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Corticospinal excitability is facilitated by combined action observation and motor imagery of a basketball free throw

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ABSTRACT

Objectives: This experiment investigated the extent to which independent action observation, independent motor imagery and combined action observation and motor imagery of a sport-related motor skill elicited activity within the motor system.
Design and method: Eighteen, right-handed, male participants engaged in four conditions following a repeated measures design. The experimental conditions involved action observation, motor imagery, or combined action observation and motor imagery of a basketball free throw, whilst the control condition involved observation of a static image of a basketball player holding a basketball. In all conditions, single pulse transcranial magnetic stimulation was delivered to the forearm representation of the left motor cortex. The amplitude of the resulting motor evoked potentials were recorded from the flexor carpi ulnaris and extensor carpi ulnaris muscles of the right forearm and used as a marker of corticospinal excitability.
Results: Corticospinal excitability was facilitated significantly by combined action observation and motor imagery of the basketball free throw, in comparison to both the action observation and control conditions. In contrast, the independent use of either action observation or motor imagery did not facilitate corticospinal excitability compared to the control condition.
Conclusions: The findings have implications for the design and delivery of action observation and motor imagery interventions in sport. As corticospinal excitability was facilitated by the use of combined action observation and motor imagery, researchers should seek to establish the efficacy of implementing combined action observation and motor imagery interventions for improving motor skill performance and learning in applied sporting settings.

Action observation (AO) involves the deliberate and structured observation of human movement (Neuman & Gray, 2013), whilst motor imagery (MI) is the internal generation and rehearsal of movement execution (MacIntyre et al., 2013). It is well-established that improvements in the performance and learning of motor skills can be obtained through both AO (Ste-Marie et al., 2012) and MI (Cumming & Williams, 2012) interventions. According to simulation theory (Jeannerod, 2001), these two types of motor simulation both produce activity in similar regions of the motor system to those involved in motor execution. Functional magnetic resonance imaging (fMRI) research has confirmed this by demonstrating that several areas known to be involved in motor planning and execution are also active during AO and MI. These areas include the supplementary motor area, premotor cortex, superior parietal lobe and the intraparietal sulcus (e.g., Filimon, Nelson, Hagler, & Serano, 2007; Grèzes & Decety, 2001; Hardwick, Caspers, Eickhoff, & Swinnen, 2017; Munzert, Zentgraf, Stark, & Vaitl, 2008). Whilst this research provides an indication of areas active during AO or MI, the increased activity recorded in fMRI experiments can represent either excitatory or inhibitory mechanisms (Holmes & Wright, 2017).

Transcranial magnetic stimulation (TMS) is another technique that has been used extensively to explore excitatory, rather than inhibitory, activity in the motor system during AO and MI conditions. The delivery of TMS to a muscle representation on the motor cortex produces a muscular contraction called a motor evoked potential (MEP) in the

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corresponding muscle. The amplitude of the MEP, measured by surface electromyography (EMG), provides a marker of corticospinal excitability (Naish, Houston-Price, Bremner, & Holmes, 2014; Rothwell, 1997). Research comparing MEP amplitudes obtained during AO or MI against various different control conditions has shown consistently that corticospinal excitability is facilitated by both AO (e.g., Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Naish et al., 2014) and MI (e.g., Fadiga et al., 1998; Grosprêtre, Ruffino, & Lebon, 2016). It is therefore assumed that AO and MI interventions contribute to improvements in motor performance and learning, at least in part, by activating and strengthening the cortical pathways involved in motor execution.

Traditionally, AO and MI have been viewed as two separate intervention techniques. As such, researchers have often compared how the two simulation techniques elicit activity in parts of the motor system. For example, TMS research has shown that both AO and MI facilitate corticospinal excitability compared to control conditions, but there is typically no difference in the extent of this facilitation between the two techniques (Clark, Tremblay, & Ste-Marie, 2004; Roosink & Zijdewind, 2010; Williams, Pearce, Loporto, Morris, & Holmes, 2012). More recently, however, there has been a shift away from the study of the independent use of AO and MI to a focus on their combined use. Specifically, there has been an increase in research seeking to identify the effects of instructing participants to engage in MI *during* AO on activity in the motor system (see Eaves, Riach, Holmes, & Wright, 2016; Vogt, Di Rienzo, Collet, Collins, & Guillot, 2013 for reviews). Typically, this involves instructing participants to observe a specific movement on video whilst imagining simultaneously the kinesthetic feelings and physiological sensations associated with the execution of the observed movement. Collectively, this emerging body of research has shown that, for a variety of movement tasks, the combined and simultaneous use of action observation and motor imagery (i.e., AOMI) produces increased activity in the motor system, compared to the independent use of either technique (Eaves, Riach, et al., 2016; Vogt et al., 2013). This effect has been shown in research using TMS (e.g., Mouthon, Ruffieux, Wälchli, Keller, & Taube, 2015; Ohno et al., 2011; Sakamoto, Muraoka, Mizuguchi, & Kanosue, 2009; Wright, McCormick, Williams, & Holmes, 2016; Wright, Williams, & Holmes, 2014), electroencephalography (EEG; e.g., Berends, Wolkorte, Ijzerman, & van Putten, 2013; Eaves, Behmer, & Vogt, 2016) and fMRI (e.g., Nedelko, Hassa, Hamzei, Schoenfeld, & Dettmers, 2012; Taube et al., 2015; Villiger et al., 2013). Based on these findings, the authors have claimed that AOMI interventions may provide a more effective strategy for improving motor performance and learning than the independent use of either technique (Holmes & Wright, 2017).

Despite convincing evidence that AOMI produces greater activity in the motor system than either independent AO or independent MI, further research on this topic is still required using sport-related motor skills. The majority of experiments examining AOMI have tended to use simple hand actions as the movement task. If practitioners are to begin implementing AOMI interventions when working with athletes for performance enhancement and motor skill learning, then it is important to first establish the effects of AOMI procedures on activity in the motor system for more complex sport-related tasks. Although some research has focused on cortical activity associated with AOMI in balance tasks (Mouthon et al., 2015; Taube et al., 2015) or bicep curl movements (Sakamoto et al., 2009), the effects on cortical activity of AOMI of sport-related motor skills remains to be established. The basketball free throw is a suitable skill to explore this issue as the topography of the motor cortex is such that the cortical representation of the forearm muscles involved in execution of this skill is located near the surface of the cranium, and so can be stimulated easily with TMS. Previous research has also demonstrated that independent AO of a basketball free throw facilitates corticospinal excitability in both expert and novice participants (Aglioti, Cesare, Romani, & Urgesi, 2008), and so the skill is suitable for exploring the effects of AOMI with TMS in the sport domain.

The aim of this experiment was to assess the extent to which independent AO, independent MI and combined AOMI of a basketball free throw would modulate corticospinal excitability, compared to a control condition. It was hypothesized that all three types of motor simulation would facilitate corticospinal excitability relative to the control condition, with the greatest facilitation of corticospinal excitability predicted to occur in the AOMI condition.

1. Method

1.1. Participants

An *a priori* power analysis was conducted using G*Power software to determine the number of participants required for this experiment. The power analysis was based on the data reported by Wright et al. (2014), who compared differences in corticospinal excitability between AO, MI and AOMI of an index finger abduction-adduction movement against a static hand control condition, and obtained effect sizes ranging from $d = 0.68–1.78$. Based on the lowest effect size ($d = 0.68$) and α set at 0.05, the power analysis indicated that in order to find significant differences between the experimental conditions and the control condition, at least 15 participants would be required to achieve a power of 80%. In order to allow for possible participant dropout or other loss of data, 18 participants were recruited to participate in this experiment.

All 18 participants were male and aged between 19 and 32 years (mean age 22.61 ± 3.45 years). They were all right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), and all had at least moderately good imagery ability, as assessed by the Vividness of Movement Imagery Questionnaire-2 (Roberts, Callow, Hardy, Markland, & Bringer, 2008; See Table 1). All participants were novice basketball players, in that they had some experience of playing the sport in practical physical education lessons at school, but had never played competitively. Furthermore, none of the participants were susceptible to possible adverse side-effects of transcranial magnetic stimulation, as assessed by the TMS Adult Safety Screen (Keel, Smith, & Wassermann, 2001). All participants provided written informed consent to take part in the experiment, which had been granted ethical approval by the University Ethics Committee at the host institution.

Table 1
Summary of participant demographic characteristics, handedness, imagery vividness scores and TMS stimulation characteristics. EHI – Edinburgh Handedness Inventory; VMIQ-2 - Vividness of Movement Imagery Questionnaire-2; OSP – Optimal Scalp Position; RMT – Resting Motor Threshold.

Demographic Characteristics				Handedness		Imagery Vividness Scores (VMIQ-2)			TMS Method Details		
Sample Size	Sex	Age	Basketball Skill Level	Handedness	EHI Laterality Score	External Imagery Vividness	Internal Imagery Vividness	Kinaesthetic Imagery vividness	OSP Location: Modal distance from Cz	Mean RMT Intensity	Mean Stimulation Intensity
18	Male	22.61 (± 3.45)	Novice	Right	87.94% (± 13.36)	27.67 (± 7)	21.11 (± 8.63)	26 (± 8.96)	4 cm lateral ($n = 17$) 0 cm anterior ($n = 9$)	48.39% (± 6.63)	54.89% (± 7.31)

1.2. Electromyography and transcranial magnetic stimulation procedure

EMG was recorded throughout the experiment using a Delsys Bagnoli 2-channel EMG system (Delsys Inc, Boston, MA). Prior to electrode attachment, participants were asked to repeatedly flex and extend their right wrist, mimicking the action of shooting a basketball free throw, whilst the experimenter felt the participants' right forearm to identify the flexor carpi ulnaris (FCU) and extensor carpi ulnaris (ECU) muscles. Once identified, the sites were cleaned using alcohol wipes and surface EMG electrodes were attached over the belly of both muscles, and a reference electrode was placed on the olecranon of the ulna bone. Recordings were taken from the FCU and ECU muscles as they are both active when flicking the wrist to release the ball from the hand during the execution of a basketball free throw. The EMG signal was recorded using Spike 2 (version 6.18) software, with a sampling rate of 2 kHz, bandwidth of 20–450 kHz, 92 dB common mode rejection ratio and $> 10^{15}\,\Omega$ input impedance, received by a Micro 1401–3 analogue-to-digital converter (Cambridge Electronic Design, Cambridge, UK).

Single-pulse TMS was delivered to the left primary motor cortex using a figure-of-eight shaped coil (two 70 mm diameter loops), orientated at a 45° angle to the central line between the nasion and inion landmarks of the cranium (Brasil-Neto et al., 1992), and connected to a Magstim 200^2 magnetic stimulator (Magstim, Whitland, Dyfed, UK). The optimal scalp position (OSP) was identified as the scalp location that produced MEPs of largest amplitude in both muscles, using a stimulation intensity of 60% maximum stimulator output (e.g., Clark et al., 2004; Williams et al., 2012; Wright et al., 2014). Once identified, the OSP was marked on a tightly fitting polyester cap worn by the participants by drawing around the coil with a marker pen. The coil was held fixed against the OSP using a mechanical arm, and accuracy of coil placement was ensured throughout the experiment by checking the coil position frequently in relation to the marking and adjusting the positioning if necessary. Resting motor threshold (RMT) was then determined for each participant by gradually reducing or increasing the stimulation intensity, until the minimum intensity capable of producing MEPs with peak-to-peak amplitudes in excess of 50 μV in five out of 10 trials was identified (Rossini et al., 1994, 2015). This stimulation intensity, plus 1% of the maximum stimulator output was identified as the RMT (see Rossini et al., 2015 for guidelines on TMS procedures). Based on the recommendations of Loporto, Holmes, Wright, and McAllister (2013) the stimulation intensity for the experiment was set at 110% of each participant's RMT to reduce the likelihood of direct wave stimulation. Modal values for the location of the OSP, and mean values for the RMT and experimental stimulation intensity can be found in Table 1.

1.3. Experimental procedure

Participants were seated at a desk in front of a 32-inch Samsung flat-screen TV, positioned at eye-level at a distance of 90 cm. Their head was placed comfortably in a custom-built head-and-chin rest, and their hands and forearms rested in a pronated position on the desktop. The lighting in the room was dimmed and blackout curtains were drawn along either side of the desk to eliminate any potentially distracting visual stimuli in the surrounding area. Whilst seated in this position, participants took part in four experimental conditions within a single testing session on the same day. As shown in Fig. 1, the four conditions were termed: static observation (control), action observation (AO), motor imagery (MI) and combined action observation and motor imagery (AOMI). Each condition required participants to complete a block of 30 repetitions of a 10-s duration video. One stimulation from the TMS device was delivered per video, resulting in a total of 30 stimulations per condition. Thirty stimulations per condition were administered as this is recommended as a sufficient number of stimulations to provide a reliable measure of corticospinal excitability (Cuypers, Thijs, & Meesen, 2014; Goldsworthy, Hordacre, & Ridding, 2016). Each stimulation was delivered 4640 ms after the onset of each video, as this corresponded with the point at which the model flicked their wrist to release the ball in the action observation video. There was a 3 s rest period between each video, resulting in a 13 s inter-stimulus interval between trials. This duration inter-stimulus interval is consistent with TMS safety guidelines and is sufficient time for the effects of previous stimulations to have subsided (Chen et al., 1997). The total duration of each experimental condition was 6 min 30 s. Following each condition participants were given a rest period of approximately 3 min before starting the next condition. This duration rest period between conditions was appropriate as MEP amplitudes return the baseline levels after 1 min (Baldi, Perretti, Sannino, Marcantonio, & Santoro, 2002), and it is also consistent with previous TMS experiments exploring AO or MI processes (e.g., Loporto, McAllister, Edwards, Wright, & Holmes, 2012; Wright et al., 2014). The entire experiment, including participant familiarization, completion of consent forms and questionnaires, EMG preparation, OSP and RMT procedures, experimental conditions and participant debriefing, lasted approximately 90 min.

1.4. Static observation (control) condition

In the static observation condition, participants were shown a silent video, filmed from a third-person visual perspective (see Fig. 1), depicting a male basketball player standing still on a basketball free throw line and holding a basketball. Participants were instructed to observe the videos and were reminded of this instruction verbally every 10 trials.

1.5. Action observation (AO) condition

In the AO condition, participants were shown a video of the same male basketball player shooting a successful basketball free throw. In this video, filmed from the same third-person visual perspective as the static observation condition, the model bounced the basketball twice before shooting a right-handed free throw that went straight through the hoop without hitting the rim or backboard. The sounds of the ball being bounced twice during the model's pre-performance routine, the 'swish' of the ball going through the net, and the ball bouncing after the shot landed were all audible in the video. Participants were instructed to observe the videos and were reminded of this instruction verbally every 10 trials.

1.6. Motor imagery (MI) condition

In the MI condition, participants were shown a video of a black screen, but heard the same audio recording as in the AO condition. Participants were instructed to actively imagine themselves shooting a successful basketball free throw in time with the audio recording. No specific instructions were provided regarding which perspective participants should image from, but they were instructed to focus specifically on imagining the feelings and sensations associated with flicking the wrist as they released the ball. Kinesthetic imagery instructions were emphasized explicitly as these have been shown to facilitate corticospinal excitability to a greater extent than visual imagery (Stinear, Byblow, Steyvers, Levin, & Swinnen, 2006). Participants were reminded of this instruction verbally every 10 trials. In addition, prior to beginning this condition, participants were asked to keep their eyes open during their imagery to maintain consistency across conditions. They were also reminded that they could refer to their mimicking of the wrist flick action during the EMG preparation procedures to recall the kinesthetic sensations associated with executing the movement.

1.7. Combined action observation and motor imagery (AOMI) condition

In the AOMI condition, participants were presented with the same

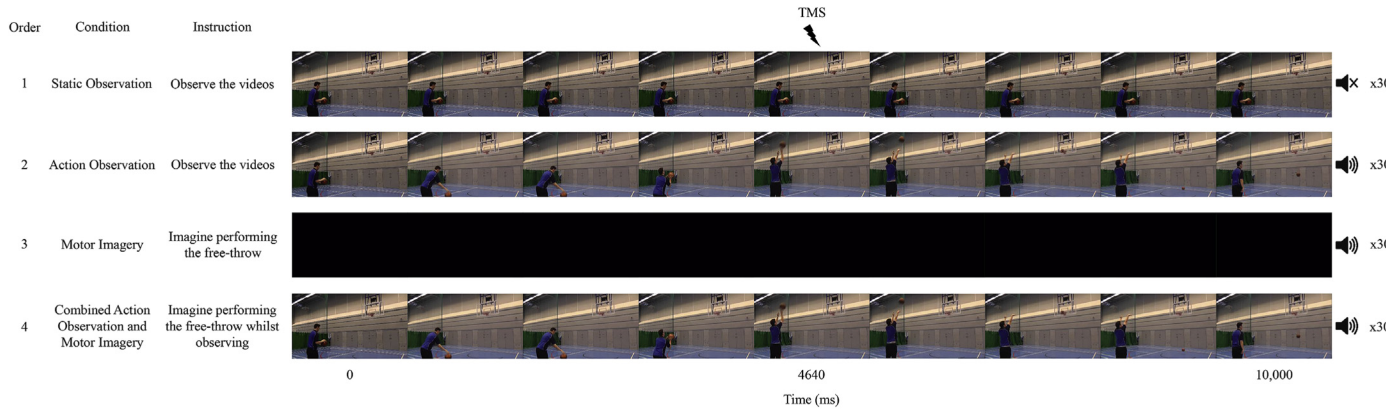

Fig. 1. A representation of the four experimental conditions.

visual and auditory stimuli they had seen in the AO condition, but were instructed to actively imagine themselves shooting a successful basketball free throw in time with the video. As in the MI condition, participants were instructed to focus specifically on imagining the feelings and sensations associated with flicking the wrist as they released the ball. Participants were reminded of this instruction verbally every 10 trials.

1.8. Order of conditions

Experimental conditions were always presented in the following fixed order: static observation, AO, MI, AOMI. The decision to utilize a fixed order of conditions was taken for several reasons. The static observation condition was always presented first to acquire a baseline MEP amplitude value before any action observation or motor imagery had taken place. This was important to reduce the chance of participants engaging in spontaneous or deliberate motor imagery during control trials, by virtue of having already being exposed to imagery instructions or the action observation stimuli. Similarly, the AO condition was presented next, before any imagery instructions were provided, in an attempt to reduce the likelihood of knowledge of prior imagery instructions eliciting forms of imagery in this condition. The MI condition was then presented as the third condition, after AO, as it was deemed necessary to have first exposed participants to basketball free throw stimuli to allow them to image the action, due to their novice status. The AOMI condition was then presented last as it was important for participants to have experienced both AO and MI conditions independently to allow them to be combined effectively. This approach to ordering conditions is consistent with previous TMS research using a similar experimental design (Wright et al., 2014, 2016).

1.9. Data analysis

An increase in EMG activity at the time of stimulation can result in an increase in the amplitude of the subsequent MEP (Devanne, Lavoie, & Capaday, 1997; Hess, Mills, & Murray, 1987). As such, the amplitude of each participant's EMG activity in the 200 ms prior to each stimulation was measured in both muscles. Any trials in which this value was greater than 2.5 SD above the mean of that participant's baseline EMG for that muscle were removed from the analysis (Loporto et al., 2013; Wright et al., 2014). This resulted in a mean of 2.35 (± 0.86) trials being removed per participant from each muscle in each condition, and so no participants were removed from the experiment due to excessive loss of data. The peak-to-peak amplitude of MEPs in the remaining trials was then measured. Due to large intra- and inter-participant variability in MEP amplitude, these data were normalized using the z-score transformation commonly used in TMS action observation and imagery research (e.g., Aglioti, Cesari, Romani, & Urgesi, 2008; Fadiga et al., 1995; Wright et al., 2014). The normalized MEP amplitude data were then analyzed with a 2 (muscle) x 4 (condition) repeated measures analysis of variance (ANOVA), using the IBM SPSS Statistics 21 software package. Whilst no significant differences were predicted between muscles due to both muscles having similar involvement in the execution of a basketball free-throw, muscle was included as a factor in the ANOVA as it was prudent to first examine whether differences between muscles existed before exploring differences between conditions. Where Mauchly's test indicated that the assumption of sphericity had been violated, the degrees of freedom were corrected using the Greenhouse-Geisser method. The alpha level for statistical significance was set at $\alpha = .05$ and effect sizes are reported as Cohen's d. Post-hoc pairwise comparisons with the Bonferroni adjustment were used to explore significant effects.

2. Results

Table 2 shows the raw MEP amplitude data obtained from each muscle in each condition. Due to the large variability both within and between participants in the raw MEP amplitudes, this data was normalized using the z-score transformation. Fig. 2 shows the normalized z-score MEP amplitude data. In this figure, a value of zero indicates the mean MEP amplitude across all conditions, with the positive and negative values indicating by how many standard deviations a particular condition was above or below the mean of all conditions, respectively. The 2 (muscle) x 4 (condition) repeated measures ANOVA performed on the z-score MEP amplitude data showed no significant main effect for muscle, $F_{(1,\ 17)} = 0.59$, $p = .45$. There was, however, a significant main effect for condition, $F_{(3,\ 51)} = 6.21$, $p = .001$. Post-hoc pairwise comparisons with the Bonferroni adjustment showed that MEP amplitude in the AOMI condition was significantly larger than in both the static observation ($p = .03$, $d = 0.75$) and action observation ($p = .05$, $d = 0.71$) conditions (see Fig. 2). No other pairwise comparisons were statistically significant. The muscle × condition interaction was not significant, $F_{(1.8,\ 30.61)} = 0.07$, $p = .91$.

Table 2
Mean raw MEP amplitude values (μV ± SD) obtained from both muscles in the static observation, action observation, motor imagery and combined action observation and motor imagery conditions.

	Condition			
	Control	AO	MI	AOMI
Flexor carpi ulnaris (FCU)	251.88 (± 94.56)	244.99 (± 84.95)	297.54 (± 109.41)	345.24 (± 167.34)
Extensor carpi ulnaris (ECU)	586.36 (± 372.49)	600.49 (± 383.02)	615.95 (± 376.17)	730.41 (± 586.47)
Mean MEP amplitude	419.12 (± 203.87)	422.74 (± 198.43)	456.74 (± 207.41)	537.83 (± 303.78)

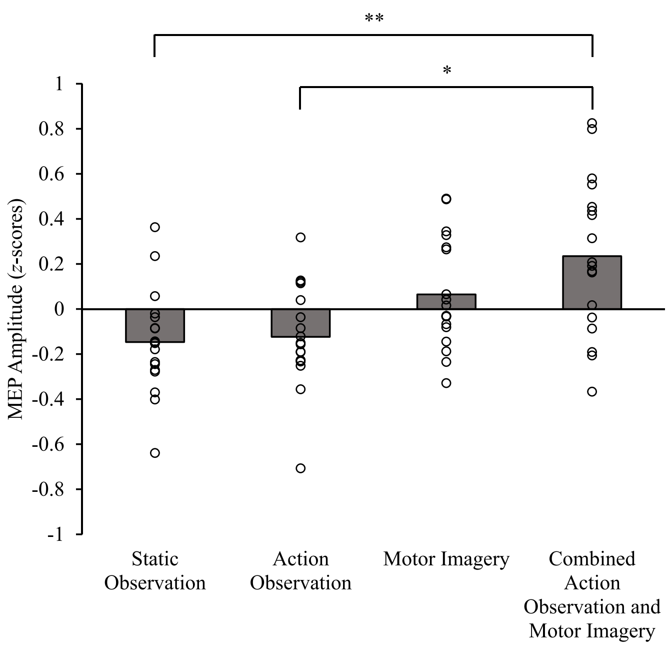

Fig. 2. Mean MEP amplitudes displayed as z-scores, recorded from the flexor carpi ulnaris and extensor carpi ulnaris muscles, for the static observation, action observation, motor imagery and combined action observation and motor imagery conditions ($^{**}p$ = .03, $^{*}p$ = .05). Positive z-score values indicate that the MEP amplitude in that condition was greater than the mean MEP amplitude across all conditions. Negative z-score values indicate that the MEP amplitude in that condition was less than the mean MEP amplitude across all conditions. Circular data points indicate z-score MEP amplitude values from individual participants.

3. Discussion

The aim of this experiment was to establish the effects of different action observation and motor imagery conditions on corticospinal excitability for a sport-related motor skill. Specifically, the amplitude of MEPs obtained during AOMI, independent AO and independent MI of a basketball free throw task were compared against a control condition. MEP amplitudes were significantly larger during AOMI, compared to both the control condition and the independent AO condition. There was no difference in MEP amplitude between either the independent AO or independent MI conditions and the control condition. As the amplitude of the MEP provides a marker of corticospinal excitability (Naish et al., 2014), these results indicate that in the current experiment corticospinal excitability was only facilitated by AOMI, but not by independent AO or MI. This finding of increased activity in the motor system during AOMI supports previous research showing increased neurophysiological activity in various motor regions of the brain during AOMI conditions using TMS (e.g., Mouthon et al., 2015; Ohno et al., 2011; Sakamoto et al., 2009; Wright et al., 2014; Wright et al., 2016), EEG (e.g., Berends et al., 2013; Eaves, Behmer, et al., 2016) and fMRI (e.g., Nedelko et al., 2012; Taube et al., 2015; Villiger et al., 2013). The findings of the current experiment add to this body of literature by demonstrating this effect in a sport-related motor skill, as opposed to simple hand movements or activities of daily living.

The facilitation of corticospinal excitability during AOMI is likely to reflect increased activity in the premotor cortex in this condition. Meta-analyses of neuroimaging data have shown that the primary motor cortex, to which TMS was delivered in this experiment, is not reliably activated during MI or AO (Caspers, Zilles, Laird, & Eickhoff, 2010; Hardwick et al., 2017; Hétu et al., 2013). The primary motor cortex, however, is linked to the premotor cortex by strong cortico-cortical connections (Fadiga, Craighero, & Olivier, 2005). Hardwick et al. (2017) recently demonstrated that the dorsal (PMd) and ventral (PMv) premotor cortices are activated consistently by both AO and MI. Although both simulation states can evoke activity in the premotor regions, multi-voxel pattern analysis has shown that AO and MI produce activity in topographically distinct regions of the premotor cortex. For example, Filimon, Rieth, Sereno, and Cottrell (2015) reported that anterior regions of PMd and posterior regions of PMv are more active during MI, whilst lateral and posterior regions of PMd and anterior regions of PMv are more active during AO. It is therefore possible that instructing participants to engage simultaneously in AOMI would produce increased and more widespread activity throughout the premotor cortex than independent AO or MI. This would manifest in an elevated MEP response via cortico-cortical connections linking the premotor and motor cortices (Fadiga et al., 2005) and would explain why the greatest facilitation in corticospinal excitability in this experiment was found during the AOMI condition.

Based on this finding, it is conceivable that greater improvements in the performance and learning of motor skills may be obtained through AOMI interventions, compared to the more established use of independent AO or MI (Holmes & Wright, 2017). Specifically, the increased activity obtained during AOMI may promote functional connectivity and plasticity within the brain, facilitating a more efficient motor execution as learning progresses (O'Shea & Moran, 2017; Ruffino, Papaxanthis, & Lebon, 2017). Although longitudinal research incorporating both neurophysiological and performance measures is required to verify this claim, some preliminary evidence indicates that AOMI interventions can modulate behavioral outcomes (see Eaves, Riach, et al., 2016). For example, Romano-Smith, Wood, Wright, and Wakefield (2018) reported that AOMI interventions can improve aiming performance in a dart throwing task. In addition, AOMI has been shown to influence automatic imitation effects (Bek, Poliakoff, Marshall, Trueman, & Gowen, 2016; Eaves, Behmer, et al., 2016; Eaves, Haythornwaite, & Vogt, 2014) and improve balance (Taube, Lorch, Zeiter, & Keller, 2014), grip strength (Sun, Wei, Luo, Gan, & Hu, 2016) and hamstring strength (Scott, Taylor, Chesterton, Vogt, & Eaves, 2017). Whilst further research is required to examine the effect of AOMI on the performance and learning of motor skills, there are possible explanations for why AOMI interventions may provide an effective tool for sport psychologists and athletes.

One possibility is that AOMI interventions may contribute to improvements in motor performance and learning by developing athletes' mental representation of a skill. Mental representations are cognitive representations for motor actions comprising a compilation of body postures and associated sensory consequences, known as basic action concepts, that are related functionally and biomechanically to the successful execution of a motor skill (Frank, Land, & Schack, 2013; Schack, 2012). These mental representations are encoded in long-term memory and guide motor skill execution (Land, Volchenkov, Bläsing, & Schack, 2013; Schack & Mechsner, 2006). According to Schack and Mechsner (2006), expert performers have mental representations that are highly organized and closely related to the functional demands of the skill, whereas the mental representations of novices are comparatively less organized and less closely related to the functional demands of the skill. Frank et al. (2013) demonstrated that mental representations of novices became functionally more organized as performance improved following physical practice. Recent research indicates that the structure of novices' mental representations can also be developed through both AO (Frank, Kim, & Schack, 2018; Kim, Frank, & Schack, 2017) and MI (Frank, Land, Popp, & Schack, 2014; Kim et al., 2017) interventions. Although both AO and MI contribute to the development of mental representations of action, it is possible that they do so through different mechanisms (Kim et al., 2017). AO provides a visual representation of an action, typically without the deliberate generation of associated kinesthetic sensations. As such, AO may enhance the structure of mental representations primarily through developing the sequencing and timing of different basic action concepts. In contrast, MI involves the generation of visual and kinesthetic aspects of a movement and so may enhance an individual's mental representation primarily by developing the sensory consequences associated with different basic action concepts. By combining the two techniques, AOMI interventions may develop the mental representation of a skill by enhancing both the sequencing between basic action concepts and the associated sensory consequences, and this in turn may lead to improvements in motor skill performance and learning.

In this experiment, corticospinal excitability was not facilitated by either independent AO or independent MI. This finding was somewhat unexpected as it is well-established in the TMS literature that both AO (e.g., Naish et al., 2014) and MI (e.g., Grosprêtre et al., 2016) usually facilitate corticospinal excitability, relative to control conditions. This effect has been demonstrated in sport-related tasks for both AO (e.g., Aglioti et al., 2008; Wrightson, Twomey, & Smeeton, 2016) and MI (e.g., Fourkas, Bonavolontà, Avenanti, & Aglioti, 2008; Wang et al., 2014). Although this finding conflicts partially with our hypothesis and with previous TMS research on this topic, it could be explained by the choice of stimuli used for the control condition in this experiment. There are inconsistencies in the choice of control conditions used across experiments exploring AO, MI or AOMI with TMS (Loporto, McAllister, Williams, Hardwick, & Holmes, 2011). Rest (e.g., Wang et al., 2014), observation of blank screens (e.g., Wrightson et al., 2016), fixation crosses (e.g., Sakamoto et al., 2009) or static images of the body or a body part (e.g., Aglioti et al., 2008; Wright et al., 2014) are all common choices of control stimuli. Loporto et al. (2011) suggest that the use of a static image of a body or body part as the control condition is the most appropriate as it ensures that any facilitation of corticospinal excitability during observation or imagery conditions is related to the observation or imagery of biological *movement*. In contrast, when using a fixation cross or blank screen it is not possible to determine whether a facilitation effect is due to the observation or imagery of biological movement *per se*, or rather just the presence of some form of visual stimuli on screen or the involvement of some form of cognitive activity (Loporto et al., 2011). The use of a static image of the body was, therefore, chosen deliberately for this experiment to provide a more stringent control condition against which the effects of the three different interventions could be compared. The fact that only AOMI produced a facilitation of corticospinal excitability relative to this stricter control condition provides justification for the use of AOMI, rather than independent AO or independent MI interventions.

Although this experiment is the first to demonstrate the effects of AOMI of a sport-related motor skill on corticospinal excitability, it is important to acknowledge several possible limitations associated with the experiment. First, the four conditions were presented in a fixed order, rather than being randomized or counterbalanced throughout the experiment. As participants always completed the AOMI condition last, it is possible that the enhanced MEP amplitude in this condition was due to either increased familiarity with the stimuli, or a carry-over effect whereby MEP amplitude was enhanced during the final condition due to residual corticospinal activity from the previous conditions. Although these explanations are plausible, Loporto et al. (2012) showed in two experiments that MEP amplitude did not change over the course of observing five blocks of the same action observation stimuli. In addition, the current experiment utilized a 3 min rest period between conditions as Baldi et al. (2002) showed that MEP amplitudes return to baseline levels after only 1 min. Taken together, it is therefore unlikely that the increased effect reported in the AOMI condition is due to familiarity with the stimuli or carry-over effects. Instead, the finding for the AOMI condition is likely to reflect increased activity in the premotor cortex resulting from combining the two simulation states.

Second, imagery perspective may have differed between the MI and AOMI conditions. Participants were told to image the feelings and sensations associated with executing the free throw, but were not instructed to use a specific imagery perspective in either condition. The third-person perspective of the video in the AOMI condition may have encouraged imagery from this perspective, whereas first- or third-person perspectives may have been used in the MI condition, depending on an individual participant's perspective preference. Imagery from a third-person perspective may produce MEPs of larger amplitude (Fourkas, Avenanti, & Aglioti, 2006), although it may also be more difficult to generate kinesthetic imagery from this perspective (Callow & Hardy, 2004). Given this conflict, future research should provide a stricter control of imagery perspective. It may also be worthwhile to investigate the effects of manipulating different AO and MI perspective combinations within AOMI interventions on various neurophysiological and behavioral measures.

A final issue to be acknowledged is that the present experiment used novice participants rather than experienced basketball players. Neurophysiological activity during AO and MI differs between experts and novices. Specifically, expert performers in a variety of skills typically exhibit increased neurophysiological activity during AO and MI compared to novices (Aglioti et al., 2008; Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Fourkas et al., 2008; Mizuguchi & Kanosue, 2017). As such, the direction of the effects reported here would likely replicate in an expert sample, although the magnitude of the effects may be enhanced. This would be a worthwhile area for future research investigating the neurophysiological effects of AOMI interventions.

In conclusion, the main finding of this experiment is that AOMI of a basketball free throw facilitated corticospinal excitability relative to the control condition, but independent AO or MI had no such effect. This finding has important implications for the design and delivery of sport psychology interventions aimed at improving sport performance and enhancing motor skill learning. Independent AO (Ste-Marie et al., 2012) and independent MI (Cumming & Williams, 2012) are well-established techniques that are used widely for improving motor skill performance and learning. The mechanism by which these methods are effective is through producing activity in brain regions that are involved in motor execution (Jeannerod, 2001). The findings of the current experiment indicate that greater activity in the motor system occurs when AO and MI are combined into a single intervention strategy. As such, implementing AOMI interventions may offer a more effective method for improving motor skill performance and learning than the independent use of either technique. There is, however, currently a lack of research examining the effects of AOMI interventions on the performance and learning of motor skills. Future research should therefore first attempt to identify the efficacy of AOMI interventions for improving movement outcome and technique across a range of skill types, for both novice and expert performers. Research could then explore optimal methods for delivering AOMI interventions by, for example, establishing the efficacy of different visual perspectives for AOMI or the effects of introducing MI alongside AO gradually in a layered manner.

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