixed factorial ANOVA with repeated measures on the last factor showed a greater decrease for athletes than for controls from no suppression to motor suppression (respectively 1.09 item/sequence vs. 1.65 item/sequence; $F(1,34) = 12.11$, $p < .01$, $\eta_p^2 = .26$), which suggests that athletes rely more extensively on motor encoding. A simple effects analysis indicated that both controls' and athletes' performance dropped from the no-suppression to the motor suppression condition ($F(1,17) = 136.77$, $p < .001$, $\eta_p^2 = .90$ and $F(1,17) = 158.99$, $p < .001$, $\eta_p^2 = .89$, respectively). Thus, the recall advantage for motor experts persisted from the simple movement recall to the verbal suppression condition, but vanished in the motor suppression condition, indicating that controls favor verbal encoding whereas athletes favor motor processes to encode movements.

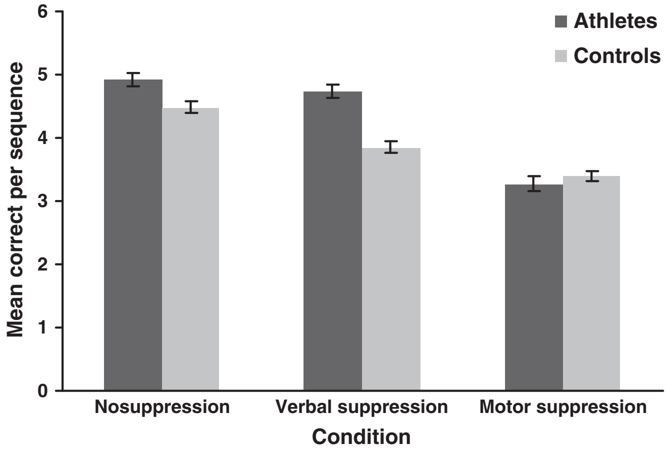

Fig. 2. Athletes and controls movement span mean item recall in the three experimental conditions. Error bars represent standard error of the means. All differences are significant ($p < .05$; dependent and independent samples), except for the difference between athletes and controls in the motor suppression condition.

Athletes performed better than controls in the no-suppression condition. Therefore, it is possible that the differential effect observed when introducing suppression tasks was due to differences in memorizing ability. To discard this possibility, ANCOVAs using no-suppression performance as covariates were conducted for each suppression task. Consistent with the results reported previously, the analyses showed main effects of expertise, even after initial performance was controlled for (verbal suppression condition: $F(1,33) = 23.43$, $p < .001$, $\eta_p^2 = .41$; whereas the effect was non-significant for motor suppression condition: $F(1,33) = 3.20$, $p = .083$, $\eta_p^2 = .09$).

4. Discussion

The aim of the present experiment was to specify how motor expertise influences the involvement of motor processes in a movement recall task. To investigate this issue, athletes and controls performed a body movement memory task, in the face of verbal and motor interference. Athletes showed higher performance than controls when no suppression task was used, which suggests that motor expertise in movement encoding extends beyond practiced movements. As such, this finding confirms previous studies (Dijkstraa et al., 2008; Smyth & Pendleton, 1994).

The two suppression tasks provided further insight into the underlying processes favored by athletes and controls to store visually presented movements. As expected from previous literature on verbal encoding of movements (Frencham et al., 2004; Helstrup, 2000), controls proved to rely strongly on verbal processes to perform the memory task, which indicates that individuals tend to favor verbal strategies to store and recall movements. However, motor suppression had a dramatic converse effect on performance, affecting athletes more than controls. In the motor suppression condition, athletes showed considerable decrease in performance compared with the verbal condition. This finding suggests that athletes' high performance in the simple movement recall task relies heavily on motor encoding. When this possibility was suppressed, recall performance dropped significantly. Moreover, when initial differences in the no-suppression condition were controlled for, this pattern of findings was not altered. In other words, the differential effects of the suppression conditions on the two groups were not due to initial differences in movement recall performance. Together, these results corroborate findings by Shebani and Pulvermüller (2013) showing that arms and legs motion impairs working memory for limb-related action words, while emphasizing the role of prior sensorimotor experience to specify impairment. In this regard, the present findings also confirm a previous study by Moreau (2012) demonstrating the influence of sensorimotor experience on spatial processing and reasoning, and lend support for the embodied approach of cognition which assumes an interrelation between conceptual and sensorimotor processes (see for example Costantini, Ambrosini, & Sinigaglia, 2012; Taylor & Zwaan, 2010; see also Barsalou, Simmons, Barbey, & Wilson, 2003, for a review).

Taken together, these findings suggest that the ability to engage motor processes is experience-dependent: extensive motor practice induces subsequent motor processing in recall. Athletes might have shifted from verbally-based to motor-based strategies, probably because verbal coding leads to action delays in sports due to interference (Hiscock, Caroselli, & Wood, 2006), and is therefore not efficient to reach an optimal level of motor performance (Boutin, Fries, Panzer, Shea, & Blandin, 2010). Verbal processes are needed at early stages of motor skill acquisition, but movements are subsequently internalized motorically, relying mainly on the implicit system (Reber, 1993). This explains why it is often difficult to describe verbally a movement, especially for athletes with a high degree of expertise. However, the present experiment underlines that a motor strategy might not be adapted in case of motor interference, because both processes compete for similar resources. This idea follows literature in the field of neuroscience which shows that understanding others' actions depend on individuals' capacity to mimic them, via the mirror system (see for a review Rizzolatti & Sinigaglia, 2010). According to this view, incongruent movements act detrimentally to action understanding, due to simultaneous activation of overlapping neural networks to process observation and execution (Kilner, Paulignan, & Blakemore, 2003).

Developing on this idea within the present experiment, the plastic changes that have occurred over time seem durable enough to handicap athletes in the motor suppression task. If individuals could easily switch between verbal and motor encoding of movements, athletes would have adapted their strategic behavior toward verbal encoding in the motor suppression task. The absence of such a flexible behavior suggests that the underlying mechanisms in motor encoding of movements involve structures that do not depend on adaptable strategies. This particular point indicates that verbal encoding and motor encoding are not controllable strategies, but rather are rooted in processes that require substantial time and effort to be altered.

Related to this point, athletes' span for movements did not seem to increase with extensive motor practice, even though evidence shows that elite athletes recognize movement patterns more quickly and accurately than novices or non-athletes (Aglioti, Cesari, Romani, & Urgesi, 2008; Didierjean & Marmèche, 2005). One could suppose that if it did, they would have coped with the surplus of motor information added by the motor suppression task. In the present study, this was clearly not the case. Despite being motor experts, athletes showed strongly impaired performance when forced to process additional motor content in the motor suppression condition. This idea is consistent with a limited and fairly rigid capacity in working memory, regardless of the content manipulated (Cowan, 2001). Rather than being able to hold more information per se, athletes seem to process motor information more efficiently, therefore allowing the involvement of motor processes in non-motor tasks, with positive outcomes.

It should be acknowledged, however, that the suppression tasks used in the present experiment are more difficult than those usually found in dual-task studies of working memory (Baddeley, Chincotta, & Adlam, 2001). Thus, there is a possibility that difficulty participated in yielding stronger effect sizes, with suppression tasks potentially placing large demands on modality-independent resources such as executive control. The rationale behind this design was that the suppression tasks needed to be complex enough to affect movement processing in individuals who handle motor patterns daily. In that sense, the expert population of the present study necessitated going beyond a specific threshold under which interference would have no effect or limited impact, in order to better understand the processes underlying movement encoding. However, the sole difficulty of the suppression tasks cannot account for the significant interaction observed between verbal and motor suppression conditions, nor for the consistency of the results when initial performance in movement recall was controlled for.

Regarding the suppression tasks implemented in the present experiment, one last point deserves particular attention. Although one might argue that the motor suppression task could induce verbal strategies in controls to help monitoring motor execution, this is not likely, since the suppression pattern was practiced before starting the motor suppression condition. In fact, participants typically verbalized the pattern the first few occurrences before the beginning of the experiment, but this verbal rehearsal disappeared prior to or at the onset of the first trial, as the experiment began only once participants mastered the motor pattern without errors. Furthermore, the fact that the motor suppression condition was not as detrimental as the verbal suppression condition for the control group, relative to the athletes group, provide further evidence against verbal coding of motor tapping in controls.

Overall, the present findings emphasize two major points. First, individual differences in strategies and processes underlying working memory tasks should be considered when assessing simple or complex spans, as similar results may arise via the recruitment of radically different components. In itself, the nature of the task does not guarantee the involvement of specific processes across individuals. Second, building up on previous literature, the paper underlines the significant impact of sensorimotor experience in a wide variety of cognitive processes, including working memory, thus providing further evidence for a tight relationship between sensorimotor and cognitive processes.

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