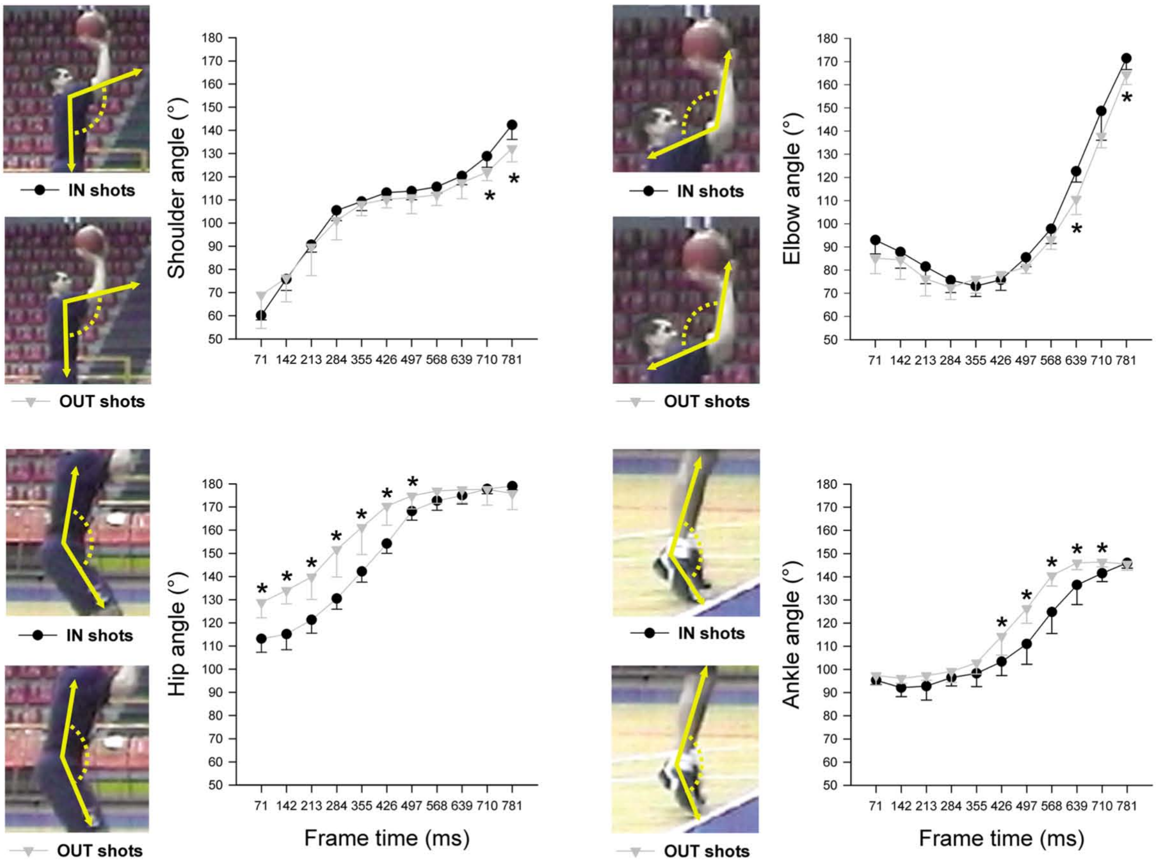
Action anticipation and motor resonance in elite basketball players

Salvatore M Aglioti, Paola Cesari, Michela Romani, Cosimo Urgesi



Supplementary Figure 1 Angles formed by the model's joints are shown in the different frames composing the IN and OUT shot movies. The angles formed by the shoulder and elbow and the hip and ankle joints are displayed. The 71 ms frame corresponds to the first frame presented during video presentation. The 426 ms frame corresponds to last frame of the video clip with minimal duration. Values of the joint angles are represented only up to the 781 ms frame, when the ball left the hand. Error bars indicate standard deviations. Asterisks indicate significant comparisons between IN and OUT shots.

Supplementary Table 1*.* Maximal EMG amplitude (MEA) recorded before the TMS pulse during the three observation conditions.

	Static image		**Basket shot**		**Soccer kick**	
	ADM	FCU	ADM	FCU	ADM	FCU
Elite players	0.10 (±0.16)	0.25 (±0.15)	–0.08 (±0.11)	–0.07 (±0.10)	0.14 (±0.17)	–0.16 (±0.14)
Expert watchers	–0.12 (±0.16)	–0.14 (±0.15)	0.05 (±0.11)	–0.04 (±0.10)	–0.02 (±0.18)	0.19 (±0.14)
Novices	–0.01 (±0.16)	–0.11 (±0.15)	–0.15 (±0.11)	–0.02 (±0.10)	0.26 (±0.17)	0.02 (±0.14)

Mean (z-scores) and standard errors of the maximal EMG amplitude in the 50 ms epoch preceding the TMS pulse, for each group (elite players, expert watchers, and novices), observation condition (static image, basket shot, and soccer kick) and recorded muscle (abductor digiti minimi, ADM and flexor carpi ulnaris. FCU). No significant observation related modulation of the EMG activity before the TMS pulse was observed.

Supplementary Table 2. Maximal EMG amplitude (MEA) recorded before the TMS pulse during observation of IN and OUT shots.

		IN shots			OUT shots		
		568 ms	781 ms	1,207 ms	568 ms	781 ms	1,207 ms
ADM	Elite players	–0.01 (±0.13)	–0.24 (±0.19)	–0.24 (±0.14)	–0.09 (±0.12)	–0.05 (±0.12)	–0.26 (±0.11)
	Expert watchers	0.06 (±0.13)	–0.24 (±0.19)	0.09 (±0.14)	0.12 (±0.12)	0.01 (±0.12)	0.10 (±0.11)
	Novices	–0.17 (±0.13)	–0.10 (±0.19)	–0.14 (±0.14)	–0.11 (±0.12)	–0.27 (±0.12)	–0.12 (±0.11)
FCU	Elite players	0.02 (±0.15)	–0.09 (±0.13)	–0.14 (±0.11)	0.04 (±0.14)	–0.05 (±0.18)	–0.08 (±0.13)
	Expert watchers	–0.14 (±0.15)	–0.19 (±0.13)	–0.08 (±0.11)	0.06 (±0.14)	–0.07 (±0.18)	0.08 (±0.13)
	Novices	–0.02 (±0.15)	–0.09 (±0.13)	–0.01 (±0.11)	0.07 (±0.14)	0.03 (±0.18)	–0.09 (±0.13)

Mean MEA (z-scores) values and standard errors are reported for IN and OUT basket shots and for each clip duration. MEA was recorded from the abductor digiti minimi (ADM) and flexor carpi ulnaris (FCU) muscle in the 50 ms epoch preceding the TMS pulse.

Supplementary Table 3. Mean and standard deviations of the angles formed by the model's joints during specific frames taken from IN and OUT shots.

	Frame time (ms)	IN shots *Mean* (°)	*S. D.* IN shots	OUT shots *Mean* (°)	*S. D.* OUT shots	t_{10}-value	*P*-level
Ankle angle	71	95.33	1.86	97.33	4.18	−1.07	0.309
	142	92.17	3.87	96.17	2.23	−2.19	0.053
	213	92.83	6.05	97.33	2.07	−1.72	0.115
	284	96.50	3.62	99.17	4.79	−1.09	0.302
	355	98.33	5.75	102.83	4.83	−1.47	0.173
	426	103.33	5.99	114.33	8.14	−2.67	**0.024**
	497	111.00	8.83	126.33	6.38	−3.45	**0.006**
	568	124.83	9.33	140.50	4.51	−3.71	**0.004**
	639	136.50	8.46	146.00	2.97	−2.60	**0.027**
	710	141.50	3.56	146.33	2.07	−2.87	**0.017**
	781	146.00	2.28	145.50	2.66	0.35	0.734
Knee angle	71	103.00	9.80	121.83	11.99	−2.98	**0.014**
	142	96.67	6.50	117.00	10.00	−4.18	**0.002**
	213	94.33	5.54	112.17	6.55	−5.09	**0.000**
	284	97.67	3.27	114.83	4.79	−7.25	**0.000**
	355	108.33	3.33	125.67	4.32	−7.79	**0.000**
	426	126.50	3.08	140.50	4.37	−6.41	**0.000**
	497	146.17	3.60	151.50	4.32	−2.32	**0.043**
	568	155.33	3.08	158.50	3.51	−1.66	0.127
	639	163.67	3.83	162.83	1.17	0.51	0.621
	710	169.00	0.89	165.50	1.52	4.87	**0.001**
	781	171.50	2.74	168.17	3.19	1.94	0.081
Hip angle	71	113.17	5.91	128.83	6.71	−4.29	**0.002**
	142	115.17	6.79	134.00	5.80	−5.17	**0.000**
	213	121.33	5.79	139.83	9.77	−3.99	**0.003**
	284	130.50	4.64	151.67	11.91	−4.06	**0.002**
	355	142.17	4.62	161.17	11.75	−3.68	**0.004**
	426	154.17	4.22	170.33	8.21	−4.29	**0.002**
	497	168.17	3.87	174.83	5.74	−2.36	**0.040**
	568	172.67	4.13	177.00	5.48	−1.55	0.153
	639	175.00	3.74	177.50	5.65	−0.90	0.387
	710	177.83	2.14	177.67	6.92	0.06	0.956
	781	179.00	1.67	175.83	7.05	1.07	0.310
Shoulders angle	71	60.17	1.94	69.00	14.5	−1.48	0.170
	142	75.83	4.96	76.33	10.4	−0.11	0.917
	213	90.67	3.20	89.67	12.4	0.19	0.852
	284	105.50	4.51	101.17	8.4	1.11	0.293
	355	109.33	3.98	108.17	5.0	0.45	0.663
	426	113.17	3.19	110.33	3.8	1.40	0.191
	497	113.83	3.71	111.00	6.9	0.89	0.396
	568	115.67	2.73	112.17	4.6	1.61	0.139
	639	120.33	3.78	117.50	7.0	0.87	0.404
	710	128.83	4.79	122.00	3.7	2.77	**0.020**
	781	142.33	6.28	132.17	5.8	2.92	**0.015**
Elbow angle	71	93.00	6.00	85.17	6.71	2.13	0.059
	142	87.83	7.05	84.50	8.50	0.74	0.477
	213	81.50	7.34	76.33	7.45	1.21	0.254
	284	75.67	5.35	72.50	5.17	1.04	0.322
	355	73.17	4.54	76.17	6.18	−0.96	0.360
	426	75.83	4.58	78.17	3.71	−0.97	0.355
	497	85.50	4.04	81.33	2.80	2.08	0.065
	568	97.83	6.37	93.17	4.17	1.50	0.164
	639	122.67	4.68	110.67	6.65	3.61	**0.005**
	710	148.67	12.61	137.83	5.04	1.95	0.079
	781	171.50	4.93	164.50	4.42	2.59	**0.027**
Wrist angle	71	159.33	5.28	153.00	7.75	1.65	0.129
	142	154.00	5.62	143.67	9.29	2.33	**0.042**
	213	133.67	5.61	140.50	8.09	−1.70	0.120
	284	129.83	4.79	137.83	10.65	−1.68	0.124
	355	131.17	3.71	136.67	12.45	−1.04	0.324
	426	132.67	4.23	139.83	9.00	−1.77	0.108
	497	131.83	4.17	142.33	9.63	−2.45	**0.034**
	568	121.67	4.76	137.67	14.40	−2.58	**0.027**
	639	109.83	5.42	128.67	14.04	−3.07	**0.012**
	710	112.50	5.32	126.17	7.33	−3.70	**0.004**
	781	173.67	7.87	160.00	16.38	1.84	0.095
Little finger angle	71	140.46	4.97	142.02	18.37	−0.20	0.845
	142	137.48	14.19	144.77	16.22	−0.83	0.427
	213	135.70	14.02	132.38	16.71	0.37	0.717
	284	144.18	11.92	136.67	12.85	1.05	0.318
	355	144.23	7.04	133.85	10.72	1.98	0.075
	426	145.38	13.73	136.00	13.24	1.20	0.256
	497	144.53	8.82	138.28	11.21	1.07	0.308
	568	147.72	9.93	145.33	13.62	0.35	0.736
	639	157.30	14.77	139.68	12.04	2.26	**0.047**
	710	155.40	9.86	140.78	12.39	2.26	**0.047**
	781	152.10	6.11	131.35	7.56	5.23	**0.000**

Eleven frames catching the model's posture at different times (from 71 to 781 ms) of the shot were analyzed. Series of independent-sample t-tests (two tails) were used to compare IN and OUT shots at each frame. Significant difference between IN and OUT shots are marked in bold.

Supplementary Note

Analysis of background EMG activity

Methods. To rule out that fluctuations of spontaneous EMG activity may explain the modulation of MEPs amplitude during the different observation conditions in experiment 2, we analyzed the background EMG activation before the TMS pulse. We calculated for each trial the maximal EMG amplitude (MEA; in µV) in the 50 ms epoch recorded from the abductor digiti minimi (ADM) and flexor carpi ulnaris (FCU) muscles before the TMS pulse. In keeping with analysis of MEPs amplitudes, the raw MEA values of each participant were normalized (*z*-scores) on the total MEAs recorded from each muscle.

Results. The one-way between-subjects ANOVA on raw MEAs recorded from the ADM muscle across the three observation conditions, revealed non significant effect of group ($F_{2,27} = 1.3$, $P = 0.288$) in that no difference between elite players (18.75 µV), expert watchers (25.27 µV), and novices (17.08 µV) was found. In a similar vein, non significant effect of group was obtained from the one-way ANOVA on MEAs recorded from the FCU muscle ($F_{2,27} = 2$, $P = 0.155$), revealing no difference between elite players (15.81 µV), expert watchers (28.67 µV), and novices (16.66 µV). Individual mean *z*-scores of MEAs were entered into a three-way mixed model ANOVA with group (elite, expert watchers, novices) as between- and muscle (ADM, FCU) and experimental conditions (basket shot, soccer kick, static image) as within-subjects effects (see **Supplementary Table 1**). No significant main effects or interactions were observed (for all effects $F < 1.48$, $P > 0.22$), thus ruling out that modulation of the background EMG activity may explain the modulation of MEPs amplitude contingent upon specific observation conditions.

We looked for any differential modulation of background EMG activity on cortico-spinal excitability during observation of IN and OUT basket shots by entering normalized MEAs into a 4-way mixed-model ANOVA with group (elite athletes, expert watchers, novices) as between- and muscle (ADM, FCU), type of shot (IN, OUT), and clip duration (568, 781, 1207 ms) as within-subjects effects (see **Supplementary Table 2**). No significant effects were obtained from the analysis of normalized MEAs (all Fs < 2.42, $P > 0.13$). The non significant effect of the 4-way interaction between group, muscle*,* type of shots, and clip duration ($F_{2,54} < 1$) showed the absence of any differential modulation of background EMG activity related to expertise, shot success, and clip duration in both muscles. Therefore, spontaneous fluctuations of background EMG activity during observation of IN and OUT basket shots did not play any role in the cortico-spinal modulation of MEPs amplitudes in any of the groups.

Kinematic analysis of the visual stimuli

Methods. To determine the difference in the kinematics of the movements performed by the model player during the six IN and the six OUT shot basket clips, we measured the angles formed by several of the model's joints by considering 11 frames, each characterized by its progressive temporal position in the clip (see **Fig. 4** and **Supplementary Fig. 1**). Note that the shortest clip presented in the psychophysics or the TMS experiment lasted 426 ms (see for example **Fig. 1**) and consisted of 6 frames. The frame-by-frame angle joints analysis was performed for 11 frames (marked with numeric labels ranging from 71 to 781 ms in steps of 71 ms which, by the way, was the duration of each frame). In the first ten frames the ball was still in contact with the player's hand, while in the 781 ms frame the ball had just left the player's hand (see **Fig. 4** and **Supplementary Fig. 1**). The definition of the joint angle profile for the basket shots presented via video to the subjects, was performed using a dedicated software for motion analysis (Dartfish Connect v. 4.0, Dartfish Ltd., Fribourg, Switzerland). We first extracted the first 11 frames from each of the 12 movies. For each frame, we defined the amplitude of the joint angles for the ankle, knee, hip, shoulder, elbow, and wrist on the right side of the basketball player’s body. We also determined the angle formed by the right little finger and the palm of the hand. The ankle joint angle was defined by considering the line connecting the tip of the right shoes with the lateral malleolus and the line connecting the lateral femur condyle and lateral malleolus. The knee joint angle was defined by considering the line connecting the lateral malleolus with the lateral femur condyle and the line connecting the great trochanter and the lateral femur condyle. The hip angle was defined by the line connecting the lateral femur condyle with the great trochanter and the line connecting the head of the humerus with the great trochanter. The shoulder joint angle was defined by the line connecting the great trochanter with the head of the humerus and the line connecting the lateral epicondyle of the humerus with the head of the humerus. The elbow joint angle was defined by the line connecting the head of the humerus with the lateral epicondyle of the humerus and the line connecting the ulnar styloid process with the lateral epicondyle of the humerus. The wrist joint angle was defined by the line connecting the lateral epicondyle of the humerus with the ulnar styloid process and the line connecting the proximal phalange of the little finger with the ulnar styloid process. Finally, the little finger-metacarpal joint angle was defined by the line connecting the proximal phalange of the little finger with the ulnar styloid process and the line connecting the distal with the proximal phalange of the little finger. For each joint, the mean angle values of the six IN and the six OUT shots were compared in each of the 11 frames by series of independent sample *t*-tests (two-tailed). This analysis allowed us to explore possible objective differences in the model's posture and to try and relate them to the psychophysical and neurophysiological effects in the experimental groups.

Results. To determine the crucial cues that differentiated IN and OUT basket shots, we analyzed the amplitude of the angle formed by the joints of the model player. The complete list of the joint angles profiles and results of independent sample *t*-tests is shown in **Supplementary Table 3**. No significant difference was found between the angle formed by the ankle joint during the IN and OUT shots in the first 5 frames and in the 781 ms frame. Interestingly, significantly higher ankle joint amplitudes were found for OUT than for IN shots from the 426 ms to the 710 ms frame. Therefore, ankle joint angle amplitudes turned out to be different in OUT and IN shots within a specific temporal window (**Supplementary Fig. 1**). The knee-joint angle amplitude was broader during OUT than during IN shots at the starting point and in the subsequent six frames. By contrast, at the 568 ms and 639 ms frames IN and OUT shots could not be discriminated on the basis of the knee angle. At the 710 ms frame the knee angle was significantly broader for IN than for OUT shots, while the difference was non significant at 781 ms. Thus, an anticipated extension of the model's knee occurred during movies where the ball landed OUT of the basket, along with a reduced extension in the last phases of the movement. The entire knee joint angle profile is shown in **Figure 4**. An anticipated flexion of the hip also occurred. Indeed, the hip angle was significantly broader for OUT than for IN shots at the starting point and in the following six frames. By contrast, no difference was observed in the remaining frames. The entire hip joint angle profile is shown in **Supplementary Figure 1**. A different pattern of results emerged from the analysis of upper limb joints. The shoulder angle was not significantly different between IN and OUT shots in the first nine frames, while it was smaller for OUT than for IN shots at the 710 ms and 781 ms frame, which was also the first frame in which the ball was no longer in contact with the hand. The entire shoulder-joint angle profile is shown in **Supplementary Figure 1**. No OUT vs. IN shot elbow angle differences were found for the first eight frames. However, a tendency for significantly narrower angles for OUT than for IN shots was found in the 639 ms, 710 ms, and 781 ms frames. The entire profile of elbow angles is shown in **Supplementary Figure 1**. No difference was observed between the wrist angle during IN and OUT shots for the first 6 frames of the videos, with the exception of the 142 ms frame, where the wrist was more extended for the OUT than for the IN shots. Higher wrist extensions were instead observed for the IN as compared to the OUT shots from the 497 ms to the 710 ms frames. Thus, in the final OUT shots wrist flexion was less pronounced than during the IN shots. Crucially however, a non significant difference was observed in the degree of wrist extension at the 781 ms frame when the ball was no longer in contact with the hand. The entire wrist joint angle profile is shown in **Figure 4**. A significantly greater extension of the little finger during the IN than the OUT shots was found at the 639 ms, 710 ms, and 781 ms frames. No difference was observed between the degree of little finger flexion during the IN and OUT shots in the preceding phases of the movies. The entire little finger-metacarpal joint angle profile is shown in **Figure 4**. Overall, the analysis of the kinematics of the joint angles during the IN and OUT shots showed that the model player anticipated the extension of the lower limb joints (ankle, knee, and hip) during the OUT shots. The difference between IN and OUT shots was not present in the last phases of the movement. A complementary pattern of results was observed for the upper limb joint angles.

Indeed, the shoulder and the elbow joints were more flexed for the OUT than the IN shots during the final movement phases. Crucially, the wrist was less extended in the OUT shots during the final phases of the movements but not at the instant when the ball left the hand, that is, during the transition from the 710 to the 781 ms frame. By contrast, the little finger was not flexed at the instant the ball left the hand in the OUT shots. As no compensation for movement errors was allowed after that instant, the angle formed by the little finger with the palm of the hand at the 781 ms frame provided crucial cues for predicting the fate of the shots. Our psychophysics study suggests that these cues might have been used only by the elite athletes and not by the novices or the expert watchers. This may also suggest that direct motor expertise with sports playing allows reading opponents' kinematics and anticipating their behavior.