

Please cite this article in press as: Wang Z et al. The effect of motor imagery with specific implement in expert badminton player. *Neuroscience* (2014), <http://dx.doi.org/10.1016/j.neuroscience.2014.06.004>

Neuroscience xxx (2014) xxx–xxx

THE EFFECT OF MOTOR IMAGERY WITH SPECIFIC IMPLEMENT IN EXPERT BADMINTON PLAYER

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Abstract—Motor skill can be improved with mental simulation. Implements are widely used in daily life and in various sports. However, it is unclear whether the utilization of implements enhances the effect of mental simulation. The present study was designed to investigate the different effects of motor imagery in athletes and novices when they handled a specific implement. We hypothesize that athletes have better motor imagery ability than novices when they hold a specific implement for the sport. This is manifested as higher motor cortical excitability in athletes than novices during motor imagery with the specific implement. Sixteen expert badminton players and 16 novices were compared when they held a specific implement such as a badminton racket and a non-specific implement such as a plastic bar. Motor imagery ability was measured with a self-evaluation questionnaire. Transcranial magnetic stimulation was used to test the motor cortical excitability during motor imagery. Motor-evoked potentials (MEPs) in the first dorsal interosseous (FDI) and extensor carpi radialis muscles were recorded. Athletes reported better motor imagery than novices when they held a specific implement. Athletes exhibited more MEP facilitation than novices in the FDI muscle with the specific implement applied during motor imagery. The MEP facilitation is correlated with motor imagery ability in athletes. We conclude that the effects of motor imagery with a specific implement are enhanced in athletes compared to novices and the difference between two groups is caused by long-term physical training of athletes with the specific implement. © 2014 Published by Elsevier Ltd. on behalf of IBRO.

Key words: implement, motor-evoked potential, motor imagery, training, transcranial magnetic stimulation.

INTRODUCTION

Physical training improves motor skills in sports (Nakata et al., 2010). In particular, previous studies have demonstrated that long-term physical training with specific implements leads to functional and structural alterations in multiple brain areas in expert players of racket sports (Lees, 2003; Maravita and Iriki, 2004), such as soft tennis (Ohguni et al., 2009), badminton (Di et al., 2012), table tennis (Jafarzadehpur and Yarigholi, 2004) and tennis (Fourkas et al., 2008).

The effects of physical training may be enhanced with mental simulation both in athletes and novices (Driskell et al., 1994; Gregg et al., 2011). Motor imagery is the mental process of a motor task in the absence of movement and muscle activity (Hanakawa et al., 2003). The effects of motor imagery are modulated by the interactions between various physiological and psychological factors in a complex manner (Decety et al., 1989; Lafleur et al., 2002; Jackson et al., 2003; Bakker et al., 2008; Saimpont et al., 2012). It is widely accepted that motor imagery and real motor execution share similar neuronal elements at cortical and subcortical levels in the motor pathways (Grezes and Decety, 2001). If a transcranial magnetic stimulation (TMS) is delivered to the primary motor cortex during motor imagery, motor-evoked potential (MEP) in the target muscle is facilitated compared to that at rest condition (Fadiga et al., 1998; Hashimoto and Rothwell, 1999). The degree of MEP facilitation depends on the excitability of the motor pathway at the time of motor imagery. Using TMS, it has been reported that expert tennis players show increased corticospinal excitability during motor imagery of a tennis forehand but not during motor imagery of a table tennis forehand or the golf drive (Fourkas et al., 2008). This study suggests that the motor cortical network is altered by long-term training with specific implements. The results further support the notion that utilization of specific implements leads to functional or structural changes in the brain (Elbert et al., 1995; Draganski et al., 2004; May et al., 2007). However, it is not clear whether the application of a specific implement during the motor imagery enhances the effect of this mental process.

Badminton is a racket sport involving intermittent movements with high intensity in short periods. The high-level performance in handling the racket requires a

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Abbreviations: ANOVA, analysis of variance; ECR, extensor carpi radialis; EMG, electromyogram; FDI, first dorsal interosseous; MEP, motor-evoked potential; MIQ, movement imagery questionnaire; RMT, resting motor threshold; TMS, transcranial magnetic stimulation.

61 fine combination of perception and action which is related
62 to high cortical functions with activity in different brain
63 regions (Lees, 2003; Maravita and Iriki, 2004). Therefore,
64 expert badminton player provides a good model for inves-
65 tigating how the long-term utilization and application of a
66 specific implement may affect the brain functions. In the
67 present study, we investigated the effect of motor imagery
68 with a specific implement (badminton racket) in athletes
69 (expert badminton players) and novices. We hypothesize
70 that the effects of motor imagery are enhanced in athletes
71 compared to novices when they handle the specific imple-
72 ment. This can be tested by measuring the different motor
73 outputs with different degrees of MEP facilitation during
74 motor imagery in the two subject groups.

75 Long-term training with implements leads to better
76 performance in athletes (Maravita and Iriki, 2004;
77 Nakata et al., 2010). However, it is not known whether
78 the performance of motor imagery with a specific imple-
79 ment is also affected by the long-term physical training.
80 We tested the motor imagery ability with kinesthetic and
81 visual items in athletes and novices (Hall and Martin,
82 1997). Our second hypothesis is that athletes will show
83 better motor imagery ability than novices when they han-
84 dle the implement. In addition, the better motor imagery
85 ability will be correlated with larger MEP facilitation during
86 motor imagery in athletes.

87 EXPERIMENTAL PROCEDURES

88 Subjects

89 Sixteen expert badminton players (athletes, eight women,
90 mean age 20.0 ± 1.4 years) and 16 age- and gender-
91 matched healthy subjects (novices, eight women, mean
92 age 20.8 ± 1.9 years) participated in the study. All
93 subjects were right-handed, confirmed using the Oldfield
94 Handedness Inventory (Oldfield 1971). Expert
95 badminton players were Chinese national first-class or

96 second-class athletes who had experience in
97 competition at national or international tournaments. The
98 average training time for athletes was 14.1 ± 1.9 h per
99 week for 11.1 ± 1.2 years. Novices were university
100 students with no formal badminton training experience.
101 All subjects provided written informed consent in
102 accordance with the Declaration of Helsinki. The
103 experimental protocol was approved by the Human
104 Research Ethics committee of the Shanghai University
105 of Sport.

106 Behavioral measures for motor imagery

107 Behavioral measures and TMS measures were
108 performed on two separate days at least two weeks
109 apart in a random order. For the behavioral measures,
110 we measured the time course of motor imagery in
111 athletes and novices. First, subject performed the motor
112 task physically. The motor task was a badminton
113 serving task. A short period of training was performed
114 before recording. A brief instruction with basic rules of
115 badminton was provided for novices. The motor task
116 was performed 20 times. An acoustic cue was given as
117 the start signal for serving. The time at the delivery of
118 cue was defined as time 0. The time course 1 s before
119 the cue to the time when the shuttlecock landed on the
120 floor was video-recorded (Fig. 1A). For the motor
121 imagery task, the subjects were seated comfortably in a
122 chair and wore an eye mask. The present study was
123 designed to investigate the different effects of motor
124 imagery with different implements (specific vs. non-
125 specific) in athletes and novices. To this end, the effects
126 of motor imagery with a badminton racket (specific
127 implement) were compared to that with a plastic bar
128 (non-specific implement) in the two subject groups
129 (Fig. 1B). A commercial plastic bar was used for a non-
130 specific implement because it had a similar weight and
131 shape as the badminton racket. We assumed that

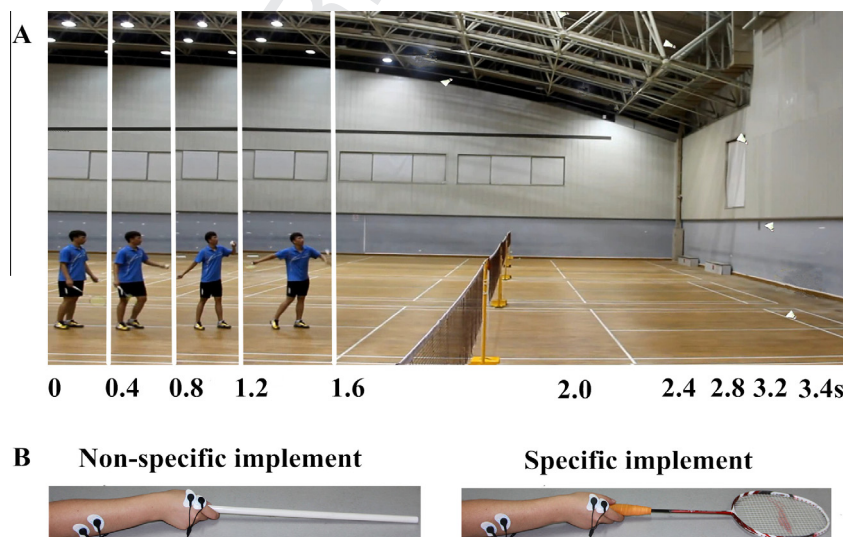


Fig. 1. Motor task and experimental setup. (A) Badminton serving performed by a representative expert player. The time course of the badminton serving was recorded. For the motor imagery task, subject was instructed to perform the task in the same way mentally. (B) Motor imagery was performed when the subject held a non-specific implement such as plastic bar (left) or when they held a specific implement such as badminton racket (right).

132 athletes can distinguish the racket from the plastic bar
133 with different hand-friendliness between two implements
134 while novices cannot. For motor imagery, subjects were
135 instructed to perform the badminton serving task
136 mentally in the situation that they were standing in front
137 of the net and facing their opponents' half of court.
138 Motor imagery of performing their own serving task with
139 a first-person perspective was likely being used by most
140 subjects with such instruction. At the end of the motor
141 imagery when the shuttlecock struck the floor in the
142 mental process the subject pressed a button. The
143 duration of motor imagery was calculated. Two blocks of
144 motor imagery with specific and non-specific implements
145 were performed on a same experimental day. Each
146 block consisted of 20 trials. The order for two blocks of
147 motor imagery with different implements was
148 randomized. However, the block for real execution of
149 the task was always performed before the blocks for
150 motor imagery.

151 To assess motor imagery ability in each subject, the
152 process of motor imagery was measured with self-
153 evaluation using the revised version of movement
154 imagery questionnaire (MIQ) (Hall and Martin, 1997;
155 Fourkas et al., 2008). We first tested the hand-friendliness
156 with different implements in two subject groups. A 5-point
157 Likert-type scale with a score of 5 corresponding to the
158 best friendliness was used. We further tested motor imag-
159 ery with different implements with detailed items for kines-
160 thetic and visual properties. The measures included
161 4 kinesthetic and 4 visual items using a 7-point scale with
162 a score of 7 corresponding to the highest clarity or inten-
163 sity during the imagery. Four kinesthetic items were diffi-
164 culty of imagery, sequence of muscle contraction, muscle
165 tension and hitting force during imagery. Four visual items
166 were difficulty of imagery, clarity of serving action, clarity
167 of shuttlecock flying path and clarity of shuttlecock landing
168 in opponent's court during imagery. The average scores
169 of 4 items for kinesthetic and visual properties were
170 calculated.

171 The strategy used by the subject during motor
172 imagery is important for this mental process. Our
173 subjects were instructed and supposed to perform motor
174 imagery with a first-person perspective. In a subgroup of
175 9 athletes and 9 novices, we tested whether the
176 subjects used the first-person perspective during motor
177 imagery with a self-evaluation questionnaire. The test
178 consisted of three introspective questions in a 5-point
179 scale. The first question asked the subject directly
180 whether the first-person perspective was used under
181 different experiment conditions with specific and non-
182 specific implements. A score of 5 to this question
183 corresponds to the strongest agreement to the first-
184 person perspective during motor imagery while a score
185 of 1 corresponds to the strongest agreement to the
186 third-person perspective. If the subject indicated that a
187 first-person perspective (scored beyond 3; 3
188 corresponding to neutral position) was used in motor
189 imagery, we asked two more questions. The following
190 two questions asked the subject whether the motor
191 imagery was easily controlled (second question) and
192 whether it was clear (third question) with the first-person

perspective. A 5-point scale with 5 corresponding to the
highest easiness or clearness was used.

Neurophysiological measures with transcranial magnetic stimulation

Surface electromyogram (EMG) was recorded from the
right first dorsal interosseous (FDI) and extensor carpi
radialis (ECR) muscles with 9-mm diameter Ag-AgCl
surface electrodes. The active electrode was placed
over the muscle belly. The reference electrode was
placed over the metacarpophalangeal joint of the index
finger for FDI muscle and was 2 cm away from the
active electrode for the ECR muscle. FDI and ECR
muscles were selected for recording because they are
representative hand and forearm muscles and they play
important roles in the badminton serving (preliminary
discussion with national badminton coaches). The signal
was amplified (1000 times), band-pass filtered (2 Hz–
2.5 kHz, Micromed, Matrix 1005, Italy), digitized at
10 kHz by an analog-to-digital interface (Micromed,
MT2502A, Italy) and stored in a computer for off-line
analysis.

TMS was applied to the left primary motor cortex with
a figure-of-eight shaped coil (outside diameter of each
loop was 9.5 cm) connected to a Magstim 200
stimulator (Magstim, Whitland, Dyfed, UK). The handle
of the coil pointed backward at 30–45° from the mid-
sagittal line. The induced current in the brain was in the
posterior–anterior direction, approximately perpendicular
to the central sulcus (Kaneko et al., 1996; Di Lazzaro
et al., 2001). The optimal location where TMS with slight
superthreshold intensity produced the largest MEP in
FDI muscle was marked with a pen as the motor hot spot.
This location was also the optimal location for ECR mus-
cle in most subjects. Resting motor threshold (RMT) was
defined as the lowest TMS intensity that evoked MEP of
more than 50 μ V in FDI muscle in at least five out of ten
consecutive trials when the muscle was completely
relaxed. We used TMS intensity of 120% RMT and pro-
duced MEP of 0.5–1 mV in FDI muscle at rest condition
in both athletes and novices.

The different effects of motor imagery in two subject
groups were compared under different experimental
conditions (specific and non-specific implements). The
subject was instructed to perform the motor imagery
after the acoustic cue. This was compared to a resting
state during which the subject held the implement and
maintained the muscle relaxation. TMS was delivered
during the motor imagery or at rest. For motor imagery,
TMS was delivered at the middle of badminton serving
during the motor imagery. The timing was adjusted
individually according to the video-recorded real-time
course in each subject because the time was different
across all subjects. In addition, the time course was also
slightly different for motor imagery and real motor
execution (see results and Fig. 2). We obtained
feedback from the subjects during the experiment. If the
subject reported that TMS was applied before the
serving began or after the shuttlecock passed the net in
the motor imagery, the recording was discarded from the

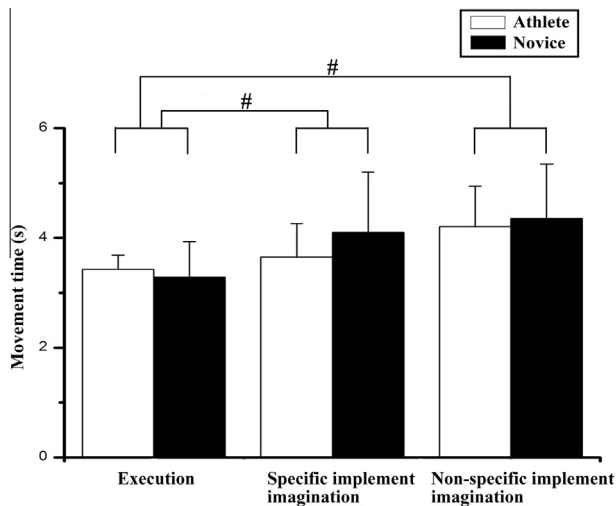


Fig. 2. Duration for performing the motor task under various experimental conditions in athletes and novices. Group analysis with data obtained from 16 athletes (white columns) and 16 novices (black columns). The ordinate shows the duration for performing the motor task under various experimental conditions. Three experimental conditions were compared: real execution of the motor task, motor imagery with specific and non-specific implements. # $p < 0.05$, post-hoc paired t -test comparing execution of real motor task to motor imagery.

final data analysis. For most subjects, TMS was delivered at about 1.5 s after the acoustic cue. We set an inter-trial interval of 10 s to avoid fatigue for the motor imagery task. For the rest condition, subjects were instructed to keep relaxed both physically and mentally. TMS was delivered in a random inter-trial interval of 12–15 s. Therefore, the interval between TMS pulses for motor imagery (inter-trial interval of 10 s + motor imagery task of about 4 s) and rest condition was similar. The experiment for TMS measures consists of four blocks (specific and non-specific implements \times motor imagery and at rest). Twenty trials for each block were recorded in a random order.

We further tested whether the different effects of motor imagery between athletes and novices with different implements (see results) were simply due to the existence of implements but not due to the type of implements during motor imagery. A subgroup of 9 athletes and 9 novices participated in this control experiment. Motor imagery without implements (no implement) was compared to same motor imagery with specific and non-specific implements. TMS was delivered in the same way as the main experiment. Six blocks (specific implement, non-specific implement and no implement \times motor imagery and at rest) with twenty trials in each block were recorded in a random order.

Data and statistical analysis

Values are reported as mean \pm standard deviation. Background EMG 50 ms before the TMS delivery was rectified and integrated. MEP amplitude was measured peak-to-peak. In addition, we also calculated the MEP ratio between MEP amplitude during motor imagery and that at rest for different experimental conditions.

The MIQ scores in athletes and novices were compared using a non-parametric Mann–Whitney U test. A two-way repeated measures analysis of variance (ANOVA) with group as the between-subject factor and implement as the within-subject factor was used to test the difference in the duration for performing the motor task and MEPs under different experimental conditions. Unpaired (between-subject comparisons) and paired (within-subject comparisons) t -test with Bonferroni correction for multiple comparisons was used for post hoc analysis if ANOVA showed significant interaction. Further analysis with non-parametric Spearman rank correlation was performed to explore the relationship between MEP ratio (motor imagery/at rest) and MIQ scores. In addition, we performed an analysis for detecting outliers before the correlation test. Subject either with MEP ratio or MIQ score located outside of mean ± 2 standard deviation (corresponding to $p < 0.05$) was defined as an outlier and was excluded from the final correlation analysis. The threshold for significance was set at $p < 0.05$.

RESULTS

Behavioral measures

The duration of badminton serving was similar for athletes and novices ($F_{1,60} = 0.40$, $p = 0.530$) although the main effect for experimental condition (real execution, motor imagery with specific and non-specific implements) was significant ($F_{2,60} = 15.50$, $p < 0.001$) (Fig. 2). The interaction between main effects of group and experimental condition was not significant ($F_{2,60} = 1.58$, $p = 0.214$). Further post hoc test revealed that the time for real motor task execution was shorter than that for motor imagery with both specific and non-specific implements ($p < 0.05$ for both comparisons) while the time course of motor imagery was not different between two types of implements.

Motor imagery ability was assessed with MIQ scores (Table 1). Athletes reported better hand-friendliness than novices with specific implements ($Z = 4.13$, $p < 0.001$). This resulted in better performance of motor imagery with kinesthetic items in athletes than that in novices ($Z = 4.35$, $p < 0.001$). However, the performance with visual items was not different between two subject groups ($Z = 0.21$, $p = 0.832$). On the other hand, there was no difference for hand-friendliness ($Z = 0.46$, $p = 0.643$), motor imagery either with kinesthetic items ($Z = 0.54$, $p = 0.588$) or visual items ($Z = 0.23$, $p = 0.819$) between athletes and novices when they held the non-specific implement.

In addition, we used an introspective questionnaire to test whether our subjects performed motor imagery with first-person perspective. The results (Table 1) showed that both athletes and novices confirmed by themselves that first-person perspective was used during motor imagery for both experimental conditions with specific and non-specific implements. This was supported by easy control and high clearness during motor imagery in both groups.

Table 1. Behavioral measures under various experimental conditions in athletes and novices

	Non-specific implement		Specific implement	
	Athlete	Novice	Athlete	Novice
Movement imagery questionnaire ($N = 16$)				
Hand-friendliness	1.9 ± 0.8	1.9 ± 0.7	4.0 ± 1.0	2.1 ± 0.7***
Kinesthetic items	4.0 ± 0.7	3.9 ± 0.6	5.7 ± 0.8	4.1 ± 0.7***
Visual items	5.1 ± 0.8	5.2 ± 0.6	5.2 ± 0.4	5.3 ± 0.5
First-person perspective ($N = 9$)				
Perspective	4.7 ± 0.7	4.7 ± 0.5	4.7 ± 0.4	4.6 ± 0.5
Control	3.9 ± 1.3	3.8 ± 1.1	4.0 ± 1.1	3.9 ± 1.3
Clearness	3.7 ± 1.3	3.7 ± 1.1	3.8 ± 1.1	3.6 ± 1.3

Test for movement imagery questionnaire was performed in all subjects ($N = 16$ for both athletes and novices). Test for first-person perspective during motor imagery was performed in a subgroup of subjects ($N = 9$ for both athletes and novices).

Hand-friendliness is scored by a 5-point scale with 5 representing the best friendliness with an implement and 1 representing the worst friendliness with the implement. Values for kinesthetic and visual items are the average scores of 4 items in each category. Each item is scored by a 7-point scale with 7 representing the best performance (intensity felt or clarity seen by the subject) and 1 representing the worst performance.

Test for first-person perspective is scored by a 5-point scale with 5 representing the strongest agreement to the first-person perspective. Further items test the easiness and clearness of imagery with this first-person perspective using the 5-point scale with 5 representing the highest easiness and clearness.

*** $p < 0.001$, non-parametric Mann–Whitney U test, comparing athlete to novice.

343 Neurophysiological measures

344 No background EMG was found in either FDI or ECR
345 muscle under any experimental condition in either
346 subject group. RMT was similar in two subject groups
347 (athlete, $43.6 \pm 3.5\%$; novice, $44.3 \pm 3.0\%$ stimulator
348 output; $t_{30} = 0.55$, $p = 0.464$).

349 We first analyzed MEP in the FDI muscle. At rest
350 condition, TMS with 120% RMT stimulus intensity
351 produced MEP with similar amplitude in both athletes
352 and novices when they held a specific implement or a
353 non-specific implement (Fig. 3A and Table 2). There
354 was no significant effect of group ($F_{1,30} = 0.19$,
355 $p = 0.668$), implement ($F_{1,30} = 0.27$, $p = 0.608$) or their
356 interaction ($F_{1,30} = 1.31$, $p = 0.261$) at rest condition.
357 However, significant effects for group ($F_{1,30} = 19.27$,
358 $p < 0.001$), implement ($F_{1,30} = 14.21$, $p = 0.001$) and
359 their interaction ($F_{1,30} = 11.59$, $p = 0.002$) were found
360 during motor imagery. Post hoc tests showed that
361 athletes had more MEP facilitation than novices when
362 they performed motor imagery with a specific implement
363 ($p < 0.001$) but not with a non-specific implement
364 ($p = 0.917$). In addition, comparison in each subject
365 group showed that MEP was larger with a specific
366 implement than that with a non-specific implement in
367 athletes ($p < 0.001$) but not in novices ($p = 0.747$).
368 Further analysis using MEP ratio between two
369 experimental conditions (motor imagery/at rest)
370 confirmed the difference between two groups in holding
371 a specific implement (Fig. 3B). ANOVA found significant
372 effects for group ($F_{1,30} = 6.165$, $p = 0.019$), implement
373 ($F_{1,30} = 7.05$, $p = 0.013$) and their interaction
374 ($F_{1,30} = 9.34$, $p = 0.005$). Post hoc tests showed that
375 the MEP ratio was larger in athletes than novices with a
376 specific implement ($p < 0.001$) but not with a non-
377 specific implement ($p = 0.335$). In addition, MEP ratio
378 with a specific implement was larger than that with a
379 non-specific implement in athletes ($p < 0.001$) but not in
380 novices ($p = 0.683$).

381 Different results were found in the ECR muscle
382 (Fig. 3C, D and Table 2). No significant main effect of
383 group (at rest, $F_{1,30} = 0.04$, $p = 0.853$; motor imagery,

384 $F_{1,30} = 0.02$, $p = 0.885$), implement (at rest,
385 $F_{1,30} = 0.31$, $p = 0.584$; motor imagery, $F_{1,30} = 0.35$,
386 $p = 0.558$) or their interaction (at rest, $F_{1,30} = 0.01$,
387 $p = 0.994$; motor imagery, $F_{1,30} = 0.06$, $p = 0.809$) was
388 found in MEP amplitude either at rest condition or
389 during motor imagery. Analysis of MEP ratio between
390 two experimental conditions showed similar results with
391 no significant group ($F_{1,30} = 0.23$, $p = 0.638$),
392 implement ($F_{1,30} = 0.03$, $p = 0.864$) effect and their
393 interaction ($F_{1,30} = 0.01$, $p = 0.999$).

394 We further tested if motor imagery without implements
395 was different from that with implements (specific and non-
396 specific) in a subgroup (Fig. 4). ANOVA explored
397 significant main effects of group ($F_{1,16} = 6.31$,
398 $p = 0.023$), implement ($F_{2,32} = 27.48$, $p < 0.001$), and
399 significant effect of their interaction ($F_{2,32} = 9.27$,
400 $p < 0.001$) for the MEP ratio. Post hoc test confirmed
401 the results from the main experiment that athletes had
402 more MEP facilitation than novices when they
403 performed motor imagery with a specific implement
404 ($p = 0.002$) but not with a non-specific implement
405 ($p = 0.959$). Importantly, additional MEP facilitation was
406 also found in athletes compared to novice under the no-
407 implement condition ($p = 0.043$). We also compared
408 different experimental conditions in two subject groups.
409 In athletes, MEP ratio with specific implements was
410 larger than those with non-specific implements and
411 without implements ($p < 0.001$ for both comparisons).
412 No difference was found between MEP ratios with a
413 non-specific implement and without an implement. On
414 the other hand, MEP ratios both with a non-specific
415 implement ($p = 0.045$) and with a specific implement
416 ($p = 0.025$) was larger than that without an implement
417 in novices. No difference was found between MEP
418 ratios with specific and non-specific implements.

419 Correlation between behavioral and 420 neurophysiological measures

421 Because both MIQ score (behavioral measure) and MEP
422 ratio in the FDI muscle (motor imagery/rest) showed

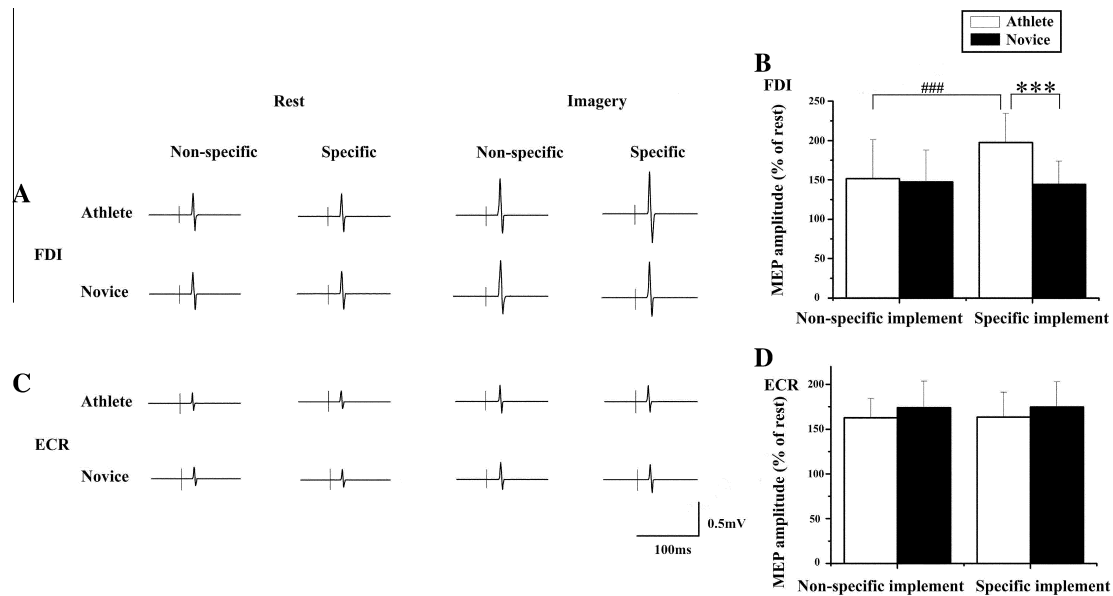


Fig. 3. Example of MEP recordings and MEP ratios under various experimental conditions in athletes and novices. (A) Recordings in first dorsal interosseous (FDI) muscle. (C) Recordings in extensor carpi radialis (ECR) muscle. Left panel shows recordings during motor imagery. (B) and (D) Group analysis for MEP ratio in 16 athletes (white columns) and 16 novices (black columns). (B) Results in FDI muscle. (D) Results in ECR muscle. The ordinate shows MEP ratio expressed as a percentage value of the MEP amplitude during motor imagery to that at rest. *** $p < 0.001$, post hoc unpaired t -test, comparing athlete to novice. ### $p < 0.001$, post hoc paired t -test, comparing specific to non-specific implements.

Table 2. MEP amplitudes (mV) under various experimental conditions in athletes and novices

	Rest		Motor imagery	
	Athlete	Novice	Athlete	Novice
FDI muscle				
Specific implement	0.69 ± 0.11	0.73 ± 0.14	1.33 ± 0.17	1.02 ± 0.14***
Non-specific implement	0.70 ± 0.14	0.71 ± 0.15	1.01 ± 0.18	1.00 ± 0.17
ECR muscle				
Specific implement	0.32 ± 0.07	0.32 ± 0.08	0.50 ± 0.09	0.51 ± 0.04
Non-specific implement	0.32 ± 0.06	0.32 ± 0.08	0.51 ± 0.05	0.50 ± 0.05

ECR, extensor carpi radialis; FDI, first dorsal interosseous.
*** $p < 0.001$, post hoc unpaired t -test, comparing athlete to novice.

423 significant differences between athletes and novices only
424 when a specific implement was used, we analyzed the
425 correlation between these two measures with a specific
426 implement. Data from all subjects showed that the MEP
427 ratio correlated with MIQ scores for kinesthetic items
428 ($Rho = 0.759$, $Z = 3.48$, $p < 0.001$) but did not
429 correlate with MIQ scores for visual items
430 ($Rho = 0.025$, $Z < 0.01$, $p = 0.930$). We further
431 separated the correlation analysis between MIQ score
432 and MEP ratio for different subject groups. The analysis
433 showed that MIQ score with kinesthetic items was
434 significantly correlated with the MEP ratio in athletes
435 ($Rho = 0.597$, $Z = 2.41$, $p = 0.016$, Fig. 5A) but not in
436 novices ($Rho = 0.355$, $Z = 1.30$, $p = 0.194$, Fig. 5B).
437 One outlier was detected for the correlation analysis
438 between the MEP ratio and MIQ score with visual items
439 in athletes. The correlation between two measures was
440 not significant even if the outlier was excluded from the
441 analysis ($Rho = 0.313$, $Z = 1.13$, $p = 0.257$, Fig. 5C).
442 There was also no significant correlation between the

MEP ratio and MIQ scores with visual items in novices
($Rho = 0.250$, $Z = 0.89$, $p = 0.371$, Fig. 5D).

DISCUSSION

We examined how the application of a specific implement during motor imagery affects this mental process. The novel findings were that the degree of MEP facilitation during motor imagery with a specific implement was larger in athletes than that in novices. Motor imagery ability in athletes was better than that in novices with the specific implement. The degree of MEP facilitation correlated with the motor imagery ability in athletes but not in novices when the specific implement was used.

Motor imagery ability

Motor imagery is a subset of mental practice process which can be applied for various sports (Gerardin et al., 2000; Wei and Luo, 2010; Dey et al., 2012) and therapy

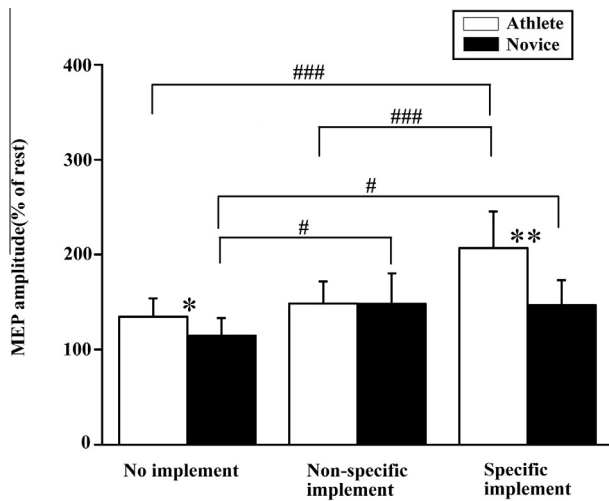


Fig. 4. MEP ratio under various experimental conditions in athletes and novices. Group analysis for MEP ratio in 9 athletes (white columns) and 9 novices (black columns). The ordinate shows MEP ratio expressed as a percentage value of the MEP amplitude during motor imagery to that at rest. * $p < 0.05$, ** $p < 0.01$, post hoc unpaired t -test, comparing athlete to novice. # $p < 0.05$, ### $p < 0.001$, post hoc paired t -test, comparing specific implement to non-specific implement or no implement.

(Page et al., 2007; Malouin et al., 2010; Grangeon et al., 2012) in combination with physical training. We found that the time consumed for motor imagery with both specific and non-specific implements was longer than the time consumed for the real motor task execution in both subject groups, suggesting that the time courses and underlying neural elements for motor imagery and real motor execution may not be completely same although they share similar components in the motor pathways (Fadiga et al., 1998; Hashimoto and Rothwell, 1999; Grezes and Decety, 2001). In addition, there was no difference in the time course between athletes and novices for either motor execution or motor imagery. Therefore, it is likely that similar neural elements are recruited in athletes and novices for both performing the motor task physically and mentally. The MIQ test used in the present study is a reliable measure to evaluate the ability of mental rehearsal of motor skills in both subject groups (Hall and Martin, 1997). Athletes reported motor imagery with better hand-friendliness with specific implements compared to novices. This led to better performance with kinesthetic items in athletes. The results suggest that with the same information by holding the implement, athletes simulate the motor task more accurately and successfully

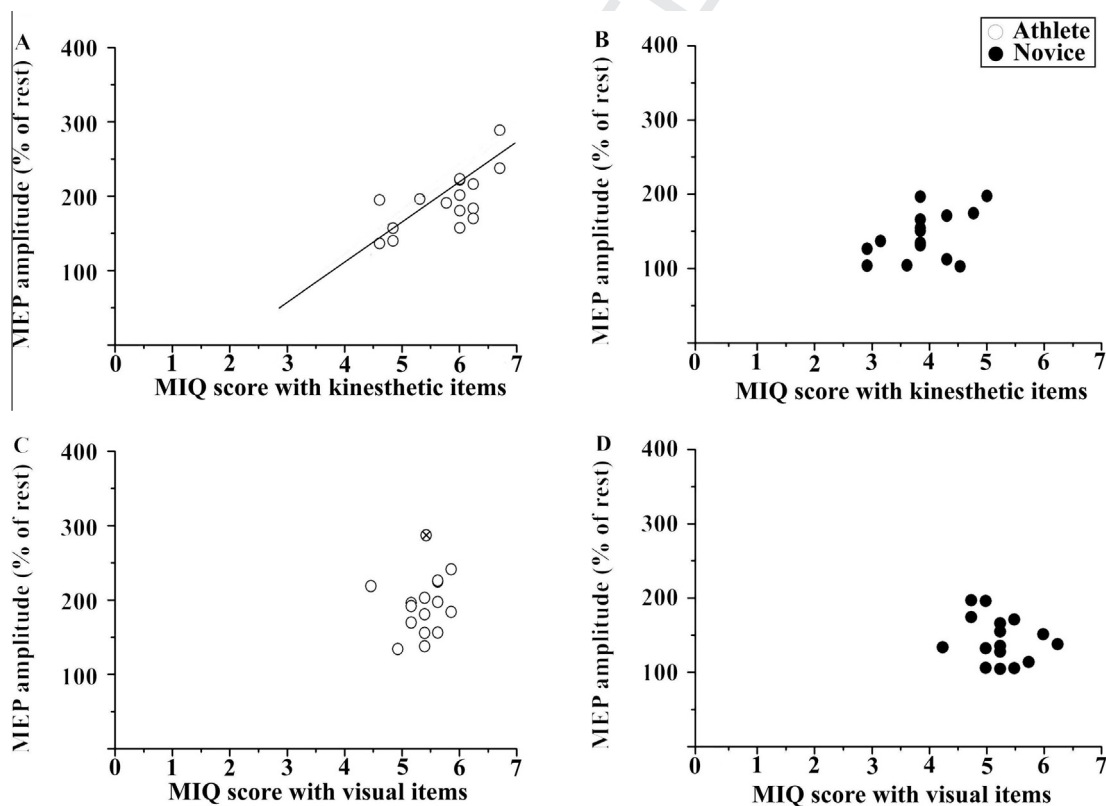


Fig. 5. Relationship between behavioral and neurophysiological measures. The ordinate shows neurophysiological measure with MEP ratio expressed as a percentage value of the MEP amplitude during motor imagery to that at rest. The abscissa shows behavioral measures of motor imagery questionnaire (MIQ) scores with kinesthetic items (A and B) and those with visual items (C and D). Left panels (A and C) show data in athletes and right panels (B and D) show data in novices. Note that an outlier (marked with "x") was detected in (C) and was excluded from the analysis. Solid line in (A) indicates that MEP ratio is correlated with MIQ score with kinesthetic items in athletes, $p < 0.05$.

483 than novices in the mental process. The results may further
484 indicate that athletes have the ability to gather essential
485 information for the mental process of the motor task
486 with the long-term training in the sport. In this regard,
487 our previous study reported similar results in basketball
488 players that athletes showed better anticipation behavior
489 than novices in observation of a basketball free throw task
490 (Wu et al., 2013). In addition, no difference between athletes
491 and novices was found for the visual items of the motor
492 imagery. The results might be explained by the fact
493 that relatively less visual information was available in the
494 present study which eliminated the difference in motor
495 imagery with visual items between the two groups.

496 Motor cortical excitability during motor imagery

497 We found MEP was facilitated during motor imagery with
498 both specific and non-specific implements in both
499 athletes and novices. The result is consistent with
500 previous studies and supports the notion that motor
501 imagery increases the motor cortical excitability (Fadiga
502 et al., 1998; Hashimoto and Rothwell, 1999; Jeannerod
503 and Frak, 1999). More importantly, athletes showed larger
504 MEP facilitation in the target FDI muscle than novices only
505 when they held the specific implement. This was confirmed
506 with the direct comparison of MEP amplitudes and indirect
507 comparison of MEP ratios (motor imagery/at rest; representing
508 the degree of MEP facilitation) between two subject groups.
509 With the experience and knowledge gained from long-term
510 training in the sport, it is likely that athletes are able to
511 perceive the essential information when they hold the specific
512 implement for the sport. Therefore, a reliable process of motor
513 imagery may be initiated with essential information for the
514 task. Alternatively, the essential information from the
515 implement may be used to convert fluent motor command to
516 the primary motor cortex during motor imagery and this leads
517 to increased MEP facilitation in athletes. On the other hand,
518 novices do not have knowledge about handling the specific
519 implement in the sport or they even cannot distinguish the
520 specific implement from a non-specific implement. This was
521 manifested as less MEP facilitation during motor imagery
522 compared to athletes. Similarly, it is also impossible for
523 athletes to gather useful information for the sport to initiate
524 the reliable motor imagery when they handle a non-specific
525 implement. Therefore, no additional MEP facilitation was
526 found for a non-specific implement, either in novices or
527 athletes. In addition, for the comparisons in each subject
528 group we found increased MEP facilitation during motor
529 imagery with a specific implement compared to that with a
530 non-specific implement in athletes but not in novices. It
531 may be argued that the additional MEP facilitation in athletes
532 is simply caused by the course of motor imagery itself but
533 not necessarily requires the application of a specific
534 implement during the motor imagery. We performed the
535 control experiment to address this question. The results
536 showed that motor imagery without implements led to a
537 larger degree of MEP facilitation in athletes than in novices,
538 consistent with previous study in tennis players (Fourkas
539 et al., 2008). Importantly, within-subject comparison
540 showed that additional MEP facilitation during
541

542 motor imagery was pronounced in athletes with specific
543 implements compared to that with no implements and
544 non-specific implement conditions (Fig. 4). The results
545 strongly support the notion that the application of a specific
546 implement during motor imagery enhances the effect of
547 this mental process in athletes. Skilled performance
548 (e.g., racket sports) involves sensorimotor tasks, requiring
549 a close coupling of actions with sensory inputs (Lees,
550 2003). If our subjects (likely only athletes, with long-term
551 training in the sport) considered the racket as an extension
552 of their body parts (Fourkas et al., 2008), such a sensory
553 encoding process would be facilitated with essential inputs
554 from the specific implement during motor imagery. Alternatively,
555 it could be inferred that long-term training develops a
556 pre-set motor program in athletes. A specific implement
557 may have priming effects on this pre-set program when it
558 is initiated. On the other hand, a non-specific implement
559 cannot facilitate or even inhibit this program with no
560 additional MEP facilitation during imagery. Interestingly,
561 novices showed increased MEP facilitation during motor
562 imagery with both specific and non-specific implements
563 compared to that with no implements. The result is
564 consistent with the idea that novices are not able to
565 distinguish specific implements from non-specific
566 implements while sensory inputs with either implement
567 may slightly enhance the sensory encoding process in
568 novices.

569 Badminton is a non contact racket sport with rapid
570 movements in changing directions. This requires a wide
571 range of muscles cooperating in a fine combination (Lees,
572 2003). Surprisingly, additional MEP facilitation during
573 motor imagery with specific implements in athletes was
574 only found in the FDI muscle (an intrinsic hand muscle)
575 but not in the ECR muscle (a forearm muscle). This was
576 different from the result of a previous study in expert
577 tennis players that both hand and forearm muscles showed
578 more MEP facilitation during imagery of the tennis
579 forehand compared to imagery of other sports (Fourkas
580 et al., 2008). Each racket sport poses a unique challenge
581 in combination of speed, power and agility, requiring
582 unique cortical strategy for perception and action in
583 motor control. The different results obtained from the
584 present study and Fourkas et al. (2008)'s study may
585 reflect the different cortical strategies used in badminton
586 and tennis. It is likely that relatively skillful control
587 within intrinsic hand muscles is required in badminton
588 while relatively powerful control in tennis may spread
589 the increased excitability into the muscles in the whole
590 arm. Motor imagery involving high level performance in
591 the absence of muscle activity may further enlarge this
592 difference in the motor pathway (Schmidt and Wrisberg,
593 2003; Miller et al., 2010; Baeck et al., 2012). However,
594 we cannot exclude the possibility that athletes with
595 higher level of skill (e.g., Olympic medalists) have
596 better control in forearm muscles which may lead to
597 additional MEP facilitation during motor imagery
598 compared to novices or athletes tested in the present
599 study (national first or second class). Such higher
600 level of motor control has been reported in pianists. In
601 addition to different patterns of finger movements,
602 pianists and novices show different patterns of forearm
603 and shoulder movements during keystroke tasks (Furuya
604 and Kinoshita, 2008). It should also be noted that the
605 functional

603 role of the primary motor cortex in motor learning is complex. It was reported that even in novices, the size of motor
604 cortical activation map increased after 5-days training of a
605 five-finger sequencing task on the piano (Pascual-Leone
606 et al., 1995). In addition, a 2-week training course of a simple
607 thumb-tapping task with the dominant hand produced
608 MEP facilitation with TMS delivered to the dominant motor
609 cortex. Similarly, the training course with the non-dominant
610 hand produced MEP facilitation in the non-dominant
611 motor cortex. On the other hand, this training course with
612 the non-dominant hand also produced an initial increase
613 followed by a later decrease in cortical excitability in the
614 dominant motor cortex (Koenke et al., 2006). Furthermore,
615 there is increasing evidence showing that the sport-related
616 motor learning process may also involve changes in motor
617 cortical areas outside the primary motor cortex. Study using
618 functional magnetic resonance imaging in middle-aged novices
619 has reported decreased hemodynamic signal strength in non-
620 primary motor areas after 40 h of golf practice when the
621 subjects performed motor imagery of the golf swing task
622 (Bezzola et al., 2012).
623

624 Relationship between neuropsychological and 625 neurophysiological factors in motor imagery

626 Another important finding in the present study was that
627 increased MEP facilitation during motor imagery with
628 specific implements correlated with the MIQ score with
629 kinesthetic items in athletes. MIQ test is a neuropsychological
630 measure which subjectively evaluates the fluency and
631 accomplishment of motor imagery (Hall and Martin, 1997).
632 MEP amplitude is a neurophysiological measure which
633 reflects the excitability of the motor pathway at the time
634 of TMS (Hallett, 2007). During motor imagery, the memory
635 of the motor task is internally recalled. The positive
636 correlation between two measures with a specific
637 implement suggests that better self-evaluation of the
638 internal process is also related to a larger increase in
639 motor cortical output indexed by the neurophysiological
640 measure in athletes. This likely indicates that the
641 accomplishment of a fluent process of motor imagery
642 requires the integration of internal process and external
643 inputs at certain regions in the cortical network
644 (Olsson and Nyberg, 2010). Our previous study with
645 functional magnetic resonance imaging performed during
646 anticipation of a motor task in athletes explored
647 increased activity in inferior frontal gyrus and inferior
648 parietal lobe where mirror neuron systems may be
649 involved (Wu et al., 2013). MEP ratio did not correlate
650 with MIQ score with visual items. This was consistent
651 with the result that motor imagery with visual items
652 was not different between two subject groups. We
653 instructed our subjects to perform motor imagery of
654 their own badminton serving (with the position standing
655 in front of the net and facing the opponent's half of
656 court). Therefore, our subjects likely took internal and
657 first-person perspective during motor imagery. In addition,
658 a questionnaire with self-evaluation from a subgroup
659 of subjects also showed evidence that they took first-
660 person rather than third-person perspective during the
661 motor imagery in the present study. Psychologically,
662 more kinesthetic property rather than visual property
663 may be involved during the course of imagery with this
664 first-person

663 perspective. However, potential contamination of visual
664 items caused by external and third-person perspective
665 should also be taken into consideration in the present
666 study and this could lead to activation of completely
667 different cortical regions during the course of imagery
668 (Jeannerod and Frak, 1999; Fourkas et al., 2006).
669 Particularly, it was impossible to control the exact
670 timing of TMS delivery in the present study because
671 the time course of motor imagery might slightly vary
672 across trials. The variation of timing for TMS delivery
673 increased the possibility that complex strategy with
674 mixed imagery of kinesthetic and visual properties
675 might contribute to the different degrees of MEP
676 facilitation in athletes and novices. In addition,
677 since the whole time course from the beginning of
678 serving to the landing of shuttlecock was evaluated,
679 the mixed strategies with different perspectives
680 might further affect the result of MIQ test. The
681 investigation for the important role of visual items
682 in motor imagery requires different a study design
683 with essential visual information to be provided
684 (Grush, 2004).

683 CONCLUSION

684 Using a TMS paradigm, Fourkas et al. (2008) demon-
685 strated that long-term utilization of a specific
686 implement causes functional changes in the brain,
687 leading to increased MEP facilitation in imagining
688 the task in the sport. Using the psychological and
689 physiological measures, the present study further
690 examined the effect of application of a specific
691 implement during this mental process of motor
692 imagery. The results that increased MEP
693 facilitation during motor imagery only with the
694 application of specific implements in athletes may
695 be helpful to develop new training methods in
696 athletes with mental practice (Peluso et al., 2005;
697 Reiser et al., 2011) and may even be helpful to
698 develop new therapies for patients with neurological
699 disorders (Page et al., 2007; Ietswaart et al.,
700 2011). Motor imagery requires integration of
701 internal memory and external inputs in the cortical
702 network (Olsson and Nyberg, 2010). Since the
703 implement (badminton racket in the present study)
704 is an indispensable part for the sports (Lees,
705 2003), it may be inferred that specific implement
706 applies important medium for the internal and
707 external components to be integrated at certain
708 cortical areas during motor imagery. In athletes,
709 long-term physical training with specific
710 implement in the sport leads to functional
711 reorganization in motor related cortical network
712 (Elbert et al., 1995; Bütetfisch et al., 2000;
713 Draganski et al., 2004; May et al., 2007; Bütetfisch
714 et al., 2004; Williams et al., 2012). This may
715 provide a functional and structural foundation for
716 athletes to adapt the implement as a medium in
717 the cortical process. We conclude that the effects
718 of motor imagery with a specific implement are
719 enhanced in athletes compared to novices and the
720 difference between the two groups is caused by
721 long-term physical training of athletes with the
722 specific implement.

723 *Acknowledgments*—This research was supported by grants from
724 the National Natural Science Foundation of China (#31371056),
725 Science and Technology Commission of Shanghai Municipality
726 (No. 11510503100) and Shanghai Key Lab of Human Performance
727 (Shanghai University of Sport) (No. 11DZ2261100).
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(Accepted 4 June 2014)
(Available online xxxx)

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