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How do we learn to "kill" in volleyball?: The role of working memory capacity and expertise in volleyball motor learning

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ABSTRACT

This study examines young volleyball players' learning of increasingly complex attack gestures. The main purpose of the study was to examine the predictive role of a cognitive variable, working memory capacity (or "M capacity"), in the acquisition and development of motor skills in a structured sport. Pascual-Leone's theory of constructive operators (TCO) was used as a framework; it defines working memory capacity as the maximum number of schemes that can be simultaneously activated by attentional resources. The role of expertise in motor learning was also considered. The expertise of each athlete was assessed in terms of years of practice and number of training sessions per week. The participants were 120 volleyball players, aged between 6 and 26 years, who performed both working memory tests and practical tests of volleyball involving the execution of the "third touch" by means of technical gestures of varying difficulty. We proposed a task analysis of these different gestures framed within the TCO. The results pointed to a very clear dissociation. On the one hand, M capacity was the best predictor of correct motor performance, and a specific capacity threshold was found for learning each attack gesture. On the other hand, experience was the key for the precision of the athletic gestures. This evidence could underline the existence of two different cognitive mechanisms in motor learning. The first one,

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relying on attentional resources, is required to learn a gesture. The second one, based on repeated experience, leads to its automatization.

Introduction

It is, by now, well established that sport and cognitive activity are highly interconnected: Diamond (2000) underlined the link between cognitive and motor development because when the first is affected (e.g., due to a neurodegenerative disorder), the second is also affected. Ellemberg and St-Louis-Deschênes (2010) compared the effect on cognitive performance of 30 min of aerobic exercise with the same time spent watching television, finding that even a single session of aerobic exercise is able to produce a significant, although not permanent, improvement in cognitive performance. Similar results were reported by Pesce, Crova, Cereatti, Casella, and Bellucci (2009) and by Davranche, Hall, and McMorris (2009). These and many other studies point to a strong connection between sport and cognitive development, but they study how physical activity affects our cognitive processes, whereas the influence in the opposite direction is still under-researched. Among the studies that examined this relation, those based on Baddeley and Hitch's (1974; see also Baddeley, 2000) model of working memory were mainly interested in identifying a specific subsystem for movement configuration (separate from the visuospatial sketchpad) by using a dual task paradigm (Quinn & Ralston, 1986; Smyth, Pearson, & Pendleton, 1988; Smyth & Pendleton, 1989); however, these first studies used very simple motor tasks and made no hypothesis on the relation between working memory and motor learning. More recently, Seidler, Bo, and Anguera (2012) showed that individual differences in spatial working memory are predictive of the rate of motor learning in both explicit and implicit sequence learning.

From a different perspective, thinking about working memory as a domain-general measure, reflecting an individual's ability to control attention, Engle (2002) suggested that working memory can be important during challenging activities in contexts that are "rich in distractors" such as sports. Behmer and Fournier (2014) suggested that neural efficiency during a new motor task is influenced by individual differences in working memory capacity, or "M capacity," assessed with the operation span. Pertaining to focusing attention and avoiding distraction, Furley and Memmert (2012) observed that basketball players with higher working memory are better at decision making, inhibiting irrelevant auditory information, and adapting their tactical decisions in a task involving videos of complex game situations.

All of these studies suggest that working memory plays an important role in facilitating motor learning and improving tactical decision making. In this study, we examined how children's and adolescents' ability in a structured sport, volleyball, is affected by working memory.

However, it is also clear that expertise—that is, the experience and amount of time that an athlete has spent practicing his or her sport—is involved in the cognitive processes related to sport ability. The role of expertise and automatization has long been recognized in cognitive development (Chi, 1978; Chi, Glaser, & Rees, 1982) and in particular seems to be very important in motor learning. In fact, whereas at the beginning performing a motor task still requires attentional resources, with practice it becomes more and more automated. A classical distinction in physical education and sport science was offered by Fitts (1964; see also Fitts & Posner, 1967), who proposed three phases of motor learning: the cognitive, associative, and autonomous stages. The first phase is characterized by a considerable cognitive load because movements are mainly controlled for in a conscious manner and learners need to use attentional resources in order to perform the correct sequence of movements: in this phase, movements are usually slow and hesitant. The associative phase begins once the athlete has acquired the basic movement pattern and is characterized by more fluent movement adjustments. Because certain motor patterns tend to co-occur, it becomes less effortful to perform them together;

they become associated. Finally, after extensive practice, the performer achieves the autonomous phase, characterized by fluent and apparently effortless motion. At this point, the athletic gesture is performed automatically and movement execution requires little or no attention; the athlete has reached expertise in that gesture, and embodied procedural knowledge prevails over declarative knowledge. Evidence supporting this stage process has been found by Eversheim and Bock (2001), who investigated the changes of resource demand during the tracking of a visual target under reversed visual feedback, and by MacMahon and Masters (2002), who tested the effects of introducing a random letter generation task (which places a high load on working memory) on explicit learning of a golf putt. As a result, the distracting task had disrupted the increment of declarative knowledge on how to perform the gesture.

In this study, we investigated the respective roles of working memory capacity and expertise in learning the motor skills required to perform an attack (i.e., the so-called "third touch," the one with which a player pushes the ball into the opponent's court) in volleyball. Focusing on a specific class of athletic gesture (attack) is a methodological choice to satisfy the need of a sufficiently objective measure of individual ability in well-controlled tasks. Attack in volleyball can be performed with gestures of different complexity, which young athletes get to master following their hierarchy of difficulty; to test motor learning, we designed a specific set of attack tasks of increasing complexity. We expected that the developmental growth of working memory capacity enables the young athletes to coordinate an increasingly large number of units of information to perform more and more difficult athletic gestures. We also expected that expertise has an effect both on the automatization of certain movements, which reduces the load they place on working memory, and on the smoothness of the athletic gesture.

Most current theories of working memory posit a central role of attentional resources in determining the capacity and functioning of working memory; for example, Cowan (1995) proposed that working memory is based on representations activated from long-term memory, with a capacity-limited focus of attention; theories of working memory involving a limited "executive attention" were also proposed by Kane and Engle (2002, 2003) and by Barrouillet and Camos (2007). The theory of constructive operators (TCO; Pascual-Leone, 1987; Pascual-Leone & Goodman, 1979) is consistent with this attention-based view of working memory and, in addition, provides a precise developmental model of capacity growth. Furthermore, the TCO assumes "schemes" as the units of cognition, which seems to be particularly suitable for sport abilities because they involve different types of information (e.g., procedural and declarative; visual, motor, and conceptual), and the definition of schemes can apply to all of them. Therefore, we use the TCO as the framework for this study.

The TCO includes two levels of constructs: schemes and general-purpose operators. Schemes, which can be described as organized sets of reactions to types of situations, are the units of analysis of cognitive processes, whereas general-purpose operators are resources of the mind without a specific content. They increase or decrease the activation of schemes and enable the formation of new ones. The outcome of a cognitive process depends on which schemes are activated and how those operators influence their activation. One of the operators postulated in the theory is an attentional resource called the M (mental energy) operator, which increments the activation of those schemes that are relevant to a task but not automatically activated. The capacity of this attentional resource is expressed as the maximum number of schemes that it can activate at the same time. Pascual-Leone (1987) suggested a possible neuropsychological base for this mechanism in the prefrontal lobes that would use the resources of the reticular system in order to activate schemes localized in different cortical areas; evidence supporting this view was provided by Arsalidou, Pascual-Leone, Johnson, Morris, and Taylor (2013). According to the TCO, M capacity develops during childhood and adolescence; at 5 or 6 years of age, a child can typically coordinate two schemes, and this number increases by 1 unit every second year until about 15 years. At that point, the individual is able to coordinate, on average, up to seven schemes.

Pascual-Leone's TCO has been supported in diverse developmental domains including, first of all, perceptual–attentional tasks such as the Compound Stimuli Visual Information task and the Figural Intersection Test (e.g., Pascual-Leone, 1970; Pascual-Leone & Johnson, 2011) and also in conditions of dual-task performance (Foley & Berch, 1997) and in relation to cognitive styles (Globerson, 1983). It has also been extensively supported in reasoning tasks such as combinatorial reasoning (Scardamalia, 1977), the "horizontality of water level" problem (e.g., Morra, 2008), problem solving in the domain of chemistry (e.g., Niaz, 1988), and arithmetical problem solving (Agostino, Johnson, & Pascual-Leone, 2010). It has been also studied in the domain of language, in particular metaphor comprehension (Johnson & Pascual-Leone, 1989), semantic and syntactic language competence (Im-Bolter, Johnson, & Pascual-Leone, 2006), vocabulary learning (Morra & Camba, 2009), writing argumentative and narrative texts (Balioussis, Johnson, & Pascual-Leone, 2012), and in the domain of children's drawing (e.g., Panesi & Morra, 2016). Furthermore, the TCO was the framework for studies of moral reasoning (Stewart & Pascual-Leone, 1992), understanding of emotions in the presence of misleading or conflicting information (Morra, Parrella, & Camba, 2011), and theory of mind during adolescence (Im-Bolter, Agostino, & Owens-Jaffray, 2016; see also Morra, Gobbo, Marini, & Sheese, 2008, for a more extensive discussion of the TCO).

Although Pascual-Leone's theory was successfully tested in several diverse domains, only rarely was motor learning studied in this framework; however, completing motor gestures also can overload M capacity. A recent study showed that M capacity is involved in the development of an early motor skill such as scribbling (Morra & Panesi, 2017). The most important experiments on motor skills, designed within the framework of the TCO, were carried out by Todor (1975, 1977, 1979; see also Pascual-Leone, 1987). In Todor's Rho Task, participants were asked to perform as quickly as possible a simple action made of two basic movements: one circular and one linear. M capacity was predictive of developmental improvements in the strategies by which the participants accomplished the task. Although the Rho Task is the only motor one for which an explicit TCO model was proposed and tested, it involves a very simple movement, hardly comparable to the complexity of real-life motor tasks.

Corbett and Pulos (1999) carried out a study on motor learning in an ecological situation with the TCO as theoretical framework. It was a longitudinal study of kindergartners' gross motor abilities such as hopping, skipping, and rope jumping. Their purpose was to analyze the relationship among gross motor development, cognitive development, and attentional skills, and they found that the ability that correlated most with M capacity was the rope jump. Indeed, to jump over the rope, children must attend to several schemes at one time to coordinate arm and leg movements. They also found correlations between cognitive measures (Piagetian tasks) and gross motor abilities; these correlations, however, were drastically reduced when controlling for attentional capacity, suggesting a causal role of attentional capacity in both cognitive and motor tasks.

These results indicate a strong relation between attentional capacity and motor skills acquisition that led us to undertake preliminary observational research (Bisagno & Morra, 2013) with a small group of young volleyball players. Our observations suggested that these young athletes seemed to be able to integrate a number of motor schemes that increased with age, improving technically in terms of mastery of the athletic gesture. In other words, a cognitive limit, such as the need to coordinate a number of schemes exceeding the individual's capacity, turned—for young volleyball players—into a limitation for more refined skill learning, if not compensated by automatization of well-accomplished gestures.

These findings suggest that M capacity represents a predictor for refined and complex motor learning. One of the main purposes of our study was to apply a general theory of cognitive development to motor learning using a precise developmental model in order to test our hypotheses in quantitative terms. In particular, we investigated whether M capacity is a prerequisite of learning specific technical gestures and how expertise is involved in this process. More specifically, the aims of this study were as follows:

- Testing the hypothesis that M capacity represents a predictor of motor learning in the specific task of attack in volleyball; that is, a higher M capacity allows young athletes to succeed in more complex attack tasks.
- Verifying the role of expertise in motor learning by testing whether the automatization of certain gestures allows experts to perform better than average in complex tasks in terms of both correct execution and precision. In other words, our hypothesis was that more experienced athletes can both accomplish more complex attack tasks and do so by performing a cleaner and more effective gesture.

To verify these two hypotheses, we collected data from a sample with a broad age range, which brought about large variability of both M capacity and volleyball expertise.

To design attack tasks of increasing difficulty, which place an increasingly high demand on M capacity, we resorted to a task analysis. For this reason, a third objective can be added to the previous two objectives: evaluating the goodness of our task-analytic model.

Method

Participants

This study involved 120 young volleyball players (105 female and 15 male), from five different clubs; the reasons why the sample is not balanced by gender are the preponderance of female rather than male volleyball teams in Southern Piedmont, Italy, where the data collection took place, and the greater availability of female volleyball players to participate. To avoid possible biases caused by the small size of the male subsample and its unequal distribution within the various age groups, we report in detail the analyses carried out only on the female subsample. In addition, we report very briefly the analyses carried out on the full sample. Participants were divided into six age groups of $n = 20$ each. The age groups were as follows:

- 6–8 years: mean age = 7 years 8 months, *SD* = 10 months (16 girls and 4 boys);
- 9 and 10 years: mean age = 10 years 0 months, *SD* = 6 months (15 girls and 5 boys);
- 11 and 12 years: mean age = 12 years 0 months, *SD* = 7 months (20 girls and 0 boys);
- 13 and 14 years: mean age = 13 years 7 months, *SD* = 5 months (20 girls and 0 boys);
- 15–17 years: mean age = 16 years 4 months, *SD* = 11 months (19 girls and 1 boy); and
- A group of adults, "expert" athletes with at least 10 years of volleyball experience: mean age = 22 years 2 months, *SD* = 2 years 6 months (15 women and 5 men).

Materials and procedure

For this study, we collected two major types of data: measures of the participants' motor skills and of their M capacity. In addition, we considered the players' years of volleyball experience and their number of training sessions per week during the current year as measures of expertise.

M capacity measures

The M capacity of each participant was measured in an individual session of about 80 min duration. Three tests were administered to each athlete in order to average performance in different domains as a control for test impurity. Two of these tests involve visual–spatial materials, namely the Mr. Cucumber test (Case, 1985) and the Figural Intersection Test (FIT; Pascual-Leone & Baillargeon, 1994; Pascual-Leone & Ijaz, 1989), whereas the Direction Following Task (DFT; Pascual-Leone & Johnson, 2005, 2011) uses verbal materials. The DFT and FIT have been validated with both adults and children also in Italy (Morra, 1994; Morra, Camba, Calvini, & Bracco, 2013), whereas the Mr. Cucumber test has been validated only with children (Case, 1985, 1995; Morra, 1994); for this reason, it was used in this research conditionally to some preliminary analysis. The tests were administered in the following order.

Mr. Cucumber test. In this test (Case, 1985), the child is shown the figure of a character, Mr. Cucumber, on whose body parts there are some colored stickers. The number of colored stickers to remember increases from level to level from 1 to 8. There are three items on each level. On levels from 1 to 5 the stimulus is presented for 5 s, and on the following levels it is presented for as many seconds as the number of stickers. The participant's assignment is to observe the position of those stickers and then, pointing on a Mr. Cucumber without any sticker on him, to indicate where they were placed. A level is considered passed if the participant succeeds in at least two of three items. The final score is represented by the highest consecutive passed level plus .33 for each correct item beyond that level.

Figural intersection test. The Figural Intersection Test (FIT; Pascual-Leone & Baillargeon, 1994) consists of a booklet in which geometric shapes are represented; for each item, on the right side of the sheet the shapes are scattered, and on the left side of the sheet instead the same shapes (possibly rotated or changed in size) overlap and form a configuration. The participant is required to identify in the configuration on the left side the intersection of the forms that are shown on the right side; some items also have one irrelevant extra shape in the left configuration that should be ignored by the participant. The number of shapes on the left side, in each item, represents the number of cognitive units that the participant needs to integrate, that is, the item's complexity. There are eight levels ranging from 2 to 9 shapes; there are 36 items in all that are not presented in order of complexity but rather in a pseudorandom order. An item is considered correct if the participant marks only the intersection of the relevant forms. A level is considered failed if the person commits two or more errors. The final score is given by the last consecutive level where the participant has achieved this criterion plus 1 for each level eventually passed beyond that. The 6- to 8-year-old subsample was administered a shorter version of the FIT from which the 10 most difficult items (belonging to levels 7–9) had been excluded.

Direction following task. In the Direction Following Task (DFT; Pascual-Leone & Johnson, 2005, 2011), the participant must follow oral instructions of different complexity (in which the cognitive load varies systematically). The materials consist of 20 plastic forms varying in shape, size, and color and a closable board, on which there are 10 square spaces of different size and color; the participant must place the forms on specified spaces, following the experimenter's directions, and each item is scored as passed or failed. Spaces can be described with one or two words (the color and/or the size), and a shape can be described with a combination of one to three features (e.g., a circle, a small circle, or a small green circle). The information load is varied by manipulating the number of objects (one or two), spaces, and features specified in an instruction, so that a particular amount of M capacity is assumed to be required to pass the items of a given type. There are five items for each of nine instruction types. Because the Italian grammar is different from the original English language of the test, Morra et al. (2013) presented scoring rules adapted for the Italian translation of the test, which were also used in this research.

Volleyball tasks

To evaluate the athlete's motor learning, six attack tasks of increasing difficulty were designed; the first of these tasks was used only with the 6- to 8-year-olds as a control task, which we expected to be performed successfully even by the youngest age group, and the subsequent ones were performed in order of difficulty by all participants until they failed. In each task, the player was required to perform a specified action in order to score a line attack (a toss that is parallel to the court's sideline) in Area 1. The player was also required, if he or she was able, to score a direct hit inside a hula-hoop ring, located in that area. Specifically, the target was 4 m away from the net—1 m beyond the "attack line"—for children up to 10 years and 7 m away from the net for athletes 11 years and older. The six tasks were as follows:

1. *Basic (control) task:* This task involves just throwing the ball with two hands toward the hula-hoop target placed at a distance of 4 m with no hedges between it and the participant. This task was performed only by participants in the 6- to 8-year-old group as a control task for comparison with the following one; as expected, all children easily succeeded in this task. Therefore, it was not taken into account in the data analyses.
2. *Tossing the ball over the net:* This task is exactly the same as the previous one, but the participant needed to roll over the net. In this task and all of the following tasks, the target distance was diversified for younger and older participants, as explained above.
3. *Set with feet on the ground:* The ball was thrown, by a partner or the coach, to the player, who needed to push it with a setting, without approach, toward the area of the field indicated by the hula hoop.
4. *Set attack with approach:* This task is the same as the previous one but was preceded by a run-up.
5. *Spike with a run-up:* This task is the same as the previous one but with a spike instead of a set.

6. *Spike against the block:* This task is exactly the same as the previous one but with the presence of an opponent who jumps with raised arms, performing a block.

The trials, all video-recorded, were performed during the regular hours of training (after about 20 min of warm-up and some basic exercises with the ball at the discretion of the coaches). For each task, each participant performed five items; a task was considered passed with a minimum of three of five correct executions. In case of two or fewer correct executions, the test was discontinued to the next level without the athlete passing the task. Performance on each task was scored in two ways:

(a) *correct execution* of the gestures: the number of items on which the athlete performed the required action without committing a foul and the ball reached the target area of the field; and
(b) *precision:* the number of correct executions in which the participant also scored a hit in the hula-hoop ring.

Task analysis

To identify the tasks' difficulty according to the TCO and, in particular, to quantify the demands they place on M capacity, we performed a task analysis indicating which schemes need to be activated with the attentional resources of the M operator. This task-analytic model is hypothetical; we postulated which schemes are involved in each task based both on the first author's experience as a volleyball coach with young athletes and on some observations gathered during our previous study (Bisagno & Morra, 2013) with a small sample of young volleyball players. For example, in that study we had a 6-year-old to toss the ball over the net and observed that he alternated between two types of error; either he pushed too low when he sent the ball to the right direction or, when he was able to overcome the net, he aimed too far and/or to the wrong place. This suggests a difficulty, for this child, in taking into account all of the information involved in the task. It also suggests that direction, distance, and vertical push are involved in this task as three distinct schemes because different errors occur when one or another of them is missing. In general, in task analysis, any common error can be regarded as a "pointer" to a required scheme.

In general, we assumed that if a certain task requires, for example, activation of four schemes by the M operator, an individual with a lower M capacity will not be able to accomplish it or will perform it in an incorrect manner—unless some of those schemes are automatized enough not to require "mental energy."

According to our task analysis:

- Basic task (throwing the ball to the target with no hedges) = M demand of 2 units, corresponding to the schemes target distance and target direction on the horizontal plane, which are two distinct pieces of information, both of which are necessary to throw the ball to the right place.
- Tossing the ball over the net = M demand of 3 units, corresponding to the previous two schemes plus a third one, the vertical push, which is necessary to overcome the net.
- Set with feet on the ground = M demand of 4 units. Assuming that—with sufficient experience—the distance and the vertical push are combined and chunked into a single representation, the schemes necessary to succeed in this task should be direction on the horizontal plane, overcoming the net, body and hands positioning (to properly embrace the ball without committing a foul), and clearance timing, which involves coordinating one's movements with the ball's parable in order to push it at the right moment.
- Set attack with run-up = M demand of 5 units: direction on the horizontal plane, overcoming the net, monitoring the airborne phase of the ball (which is necessary to choose the time for jumping), run-up control" (i.e., the sequence of steps and takeoff considered as a single scheme because the neatness of this movement should already have been well practiced and automated without the ball), and attack timing (in harmony with the ball's downward trajectory). The hand positioning for set as a technical gesture should already be fully acquired at this point, and, therefore, is considered automatized enough not to demand attentional resources from the individual.

- Spike with run-up = M demand of 6 units: direction on the horizontal plane, throwing depth, monitoring of the airborne phase of the ball, run-up control, attack timing (in this case the need to hit the ball just above the net tape), and (control of the) closing movement of the wrist, which is needed to confer to the ball the spike's characteristic downward trajectory.
- Spike against the block = M demand of 7 units. It seems plausible to assume that the presence of the block performed by one opponent, in the final task, adds an extra load of 1 unit of information to represent the obstacle that must be avoided.

As explained above, this task-analytic model is hypothetical, and checking its accuracy through the results was one of the goals of this study.

Results

Predictors and dependent variables

The following variables were considered as predictors:

– M capacity, defined as the average of the scores in the three tests: the Mr. Cucumber test, the Figural Intersections Test, and the Direction Following Task; and
– Two measures of experience, namely the number of years playing volleyball and the current number of training sessions per week.

Four dependent variables are considered in the following analyses; two of them are related to correct execution of volleyball trials, and the other two are related to the precision of the athletic gestures, that is, to the perfect hits into the hula-hoop ring. In particular, we calculated the following:

(a) Total number of correct executions, which is given by the sum of all the items properly accomplished by an athlete in all task levels except the basic task. The maximum possible score was 25 (5 items in each of the five tasks).
(b) Volleyball level, defined as the highest task at which the participant performed correctly on at least three trials (maximum possible score = 6).
(c) Total precision, which simply consists of the number of perfect hits into the hula-hoop ring at all task levels except the basic task (maximum possible score = 25).
(d) Corrected precision, defined as the mean of the regression residuals, across all task levels performed by the athlete, of the number of perfect hits on the number of correct trials. Because the athletes who succeeded in a higher number of tasks would have had more chances to score hits into the hula-hoop ring, this variable was constructed as a measure of motor precision that controls for simple correct execution.

Preliminary analyses

It was verified that all tests used to assess M capacity were correlated among them; actually, all of the tests showed a highly significant correlation with one another ($p < .001$; see Table 1) even partialing out the effect of age; these results are consistent with the literature (e.g., Pascual-Leone & Johnson, 2011).

The two measures of experience (number of years playing volleyball and current number of training sessions per week) instead were only weakly correlated ($r = .18$, $p = .08$) when controlling for age.

Because the scores in the M capacity tests are meant to measure the number of schemes that the participant is able to integrate, it is also important to check that their means and age trends do not diverge excessively from one another. To assess the impact of age on the three test scores, we ran a multivariate analysis of variance (MANOVA) with three dependent variables (FIT, Mr. Cucumber, and DFT) in which age group was the between-participants factor. The age group factor was significant, with Pillai's trace = .756, corresponding to $F(15, 297) = 6.67$, $p < .001$. This effect was also highly

Table 1
Descriptive statistics and correlations between all variables.

	Mean	*SD*	DFT	CUC	FIT	Volleyball years	Training sessions per week	Correct executions (trials)	Volleyball level	Total precision	Corrected precision
DFT	5.19	1.71		.374***	.503***	.020	.154	.411***	.375***	−.005	−.095
CUC	5.59	1.66	.609***		.528***	.199	.128	.539***	.468***	.077	−.027
FIT	5.71	2.04	.688***	.697***		.113	.172	.522***	.443***	.061	−.050
Volleyball years	5.32	4.19	.558***	.605***	.569***		.175	.223*	.117	.335**	.293**
Training sessions per week	2.58	0.72	.385***	.358***	.388***	.465***		.323**	.306**	.120	.032
Correct trials	14.52	4.79	.679***	.735***	.724***	.727***	.523***		.899***	.173	−.055
Volleyball level	3.03	1.04	.643***	.686***	.670***	.650***	.505***	.948***		.083	−.098
Total precision	1.56	2.35	.206*	.260**	.246*	.445***	.250	.359***	.289**		.943***
Corrected precision	0.00	0.53	−.027	.023	.004	.203*	.061	.019	−.019	.911***	

Note. Correlations with age partialed out are above the diagonal, whereas Pearson correlations are below it. DFT, Direction Following Task; CUC, Mr. Cucumber test; FIT, Figural Intersection Test.

* $p < .05$.
** $p < .01$.
*** $p < .001$.

significant for each particular test, $F(5, 99) = 26.57$, $p < .001$, $\eta^2 = .573$ for the DFT, $F(5, 99) = 15.27$, $p < .001$, $\eta^2 = .435$ for the Mr. Cucumber test, and $F(5, 99) = 17.89$, $p < .001$, $\eta^2 = .475$ for the FIT.

To obtain a more detailed decomposition of the effects of age and test, and to assess whether there were any differences between the test scores, we also ran a mixed-design analysis of variance (ANOVA) in which age group was the between-participants factor, whereas the within-participant factor was the test (with three levels: FIT, Mr. Cucumber, and DFT). This analysis yielded significant effects of age group, $F(5, 99) = 31.30$, $p < .001$, $\eta^2 = .613$, the test, $F(2, 198) = 7.87$, $p < .001$, $\eta^2 = .074$, and a nonsignificant interaction, $F(10, 198) = 1.85$. A polynomial decomposition of the age group effect revealed a strong linear component ($p < .001$), a minor quadratic component ($p < .01$) due to reduced growth after 13 years of age, and nonsignificant higher-order components. Paired t tests with Bonferroni correction revealed that the DFT mean score (5.19) was somewhat lower than the means of both the Mr. Cucumber test (5.59) and the FIT (5.70), $t(104) = 2.79$, $p < .02$ and $t(104) = 3.52$, $p < .01$, respectively; the means of the Mr. Cucumber test and the FIT did not differ from each other, $t(104) = 78$.

It is unclear why the DFT had a lower mean than the other two tests; previous research with both children and adults yielded similar means with directions in both English (Pascual-Leone & Johnson, 2005, 2011) and Italian (Morra et al., 2013). Perhaps the particular population of volleyball players is particularly apt at encoding visuospatial materials; this point may call for further research. Nevertheless, the mean score of each test in each age group, shown in Table 2, was very close to the theoretical expectation except for slightly higher than expected means of the Mr. Cucumber test in the two youngest age groups and the FIT in the 13- and 14-year-old group. As a conclusion of these preliminary analyses, we decided to define the measure of M capacity as the average of all three tests because although the difference among tests was significant, the effect size was not large, the Test × Age Group interaction was nonsignificant, and there was a strong linear increase with age, with nearly all mean scores (Table 2) in agreement with the literature. In particular, the Mr. Cucumber test also proved to be adequate for the older age groups.

As a preliminary analysis to verify the role of M capacity and experience as predictors of volleyball performance, we examined correlations when controlling for age. Partial correlations only retain individual differences, statistically eliminating the age-related variance, thereby ensuring that a correlation between a volleyball measure and a predictor is not an artifact due to variance shared with other age-related variables. As can be seen in Table 1, even when controlling for age, the correlations between each of the M capacity tests and the measures of volleyball correct execution remained very high, whereas the "precision" measures were not related to M capacity. Considering the average of M capacity tests, its partial correlation with volleyball level was $r = .53$, $p < .001$, and with correct executions it was $r = .61$, $p < .001$. Among the measures of experience, trainings per week correlated with both measures of execution, whereas years of volleyball positively correlated with both measures of precision and, to a lesser extent, with the number of correct trials.

Table 2
Means and standard deviations of the M capacity tests by age group.

	DFT		FIT		CUC	
	Mean	SD	Mean	SD	Mean	SD
6- to 8-year-olds	3.16	0.75	3.38	0.81	3.68	1.00
9- and 10-year-olds	3.73	0.98	4.40	1.30	4.84	1.34
11- and 12-year-olds	5.03	1.27	5.15	1.93	5.13	1.57
13- and 14-year-olds	5.70	1.30	6.80	1.50	6.17	1.40
15- to 17-year-olds	6.95	1.31	7.10	1.52	6.54	1.15
Adults	6.10	1.02	7.00	1.65	7.02	0.95

Note. DFT, Direction Following Task; FIT, Figural Intersection Test; CUC, Mr. Cucumber test.

Regression analyses

Regression analyses were performed for each of the four dependent variables: total number of correct executions, volleyball level, total number of perfect hits, and corrected precision, including M capacity and experience measures as predictors. We used a stepwise method with $p < .05$ as the inclusion criterion.

For the total number of correct executions, as one can see in Table 3, the predictors accounted for a large portion of variance, and the main predictor was M capacity (ß = .55), followed by years of volleyball (ß = .30) and training sessions per week (ß = .15). This result is consistent with our hypothesis that an adequate M capacity is required to coordinate all relevant motor, perceptual, and cognitive schemes. Similar results were found analyzing volleyball level; also in this case, M capacity was the first predictor (ß = .54), followed by years of practice (ß = .22) and trainings per week (ß = .17). We also calculated the unique variance accounted for by each predictor and the portion of variance shared by more than one predictor. M capacity by itself shows an R^2 value of .17, meaning that it explains 17% of the variance—much more than the other predictors. Moreover, a large amount of variance was shared among all three predictors ($R^2 = .23$) and between M capacity and years of volleyball ($R^2 = .25$). This is explained by the fact that M capacity, years of volleyball, and number of training sessions per week all increase with the age of the participant, so it is not surprising that they share a large portion of explained variance. A similar pattern was found for volleyball level. The prominent role of M capacity as a predictor of acquisition of volleyball skills is the main finding in this study.

Whereas the results for correct performance clearly pointed to a major role of M capacity in learning the actions involved in the attack, very different results emerged for precision (see Table 3). The variance accounted for in these analyses was much less than that for the correct performance variables. In both cases, years of volleyball experience was the only significant predictor (ß = .45 for total precision and ß = .25 for corrected precision). The partial correlations for the other predictors at the point when the stepwise procedure stopped indicate clearly that the excluded variables did not contribute to precision scores. From these results, it seems that expertise is essential not only for the ability to perform more complex tasks or to integrate a higher number of schemes but also for the nicety of the gesture. Hence, it is conceivable that—through years of practice—the described technical gestures become smoother and acquire a more fine-grained motor coordination, thereby facilitating the more experienced athletes in hitting a small target such as the hula hoop.

Cross-classification prediction analyses

Having verified the prediction that M capacity is involved in the correct execution of the various technical gestures, we tried to infer whether there is a minimum (threshold) prerequisite M capacity for accomplishing each given technical gesture. To do so, we classified participants according to their

Table 3
Regression analyses for each dependent variable.

Predictor	Correct executions ($R^2 = .74$)			Volleyball level ($R^2 = .64$)			Total precision ($R^2 = .20$)			Corrected precision ($R^2 = .06$)		
	β	p	Unique R^2	β	p	Unique R^2	β	p	Partial correlation	β	p	Partial correlation
M capacity	.55	<.001	.17	.54	<.001	.16	–	n.s.	−.03	–	n.s.	−.18
Years of volleyball	.30	<.001	.05	.22	.009	.03	.45	<.001	–	.25	.010	–
Training sessions per week	.15	.012	.02	.17	.014	.02	–	n.s.	.05	–	n.s.	−.02

Note. The unique R^2 of each predictor is reported for correct executions and volleyball level. The total R^2 is much larger than the sum of unique variances because a large amount of variance was shared by two or more predictors (see text). Reporting unique R^2 is not necessary for total precision and corrected precision because only one predictor was found to be significant. For these two latter analyses, we indicate the partial correlation of each variable at the point when the stepwise procedure stopped.

M capacity, approximated to the nearest integer (3–8), and the volleyball level they reached. The contingency table (Table 4) shows the observed frequency of participants with a certain M capacity who passed each level. A prediction analysis of cross-classification (Hildebrand, Laing, & Rosenthal, 1977) was performed on these data; our theoretical prediction stated that all frequencies should be zero for the volleyball levels that (according to our task analysis presented above) require a larger M capacity than the participant has. This test compares the observed frequencies in the critical cells (i.e., in the cells for which a frequency of 0 is predicted) with those expected by chance (expected frequencies reported in parentheses in Table 4 only for the critical cells). Hildebrand et al.'s (1977) index *Del* expresses the degree to which the prediction that a certain set of cells has null frequency explains the difference between observed and expected frequencies in the critical cells. A positive value of *Del* indicates that the observed frequencies in the critical cells are lower than those expected by chance; its maximum value is 1 (when all of the critical cells are empty). A z value and a confidence interval can be calculated for *Del*. If the confidence interval includes only positive values, then the prediction is better than chance; if the interval, besides being positive, also includes $Del = 1$, then one can accept the hypothesis that the frequencies in the predicted cells are not different from zero.

The predictions based on the originally hypothesized task analysis were not confirmed, $Del = .406$ ($SE = .119$), $z = 3.41$, $p < .001$, 99% confidence interval (CI) [.098, .714]; although the positive value of *Del* was highly significant and the whole confidence interval lied in the positive range, it did not include the value of 1. Actually, two cells predicted to be empty instead had a high frequency; that is, a sizable number of participants with an M capacity of 3 were able to perform the set with feet on the ground, and some participants with an M capacity of 4 were able to perform the set with a run-up. This suggests that our original task analysis (the one presented in a previous section) overestimated by 1 unit the M capacity required for the set with feet on the ground and for the set with run-up.

Consequently, we revised the initial model. We did not alter the general prediction of an M capacity threshold for each task, with increasing thresholds for more complex tasks and the specific assumptions that these thresholds would be 6 units for the spike and 7 units for the spike against the block. However, now we assumed thresholds of 3 units (instead of 4) for the set with feet on the ground, and 4 units (instead of 5) for the set with run-up. This "revised prediction" entails that only the cells highlighted in Table 4 should be empty. As one can see in the table, the total of observed frequencies in the

Table 4
Contingency table between volleyball level and M capacity.

M capacity	3	4	5	6	7	8
Spike against the Block	0 (0.86)	0 (0.52)	1 (1.14)	0 (1.00)	3	1
Spike	0 (5.31)	0 (3.25)	2 (7.09)	11	9	9
Set with Run-up	1 (7.20)	5 (4.40)	17	10	8	1
Set (feet on the ground)	11 (2.91)	4	2	0	0	0
Toss	5	2	2	0	0	0
Basic Task	1	0	0	0	0	0

Note. The numbers in parentheses indicate the frequencies expected by chance in the cells that, according to the predictions derived from our original task analysis, should be empty. The cells with gray shading are those predicted to be empty according to our revised task analysis (see text).

critical cells was 4 compared with a total of expected frequencies in the critical cells = 26.37; Del = .848 (SE = .074), z = 11.40, p < .001, 99% CI [.656, 1.040]. Because the confidence interval is entirely positive and includes Del = 1, this revised prediction can be considered accurate. Of course, revising a quantitative prediction also implies revising the task analysis on which the original prediction was based. In the final Discussion, we explain in more detail which aspects of the task analysis need to be modified according to the revised prediction and which behavioral observations suggest that it is justified to do so.

Analyses on the full sample

We also performed all of the analyses reported above on the entire sample (N = 120) and found results substantially similar to those for the female subsample; although the values of correlations or other statistics changed by 1 or 2 hundredths, the pattern of significant results remained the same. In particular, also in the entire sample M capacity turned out to be the crucial predictor for the proper execution of the attack in volleyball, whereas regarding precision the only significant β was obtained for years of volleyball.

Discussion

The aims of our study were (a) testing the hypothesis that M capacity represents an important predictor of motor learning in the specific task of attack in volleyball, (b) verifying the role of expertise as a predictor of both correct execution and precision, and (c) evaluating the adequacy of our task-analytic model.

We found that the results supported the first two hypotheses of this research. M capacity proved to be a highly predictive variable for correctly performing the attack in volleyball; conversely, expertise seems to represent the crucial predictor of the technical gesture polish.

This clear dissociation between the measures of correct execution and those of precision seems to indicate the existence of different learning processes serving different purposes. This seems consistent with Fitts's (1964; see also Fitts & Posner, 1967) theory, namely that when an athlete learns a new motor gesture, he or she goes through three stages—cognitive, associative, and autonomous—which differ from one another in both the degree of mastery with which the gesture is accomplished and its demand of attentional resources. So, in the cognitive phase, when a gesture is learned in the first place, one needs to rely on M capacity, exploiting attentional resources, whereas in the associative stage, motor sequences are easier to accomplish because their succession has been repeated many times. Pascual-Leone (1976a, 1976b; see also Pascual-Leone & Goodman, 1979) made a similar distinction by positing two different types of learning that lead to the formation of a superordinate scheme from the coordination of two (or more) schemes activated simultaneously. He described two L (for structural learning) operators labeled LC and LM. The first one involves a gradual learning process based on the repeated coactivation of two or more schemes; LM learning, on the other hand, is rapid and produced by the use of the M capacity. Based on these theories, we can suggest that the cognitive phase involves the LM operator, whereas in a subsequent associative phase the LC operator is summoned, which coordinates different schemes because of their repeated coactivation, that is, experience. In other words, to correctly perform a motor task, the fundamental requirement is the ability to integrate all motor schemes involved; once the "basic" movement has been acquired, repeating it again and again allows the athlete to automatize it and increase its precision in order to reach a nearly perfectly polished gesture.

It is reasonable to think that M capacity and expertise jointly influence performance; for example, experience can lead to automatization or chunking of certain motor schemes, thereby lightening the M demand for a given motor task. On the other hand, well-developed M capacity can assist the athlete in quickly learning the technical gestures, allowing faster improvement.

Our main result of a prominent role of M capacity in motor performance seems consistent with findings of other studies (Behmer & Fournier, 2014; Furley & Memmert, 2012; Seidler et al., 2012), which showed how individual differences in working memory are related to motor sequence learning and decision making in complex situations. This study also confirms Corbett and Pulos's (1999) idea that the motor abilities that correlate most with M capacity are the most complex ones, which require one to attend to several schemes at one time; this not only is true for very young children but also can be seen as a developmental pattern.

Finally, our third hypothesis (Bisagno & Morra, 2013) that M capacity sets a limit in performing certain gestures was supported by the prediction analyses of cross-classification; the more specific task analysis predictions were confirmed only in part, but the results themselves offered indications on how to improve the model. In particular, it was possible to observe how the set from standstill, which—according to our task analysis—should have requested an M capacity of at least 4 units, was actually performed by athletes with an M capacity of 3 units. In the same way, the set with run-up seems to require fewer attentional resources than predicted (4 instead of 5 schemes); we can use this information to correct our task analysis.

The schemes that we assumed to be necessary for the execution of the set from standstill were direction on the horizontal plane, passing over the net, body and hands positioning, and clearance timing. Those for the set with run-up were direction on the horizontal plane, passing over the net, monitoring the airborne phase of the ball, run-up control, and attack timing. To discover where the flaw in our model was, we returned to the video-recordings and noted that, in the set with feet on the ground, errors due to wrong positioning of body and hands were practically nonexistent. It is quite possible that the body and hands positioning, in the set gesture, is so extensively trained that it does not represent a load for M capacity. Regarding the set with run-up, it seems possible that the direction on the horizontal plane and passing over the net schemes at this point are actually chunked into a single representation; this possibility was suggested to us by the rarity of observation of balls thrown against the net in the video-recordings of sets with run-up. Our task analysis of the spike instead seems to already be accurate. The six hypothesized schemes were direction on the horizontal plane, throwing depth, monitoring the airborne phase of the ball, run-up control, attack timing, and closing movement of the wrist. Further observation of the recordings of the athletes engaged in the task, and of their most common errors, confirmed in particular that monitoring the airborne phase of the ball and attack timing are actually different schemes. The errors related to this skill, in fact, seemed to be mainly of two types; some athletes started the run-up in the wrong moment, and others delayed the "stroke" with their arm too much.

The possibility of testing a precise task analysis model is one of the advantages of the TCO; indeed, this framework affords a quantification of individual participants' M capacity and a quantitative evaluation of the capacity demand of each task, and it offers a developmental model of capacity growth. Studying the role of working memory in this perspective allowed us not only to find a global relation with motor learning but also to formulate specific quantitative hypotheses; this is not possible in all approaches. For example, we can make a comparison with another recent study by Buszard et al. (2017), who found differences in basketball shooting learning between children (aged 8–10 years) of higher and lower working memory capacity. However, the framework they used did not allow them to formulate precise assumptions on the cognitive demand of learning from the instructions provided to the participants, or on the size of the working memory capacity of the participants, derived from the working memory tasks they used. Consequently, in Buszard and colleagues' study, only an interesting but global relation between working memory capacity and motor performance could be detected. Thus, an advantage of the TCO framework is enabling more fine-grained predictions on performance as well as putting them in relation with a more general cognitive-developmental model.

Identifying in the TCO a good framework for the theoretical modeling of motor learning processes can be useful not only for research purposes but also for practical applications. In fact, knowing the M demand of each technical gesture would allow us to improve training curricula for young athletes and, through a separate automatization of some schemes involved in movements, could facilitate faster learning of complex tasks. Besides the creation of customized curricula, the task analysis of movements could assist in training those "late" athletes who start playing sports after 10 years of age and, therefore, must quickly learn complex athletic gestures. Also on the practical side, the benefits that coaching could gain from this line of study are, therefore, many and worthy of being explored.

A limitation of our research is the low number of male participants in the sample and their uneven distribution among the age groups; for this reason, our findings are generalizable only to female volleyball athletes. However, we have no reason to think that male athletes rely on different cognitive processes when they are learning a new motor gesture. To verify this, it would be interesting to repeat this study with both a male sample and a female sample.

Another possible development could be studying the role of M capacity and expertise in other sports with different characteristics; indeed, a classical categorization of sports distinguishes them according to the prevailing type of movement: Poulton (1957) defined as "open-skills sports" those occurring in contexts with a high number of uncontrollable variables such as volleyball, all other team sports, and disciplines involving a direct opponent (e.g., fencing, combat sports, tennis). In these sports, the gesture cannot be completely programmed in advance, so the load placed on M capacity seems to be quite high. By contrast, "closed-skills sports" are characterized by an environment with a low number of uncontrollable variables because every single gesture is highly automatized. This happens in disciplines such as gymnastics, dance, shooting, and bowling. It would be interesting to test the hypothesis that in open-skills sports, where specific techniques are learned and then adapted to the contingent game situation, M capacity is very predictive of high performance because athletes have a higher amount of information to "handle," whereas in closed-skills sports, where automatization reduces the load placed on working memory, expertise should be more predictive of good performance. (See also Furley, Schweizer, & Bertrams, 2015 on the distinction between automatic and WM-demanding processes in sport performance.)

Finally, it would be interesting to expand this study by including a greater number of predictors of sports performance such as executive functions, attentional style, and emotion regulation. Research on the role of executive functions in sports performance is rather limited and very recent; most studies find a significant role of executive function in predicting a good performance, mainly in team sports (Chang et al., 2013; Nakamoto & Mori, 2008; Verburgh, Shreder, Van Lange, & Oosterlaan, 2014; Wang et al., 2013), so it seems legitimate to hypothesize that open-skills sports, where a fast reaction to the unexpected is needed, involve executive mechanisms more strongly than closed-skills sports. Moreover, it would be interesting to investigate the relation between executive functioning—inhibitory mechanisms in particular—and working memory in predicting sport performance; indeed, this relation is already attested in other domains such as academic performance and problem solving (Rosen & Engle, 1998; Zook, Davalos, DeLosh, & Davis, 2004). In addition Pascual-Leone (1983; see also Howard, Johnson, & Pascual-Leone, 2014) hypothesized a role of inhibition in synergy with the M operator. However, this relation is still under-researched in the motor performance field even though some studies (e.g., Furley & Memmert, 2012) found a relation between working memory and inhibitory control, which could suggest a moderation effect. Regarding attentional style, Nideffer (1976) suggested that different kinds of sport could benefit from different regulation of both focus and direction of the attention; for example, athletes of open-skills sports could benefit from a more widespread and external focus of attention in order to monitor the environment, whereas athletes practicing closed-skills sports would find a narrow and internal focus of attention more effective in order to correctly practice their routines. Finally, emotion regulation could play a moderating role in the relation between M capacity and performance. In this respect, some studies highlight how negative emotions (i.e., competitive anxiety) can subtract cognitive resources from the athlete, thereby worsening his or her performance (Baumeister, 1984; Beilock, 2007; Hill, Hanton, Matthews, & Fleming, 2010; Klein & Boals, 2001); on the other hand, Talarico, Berntsen, and Rubin (2009) suggested that positive emotions could "enhance" various memory systems. Another interesting hypothesis to test is whether there is a moderation effect of the negative and/or hedonic tone experienced by athletes before the competition on the relation between M capacity and sports performance.

In conclusion, we think that this study shows that it is rewarding to formulate detailed and developmental models in order to examine the role of working memory and cognitive processes and to derive testable hypotheses on the acquisition of abilities, also in the field of sports.

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