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Romano-Smith, S,[a†] Roberts, J. W.,[a*] Wood, G.,[b] Coyles, G.,[a] Wakefield, C. J.[a]

[a]: School of Health Sciences, Liverpool Hope University, Taggart Avenue, Liverpool, L16 9JD, UK

[b]: Research Centre for Musculoskeletal Science and Sports Medicine, Department of Sport and Exercise Science, Manchester Metropolitan University, UK

Corresponding author:

Dr Stephanie Romano Smith

School of Life Sciences and Education, Staffordshire University, Leek Road, Stroke-on-Trent, ST4 2DF, UK

Tel: 0178229495

E-mail: stephanie.romanosmith@staffs.ac.uk

[†]Affiliation of author SRS has now changed to School of Life Sciences and Education, Department of Sport and Exercise, Staffordshire University, Leek Road, Stroke-on- Trent, ST4 2DF, UK

[*]Affiliation of author JWR has now changed to Liverpool John Moores University, Brain and Behaviour Laboratory, Research Institute of Sport and Exercise Sciences (RISES), Liverpool John Moores University, Tom Reilly Building, Byrom Street, Liverpool, L3 5AF

Highlights

- Examined the sensorimotor processes underlying motor performance by AOMI
- Simultaneous and alternate AOMI equally enhance motor performance
- Incongruent AO within simultaneous and alternate AOMI attenuates motor performance
- AO and MI may utilise a common lower-level sensorimotor process
- Fixation during AO disrupts motor improvements, which suggests a role for eye movements

Abstract

Combining the motor simulation techniques of action observation and motor imagery (AOMI) is known to enhance motor performance more than when these techniques are presented in isolation. The present study examined the involvement of lower-level sensorimotor processes for the improvement in a dart-throwing task using AOMI. Novice participants (n = 70) were assessed on their dart-throwing both before and after a six-week AOMI training intervention that was contingent upon the random allocation of groups. Participants were randomly allocated into groups involving AOMI, where they observed either a congruent action, incongruent action or fixation cross (control), while simultaneously or alternately imagining the dart-throwing task. Dart-throwing performance was significantly more improved for the simultaneous- and alternate-congruent groups compared to the simultaneous-fixation and control groups. There was no indication of improvement by any of the other groups. This improvement appeared to coincide with lower EMG activity at the agonist and antagonist muscles, which would indicate greater movement efficiency. The findings suggest that AOMI involves a common lower-level sensorimotor process, which can lead to motor facilitation or interference, dependent upon whether the simulation techniques are congruent or incongruent with each other, respectively. What's more, this feature does not appear to differ as a function of the structure of delivery (i.e., simultaneous vs. alternate).

Key words: motor performance, motor interference, EMG, eye movements

Introduction

Motor simulation techniques have been shown to aid motor learning (O'Shea & Moran, 2017). Among these techniques are motor imagery (MI), which is defined as the internal generation and mental rehearsal of action without overt physical output (Eaves, Riach et al., 2016; Jeannerod, 2001); and action observation, which involves the deliberate and structured viewing of a model demonstration (Hodges et al., 2007; Neuman and Gray, 2013; Ste-Marie et al., 2012). Broadly speaking, the benefits served by each of these training or learning interventions may not be mutually exclusive because they each involve the activation of a neural network that is also responsible for motor execution (Jeannerod, 2001).

While the benefits of AO and MI interventions on their own are somewhat well established (Agosti & Sirico, 2020; Gatti et al., 2013), more recent evidence indicates that there is an even greater benefit on motor performance and learning when combining AO and MI (AOMI) compared to AO or MI alone (Marshall et al., 2019; Romano-Smith, Wood, Wright, et al., 2018; Romano-Smith, Wood, Coyles, et al., 2019; Scott et al., 2018; Sun et al., 2016; Taub et al., 2014; for a recent review, see Scott et al., 2021). This benefit coincides with the enhanced engagement of the motor system as is indicated by the increased corticospinal excitability (Sakamoto et al., 2009; Wright, et al., 2014; Wright et al., 2016), and more widespread neural activity (Berends et al., 2013; Macuga & Frey, 2012; Villiger et al., 2013) when undertaking AOMI compared to AO or MI alone. In an attempt to explain these findings, the *dual-action simulation hypothesis* (DAS; Bruton et al., 2020; Eaves et al., 2016) suggests there are two parallel processing streams that can simultaneously represent observed and imaged actions, which can then either merge or compete with each other based on their content and relevance (Eaves et al., 2012; Eaves et al., 2016). Alternatively, the *visual guidance hypothesis* (VG; Meers et al., 2020; see also, Vogt et al., 2013) suggests that

AO may provide a visual guide in order to facilitate MI, which can alone sufficiently engage the motor system.

More recently, our research group has additionally explored the influence of the structure of AOMI interventions; that is, the presentation of AO and MI in simultaneous (S-AOMI) and alternate (A-AOMI) fashion. Initial findings in stroke patients indicated that upper-limb function may improve more following S-AOMI compared to A-AOMI (Sun et al., 2016; see also, Kim et al., 2018). However, it has been shown that the learning of a Taekwondo move can be more greatly advanced by A-AOMI compared to AO or MI alone (Kim et al., 2020). Meanwhile, our recent study in young healthy adults attempting a dart-throwing task indicated that performance outcome scores could be equally improved by both S-AOMI and A-AOMI (Romano-Smith, Wood, Wright, et al., 2018). In an attempt to further detail the underlying neuromuscular function using surface electromyography (EMG), we also found that S-AOMI and A-AOMI generated a similarly lower magnitude of activity at the triceps brachii muscle (agonist) during the latter throwing phase (Romano-Smith et al., 2019); potentially highlighting the increased movement efficiency (Lohse et al., 2010) that is a hallmark of highly-skilled, expert-like movement control (Gatti et al., 2013; Duchateau et al., 2006; Lohse et al., 2010).

At this juncture, we may prematurely assume that both S-AOMI and A-AOMI involve similar or the same sensorimotor processes. However, it is possible that while both interventions have obtained similar behavioural outcomes, they may manifest from slightly different processes. This possibility resembles that of previous models that indicate separate, but not mutually exclusive, processes may underpin motor learning (e.g., early vs. late mediation: Vogt & Thomascke, 2007; effector-dependent vs. -independent: Bird et al., 2005; Heyes & Foster, 2002; Gruetzmacher et al., 2011; bottom-up vs. top-down: Hayes et al., 2014; Roberts et al., 2014). To elucidate, the S-AOMI may primarily engage lower-level motor processes, where the neural network that is responsible for execution may be more greatly activated by AOMI (Macuga & Frey, 2012; Wright et al., 2018). This possibility is consistent with previous suggestions that AOMI involves neural processes that unfold at the very same time (e.g., DAS (Bruton et al., 2020; Eaves et al., 2016), VG (Meers et al., 2020)). Meanwhile, the A-AOMI may additionally comprise higher-level cognitive processes that accommodate for some degree of deliberation or comparison between each of the AO and MI trials. Indeed, research from the motor learning literature consistently highlights a benefit of having the opportunity to deliberate or contemplate previous trial attempts (Guadagnoli & Kohl , 2001; Swinnen et al., 1990), or switching between different routines or variations of a set task (Hall et al., 1994; Shea & Morgan, 1979). Moreover, the potential for motor learning through AO and/or MI is additionally accompanied by the recruitment of the lateral prefrontal neural regions, which are synonymous with attentional processes including action monitoring and movement reorganization (Buccino et al., 2004; Higuchi et al., 2012; see also, Eaves, Behmer, et al., 2016). Thus, it is further possible to capture the learning or adaptation from AO and/or MI by also recognizing the importance of events that take place in between each of their presentations. These particular learning processes may lend themselves more to the A-AOMI intervention because of its separated and delayed presentations of AO and MI.

The aim of this experiment was to further expand upon our previous findings using dart-throwing (Romano-Smith et al.,2019), and more specifically, disentangle the sensorimotor processes that underpin motor learning by S-AOMI and A-AOMI. In this regard, we adapted a secondary task paradigm, where participants would either simultaneously or alternately observe congruent (dart-throwing; elbow extension along the midsagittal axis) or incongruent (internal shoulder rotation along the frontal axis) movements with respect to the imagined dart-throwing task. This manipulation has often been used to highlight the involvement of lower-level motor processes, where if AO and MI were to similarly engage the neural network that is responsible for execution, then it would facilitate (congruent) and/or interfere (incongruent) with any subsequent movement or motor learning (Kilner et al., 2003; Mattar & Gribble, 2005; Piedimonte et al., 2018; Ramsey et al., 2010). Of interest, a similar principle was adapted for recent investigations on the corticospinal excitability and eye movements generated during AOMI when the MI component was either congruent or incongruent with the AO component (Bruton et al., 2020; Meers et al., 2020). Specifically, these studies demonstrated that excitability was a product solely of the MI component (Meers et al., 2020), or excitability and eye movements reflected a combination of both the AO (i.e., index finger abduction-adduction) and MI (i.e., little finger abduction-adduction) components (Bruton et al., 2020). However, it is important to note that the present study differed in two ways. Firstly, we manipulated AO while retaining MI because the former can be conveniently modified and set-up prior to commencing the study, and the latter can simply remain specific to the learning objective (i.e., dart-throwing) for the learners to control. Secondly, the AOMI could be uniquely delivered in alternate fashion meaning there was potentially less opportunity for the previously stated dual or simultaneous processes to take place.

In line with the suggestions of dual or simultaneous processes (Bruton et al., 2020; Eaves et al., 2016; Meers et al., 2020), it is predicted that if the S-AOMI involves AO and MI utilising a common neural network including a similar set of eye movements, then learning will be attenuated having simultaneously observed an incongruent movement because it would interfere with any benefit served by MI. At the same time, if the A-AOMI involves a different set of neural and eye movement processes, then learning should continue to unfold having alternately observed an incongruent movement because any benefit served by MI would still be upheld as if it were delivered on its own. Moreover, we incorporated a condition where participants simultaneously or alternately observed a fixation cross to act as a control. That is, the typical AO (congruent/incongruent) was replaced by the requirement to fixate on a cross, which would presumably limit any interference and continue to enable learning by MI (aside from prohibiting the potential contribution of eye movements; Wakefield, et al., 2020).

Method

Participants

Because the present study was heavily adapted from previous studies that were conducted within our lab (Romano-Smith et al., 2018; 2019), the current number of participants within each group were intended to remain as close as possible to the original target sample. As a result, there were 70 participants (35 males, 35 females*; mean age* = 28.1 *years, SD* =5.96) that agreed to take part in the study; all with limited darts experience (including no targeted or deliberate practice, no competitive experience, >3 years from when they recalled having last possibly attempted a dart throw within a recreational setting) and no previous MI training. Participants were equally distributed to 1 out of 7 groups; therefore, there were 10 participants per group that were age- and gender-matched. Participants had normal or corrected-to-normal vision and reported being right-hand dominant (Oldfield, 1971). The experiment was ethically approved by the department research ethics board.

Measures

Movement Imagery Questionnaire-Revised (MIQ-R)

The MIQ-R (Hall & Martin, 1997) is an 8-item inventory that assesses the ability to perform visual and kinesthetic imagery. Participants had to imagine a series of movements using an internal kinesthetic or visual modality and rate the degree of ease or difficulty that was experienced by using a 7-point Likert scale (1 = very hard to feel/see; 7 = very easy to feel/see). The validity and consistency of the MIQ-R has been demonstrated by Gregg et al. (2010), and has been used previously in imagery studies involving far-aiming tasks (e.g., Romano-Smith et al., 2018; Romano-Smith et al., 2019; Smith et al., 2008)

Imagery Diary

Participants were provided with an imagery diary, which they could complete after each MI session throughout the intervention period. Participants noted any difficulties, feelings or concerns that were experienced when engaging in MI (for further guidelines, see Goginsky & Collins, 1996). Engagement within the session was measured using a frequency count of the number of sessions completed from a possibility of 18 sessions. The vividness and controllability of the imagery were also rated on a 7-point Likert scale (1=not at all vivid / controllable;7=very vivid / controllable).

Performance

The performance measure was based on the points scored from dart-throwing toward a dartboard. In line with the American Darts Organization regulations, the dartboard was mounted 172.72 cm from the ground and located at a distance of 236.86 cm from the throwing line. The dartboard was 45.72 cm in diameter and featured 10 concentric circles (2 cm wide) with the centre assuming the highest score (10 points) and outer edge assuming the lowest score (1 point). Darts landing outside the board were scored as 0 points (see Fig. 1)

[Insert Fig.1 about here]

Electromyography (EMG)

Muscle activation patterns were measured using electromyography (EMG) during the pre-test and post-test procedures, by placing pairs of 10-mm Trigno EMG electrodes (Delsys

Inc.) sampling at 1500 Hz with a 20-mm separation on the belly of the biceps brachii, triceps brachii, flexor carpi radialis and extensor carpi radialis (for similar regions, see Lohse et al., 2010; Mousavi et al., 2019). EMG signals were initially processed using a Hamming bandpass filter of 20-350 Hz and converted using a root mean square (RMS) calculation with a 100-ms time-window (Fukuda et al., 2010; for examples in dart-throwing, see Romano Smith et al., 2019; Zachry et al., 2005). Data from each individual trial were then normalised with respect to the peak activation for that corresponding trial.

A digital recording of the dart-throwing movement was made via a secure webcam (30 Hz), which was located perpendicular to the throwing direction and adjacent to the non-throwing limb. The EMG and digital recordings were synchronised using Noraxon MR3.10 analysis software (Scottsdale, AZ, USA). The points of maximum elbow flexion (throw preparation) and extension (throw completion) were marked as the key events of the complete throwing action courtesy of a frame-by-frame analysis. Mean muscle activation between each of these events was calculated and expressed as a percentage of the peak activity.

Procedure

The study followed a mixed-measures design including a pre- and post-test within seven groups of participants that each undertook different forms of an AOMI intervention. Participants were initially introduced to the task by the experimenter and completed the MIQ-R (Hall & Martin, 1997). Participants physically attempted the dart-throwing task during a pre- and post-test in order to assess their baseline dart-throwing ability and any subsequent improvement, respectively. They were instructed to aim as close as possible to the centre of the dartboard and obtain the highest possible score. In between each of these tests, participants received a training intervention that was assigned according to randomly allocated groups: simultaneous-congruent, alternate-congruent, simultaneous-incongruent, alternate-incongruent, simultaneous-fixation, alternate-fixation, and control (Fig. 2).

The experimental groups could be discriminated by their unique combination and structure of MI and AO. For the MI component, each of the experimental groups imagined dart throws from a first-person perspective with the sound of the dart hitting the dartboard to ensure imagery unfolded within real-time; that is, at the same rate of the AO component. In order to facilitate MI and promote a high-fidelity to physical execution (Lang, 1977; 1979), participants were initially prompted by the reading of an individualised imagery script that could be progressively adapted or revised by the participants themselves across the course of their training. Based on the stimulus and response training from Lang et al. (1980), this process involved appropriately capturing the environmental surroundings (stimulus proposition), physical experiences (e.g., muscle contraction, heart rate, etc) (response proposition), and stimulus-response relationships (meaning proposition) (for a similar procedure, see Romano-Smith et al., 2018; Romano-Smith et al., 2019). Following the completion of each training session with MI, participants had to update their own imagery diary.

For the AO component, participants viewed either a congruent action, incongruent action, or fixation cross (Fig. 3). The congruent action consisted of a model dart throw taken from the first-person perspective. The incongruent action involved upward internal rotation of the shoulder taken from the first-person perspective. The cross featured two intersecting white lines at the centre of a black background, which participants had to fixate on. Meanwhile, the control group observed one continuous block of video interviews with a professional dart player, which did not provide any technical insights on dart-throwing and roughly equated to the time of the other experimental group interventions.

The structure for each of the AO and MI components was also manipulated by presenting them in simultaneous or alternate fashion. The simultaneous structure involved closely observing the visual stimuli (congruent, incongruent, fixation), while also imagining the dart throw at the very same time. The alternate structure involved closely observing the visual stimuli followed by the independent or separate imagining of the dart throw whilst in in view of the dartboard. Each of the training sessions featured 6 blocks of 5 trials for all of the experimental groups (30 trials; see Fig. 2) (Smith & Holmes., 2004; Romano-Smith et al., 2019). A single trial for the simultaneous groups involved AO and MI taking place in one instance, while a single trial for the alternate groups involved AO followed MI with each component taking place in separate instances – thus making the duration of the intervention slightly shorter in time for the former compared to the latter. There were 3 sessions per week for 6 weeks. All participants were instructed to separate each session by a minimum of 48 hours of rest to avoid any fatigue and/or boredom (Romano-Smith et al., 2019). The pre- and post-test consisted of 5 initial familiarisation trials followed by 30 performance trials.

[Insert Fig.2 and Fig, 3 about here]

Data analysis

To evaluate any potential differences between the allocated groups in their inherent imagery ability, the ratings from the kinesthetic and visual sub-scales of the MIQ-R that were measured near the start of testing were analysed using separate one-way Analysis of Variance (ANOVA). To indicate whether participants actively engaged in the required MI, the reported accounts of the sessions from each participant imagery diary were accumulated and analysed using a one-way ANOVA.

The points from each individual dart throw were accumulated across all trials within the pre- and post-test to generate a performance score out of 300 (10 max. points x 30 trials). To obtain the most consistent or representative muscle activation patterns, and to avoid any on-off transient phenomena including muscular exertion (Ahmadi et al., 2007; Lohse et al., 2010; Merletti et al., 1985), participant mean EMG data were taken only from trials 2-4 within the blocks 2-4.

Performance and EMG measures were analysed using Analysis of Covariance (ANCOVA) with pre-test scores as the covariate and group as the fixed factor. The assumption of homogeneity of regression slopes was evaluated courtesy of the interaction term (group x pre-test).[1] Effect sizes were indicated by partial eta-squared (η_p^2). Significant main effects were decomposed using the Fisher Least Significant Difference (LSD) post hoc procedure. Statistical significance was declared at $p \leq .05$.

Results

Self-report data

For the ratings from the MIQ-R, there was no significant main effect of group for the kinesthetic, $F(6,69) = 1.65$, $p = .144$, $\eta_p^2 = .13$, and visual, $F(6,69) = .87$, $p = .522$, $\eta_p^2 = .07$, subscales (Table 1). For the frequency of sessions taken from the imagery diaries, there was no significant main effect of group, $F(5,54) = 1.69$, $p = .152$, $\eta_p^2 = .13$. It appeared all participants clearly undertook the MI with reports available on at least 14 out of a possible 18 sessions.

[Insert Table 1 about here]

Performance

For performance outcomes, there was a significant main effect of group, $F(6,62) = 2.26$, $p = .049$, $\eta_p^2 = .18$ (Fig. 4). Post hoc analysis indicated a significantly higher score for the simultaneous-congruent compared to the simultaneous-fixation ($p = .039$) and control ($p = .007$) groups. Additionally, there was a significantly higher score for the alternate-congruent compared to the simultaneous-fixation ($p = .026$) and control ($p = .005$) groups. There were no further significant differences for the remaining pairwise comparisons ($ps > .05$).

[Insert Fig. 4 about here]

EMG measures

For the biceps brachii, the main effect of group approached conventional levels of significance, $F(6,62) = 2.15$, $p = .060$ $\eta_p^2 = .17$, which indicated a trend toward the simultaneous-fixation group generating the highest muscle activity (Table 2).

For the triceps brachii, there was a significant main effect of group, $F(6,62) = 3.08$, $p = .011$, $\eta_p^2 = .23$. Post hoc analysis indicated significantly less activation for the simultaneous-congruent compared to the alternate-incongruent ($p = .047$), simultaneous-fixation ($p = .003$) and control ($p = .001$) groups. In a similar vein, there was significantly less activation for the alternate-congruent compared to the simultaneous-fixation ($p = .014$) and control ($p = .007$) groups. In addition, there was significantly less activation for the alternate-fixation compared to the control group ($p = .032$).

Meanwhile, there was no significant main effect of group for either the flexor carpi radialis, $F(6,62) = .91$, $p = .494$, $\eta_p^2 = .08$, nor the extensor carpi radialis, $F(6,62) = .71$, $p = .641$, $\eta_p^2 = .07$.

[Insert Table 2 about here]

Discussion

The aim of this experiment was to further expand on previous motor learning findings by combining AO and MI, and more specifically, disentangle the sensorimotor processes that underpin their benefit. More specifically, we explored the possibility of whether S-AOMI and A-AOMI feature contributions from different processes. Namely, we anticipated that the lower-level sensorimotor processes that may potentially more heavily contribute toward S-AOMI would render an inability to learn when one of the simulation components (i.e., AO) was incongruent with the other (i.e., MI). On the other hand, we anticipated that the potentially higher-level cognitive processes that may additionally contribute toward A-AOMI would render a continued capacity to learn regardless of whether the simulation components were congruent or incongruent with each other.

Firstly, in line with our previous findings (Romano-Smith, et al., 2019), we showed an improvement in motor performance following both the simultaneous-congruent and alternate-congruent interventions compared to the simultaneous-fixation and control groups. However, there was no indication of learning for either of the simultaneous-incongruent and alternate-incongruent interventions. These behavioural findings were corroborated by EMG recordings, where the improvements in dart-throwing performance appeared to coincide with a decrease in activity for the key agonist (triceps brachii) and antagonist (biceps brachii) muscles. This pattern of activity may characterise a skilled level of performance because it represents the recruitment of fewer motor units, and thus greater efficiency, which is one of the hallmarks of expert-like performance (Duchateau et al., 2006; Lohse et al., 2010).

The benefit that was served by the combined AO and MI interventions for simultaneous-congruent and alternate-congruent groups has been previously explained by learners more greatly recruiting a common neural network that is synonymous with physical execution (Berends et al., 2013; Eaves et al., 2016; Taube et al., 2015).This learning may also be seen as additive in nature compared to the much smaller and independent benefit that is usually served by AO and MI alone. Likewise, the smaller magnitude muscle activation patterns that occurred within each of these groups would seem to suggest a more enhanced neuromuscular function. To elucidate, an enhanced performance combined with lower muscle activity may indicate a more automatized mode of control as opposed to poorer performance manifesting from a larger magnitude and more abrupt muscle activation pattern, which is synonymous with the conscious constraint of action (Wulf et al., 2001; Zachry et al., 2005).

In line with this argument, it was shown that learning could no longer take place when participants had to observe a movement (internal shoulder rotation) that was incongruent with their imagery (dart-throwing). While there was not necessarily a statistically significant difference between the congruent and incongruent groups, their differences with respect to the remaining group interventions including the control group would suggest otherwise (for a similar pattern of results, see Brown et al., 2009; Marshall et al., 2019); particularly as it was aligned with key theoretical stances and related empirical findings. Thus, knowing as we do that AOMI (Bruton et al., 2020; Wright et al., 2018), and AO (Fadiga et al., 1995; Iacoboni et al., 1999; Iacoboni & Dapretto, 2006) and MI (Fadiga et al., 1999; Grezes & Decety, 2001; Villiger et al., 2013) alone are capable of engaging neural regions that are associated with physical execution, it is assumed that this interference operates at the lower-level sensorimotor processes (Mattar & Gribble, 2005; Ramsey et al., 2010). To elucidate, the observation of an incongruent human movement may have awakened an internal representation that was specific to the observed movement, while at odds with the representation recruited through motor imagery (see Blakemore & Frith, 2005).

The extent of this learning and interference across the simultaneous and alternate groups appeared to be relatively similar or consistent. In a similar vein, the muscle activation patterns within each of these groups appeared to be highly similar, which would suggest a similar mode of control and related neuromuscular function. This was despite the clear differences in being able to continuously match or actively off-set the AO and MI for simultaneous and alternate groups, respectively. Thus, it would appear that both groups equally engaged lower-level sensorimotor processes. That said, it is possible that there are subtle or other psychological differences that remain elusive or beyond the remits of the present study. For example, it is possible that the simultaneous and alternate interventions may be differentiated by their use of attentional resources. While it has been argued that a simultaneous intervention may occupy fewer resources by allowing AO and MI to be combined (Scott et al., 2021), it is also possible that it inversely uses more resources, given that it could also be described as a dual-task intervention (Eaves, Behmer, & Vogt, 2016; see also, Hayes et al., 2014; Mattar & Gribble, 2005). Moreover, while the alternate intervention appears to indicate the involvement of lower-level sensorimotor process, this does not preclude its use of additional explicit or verbalizable knowledge that can also contribute to the learning process (Beilock & Carr, 2001).

Perhaps surprisingly, the simultaneous- and alternate-fixation groups that featured a white-on-black cross in observation failed to exhibit any improvement. Indeed, the absence of any incongruent AO, along with the continuation of MI, may anticipate at least some indication of motor learning.[2] However, a viable explanation for this outcome may relate to the role of eye movements. That is, in addition to a common neural network, it is suggested that AO and MI share similar patterns of eye movements as physical execution (Causer et al., 2013; Heremens et al., 2008; McCormick et al., 2012a,b; Wakefield et al., 2020; see also Flanagan & Johansson, 2003). Thus, in the presence of a static cross in order to fixate on or generally suppress eye movements, the functional correspondence between MI and execution may be limited, which would diminish the benefit for motor learning (Heremens et al., 2011). This issue may not have been as prevalent for the alternate-fixation group because they had MI without the cross being simultaneously present, which may explain how they were slightly better or had lower muscle activation (greater efficiency) than the simultaneous-fixation and control groups.

Limitations

While the present study further examined the sensorimotor processes that underpin learning using different structures of AOMI, it is important to acknowledge the possible limitations. Firstly, while the present study design captures the improvement of a novel or unpractised movement skill to indicate motor learning, it does not feature the delayed retention and transfer tests that would respectively assess the relative permanence and adaptation that also characterise motor learning (Schmidt et al., 2019; for similar approaches, see Marshall et al., 2019; Scott et al., 2018; Taube et al., 2014). That said, we strongly suspect learning to have unfolded in this instance because the superior outcomes for the simultaneous- and alternate-congruent groups coincided with the muscle activation patterns from the EMG data, which indicated a smaller magnitude and more expert-like response. That said, the present study adopted surface electrode EMG, which may not necessarily provide a direct indication of neuromuscular function that could otherwise be detected using fine-wire intramuscular EMG with a decreased risk of cross-talk between muscles (Yue et al., 1995; Felici & Del Vecchio, 2020). Along these lines, there are perhaps further insights to be drawn from the use of TMS as a direct indication of the cortical level processes during AOMI (e.g., Bruton et al., 2021; Meers et al., 2020; Wright et al., 2018).

Despite the interference witnessed when being exposed to an incongruent secondary task, it is possible that the incongruent movement comprising AO within the present study could have partially facilitated or been coordinated with the MI. This possibility has been mostly highlighted by some of the empirical findings underpinning the dual-action simulation hypothesis, where it is possible to simultaneously utilise representations for AO and MI that can perhaps merge together depending on their degree of similarity (Bruton et al., 2021; see also Vogt et al., 2013). It is precisely this logic that could explain why the present differences between congruent and incongruent groups were comparatively limited.

However, perhaps most importantly, one of the underlying issues that is inherent within this sort of research; specifically, the comparison between S-AOMI and A-AOMI, involves the potentially confounding influence of volume (i.e., number of trials) and time spent within practice (ie.., simulation). That is, because of the differences in structure for each of these combined interventions, it also incurs differences in either the volume or time. For example, the present study features the same number of AO and MI trials for S-AOMI and A-AOMI interventions, although incidentally there are twice as many simulations for the latter compared to the former. In this regard, such comparisons within the literature may be somewhat misguided in terms of their underlying assumptions or inferences surrounding sensorimotor processes. While the findings from our research group to-date tend to indicate a limited difference between S-AOMI and A-AOMI, we still cannot deny the possibility that manipulations targeting volume and time of practice could also have an influence on learning outcomes. Thus, it is useful perhaps to have future studies systematically control the volume and time that is coincident with any manipulation of structure (e.g., x30 trials AO and MI vs. x15 trials AO and MI in simultaneous and alternate structures). Finally, with this in mind, because of the potential for AO to coincide with spontaneous MI (Meers et al., 2020; Vogt et al., 2013), it is relevant to consider ways to control for this possibility including manipulation checks (e.g., Bruton et al., 2021) that ensure AOMI combinations unfold as intended.

Applied implications and future recommendations

In summary, the results of the present study provide further insight on the benefits served by AOMI interventions for motor learning. More specifically, we highlight how the benefit of either simultaneous or alternate presentations of AO and MI appear to utilise the same lower-level sensorimotor processes. What's more, we suspect that the suppression of eye movements may prohibit the benefit of AOMI. These differences were also reflected within the muscle activation patterns, where a smaller magnitude of activity coincided with better outcomes, and thus more efficient neuromotor control.

These findings lend further support to the benefits served by AOMI interventions for motor learning. What's more, they allude to the importance of the congruency or similarity between the AO and MI components within a combination of AOMI – the closer they are to each other, then the greater the benefit for motor learning. Meanwhile, there appear to be rather limited differences between the benefits served by simultaneous and alternate structures. In this regard, for example, learners may save themselves more time when undertaking S-AOMI, although if there were to be any need to distinguish presentations of AO and MI as in A-AOMI (e.g., instructions, coaching points, etc), then they should be done without any fear of mitigating key lower-level sensorimotor processes. That said, more needs to be done to explore the potential differences in attentional processes and/or strategies that may coincide with each of these delivery structures. Finally, future research may further explore the additive benefit of AOMI by investigating the potentially different sources of information that are gleaned from each of the AO and MI components. For example, access to the biological motion trajectory during AO (Grossman et al., 2000; Kilner et al., 2003; Press et al., 2011) may provide a spatiotemporal kinematic referent for updating an already engaged internal representation courtesy of MI (for a similar argument, see Glover & Baran, 2017).

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Footnotes

1) There was no significant effect for the interaction term (group x pre-test) in any of the dependent measures (*Fs* range = .49-1.73, *ps* range = .13-.82), which suggests that the assumption of homogeneity of regression slopes was met.
2) In light of the learning from each of the congruent groups, but neither of the fixation groups, it could be argued that the availability of congruent AO is the sole feature to enable learning given that all the groups had the same MI. Thus, we compared the present data from the congruent groups (simultaneous-congruent, alternate-congruent) with two of our previous data sets involving only AO (Romano-Smith, Wood, Wright, et al., 2018 (study 1); Romano-Smith, Wood, Coyles, et al., 2019 (study 2). Using ANCOVA with pre-test as the covariate and group as the fixed factor (assuming homogeneity of regression slopes; group x pre-test: $F(3,32) = .65$, $p = .588$), we found a significant main effect of group, $F(3,35) = 3.46$, $p = .027$, $\eta_p^2 = .23$, which indicated higher scores for the congruent groups from the present study compared to AO alone (simultaneous-congruent > AO (study 1) ($p = .040$), AO (study 2) ($p = .083$); alternate-congruent > AO (study 1) ($p = .010$), AO (study 2) ($p = .021$). This outcome refutes the suggestion of learning solely through AO, and demonstrates the advantage of having AO accompanied by MI.

Figures and Tables Captions

Fig.1 A still shot of the task performed.

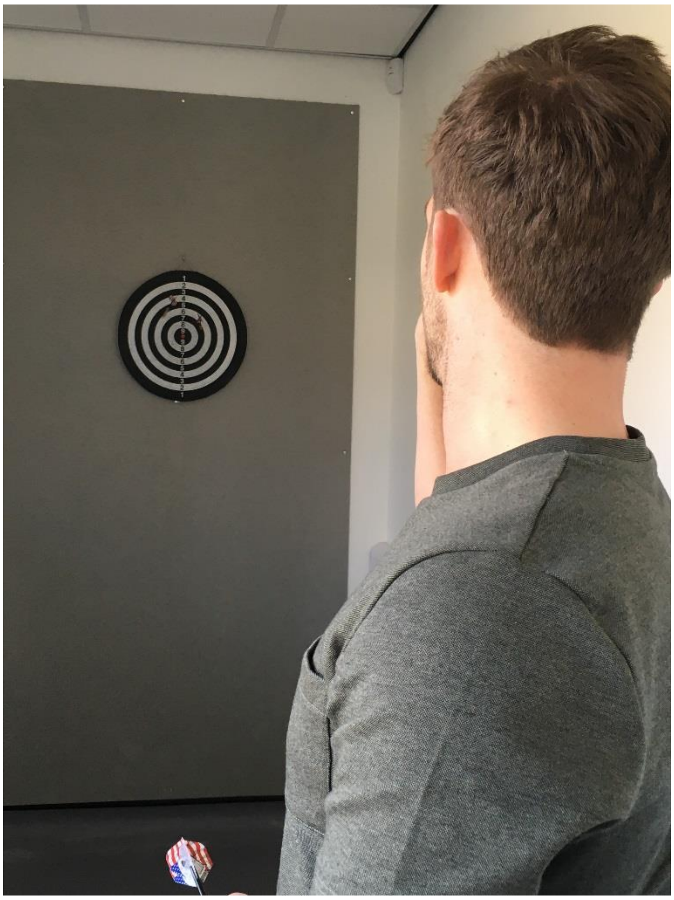
Fig. 2. Representative illustration of the timeline of events across the six weeks of training (*upper panel*) and within a single session of training (*lower panel*)

Fig. 3. Representative illustration of the timeline of events for the AO and MI (left-to-right) within the experimental AOMI interventions. The present illustration features only four events that are each synonymous with an individual trial (total = 30 trials). *Dotted arrows* comprising the incongruent stimuli indicate the direction of the observed arm movement.

Fig. 4. Adjusted mean dart-throwing scores (out of 300) as a function of group. Error bars represent the standard error (SE) of the mean. (*) indicates a significant pairwise difference at $p < .05$.

Table 1 Mean (±SE) MIQ-R scores (kinesthetic and visual) and frequency of training sessions for each group.

Table 2. Adjusted means (±SE) for the EMG activation across all throws (normalized (%) to peak) at the biceps brachii, triceps brachii, flexor carpi radialis and extensor carpi radialis.



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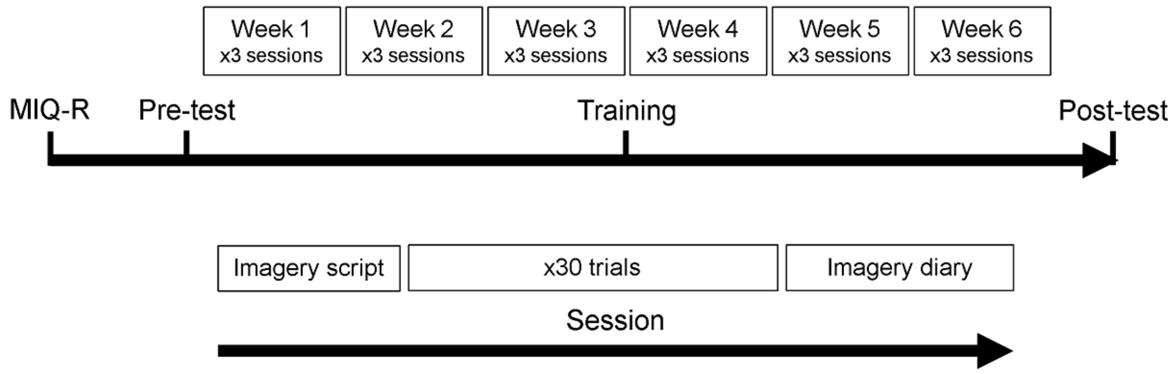
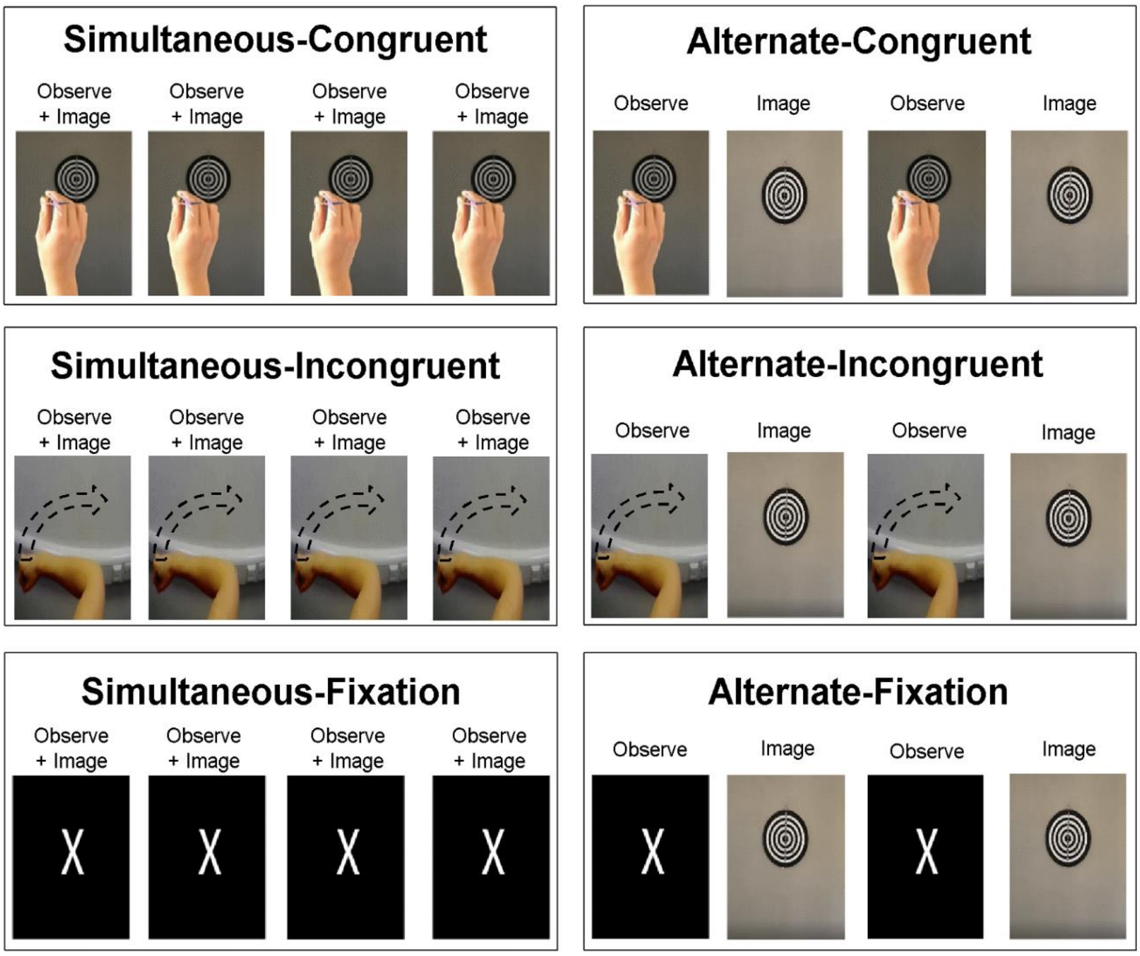


Fig. 2. Representative illustration of the timeline of events across the six weeks of training (*upper panel*) and within a single session of training (*lower panel*)



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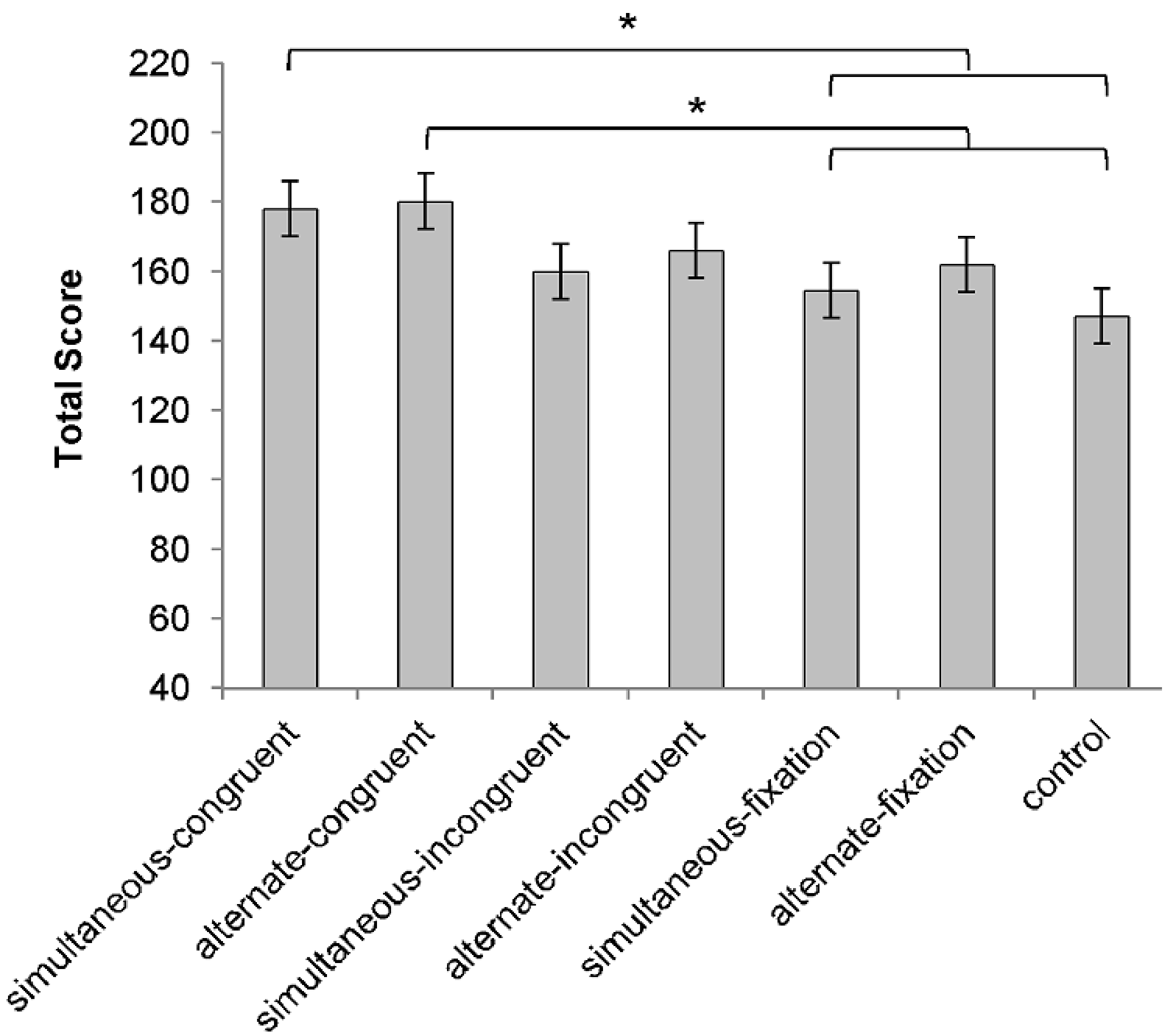

Fig. 4. Adjusted mean dart-throwing scores (out of 300) as a function of group. Error bars represent the standard error (SE) of the mean. (*) indicates a significant pairwise difference at $p < .05$.

Table 1

Mean (±SE) MIQ-R scores (kinaesthetic and visual) and frequency of training sessions for each group.

	MIQ-R Kinaesthetic	MIQ-R Visual	Frequency
simultaneous-congruent	6.30 (0.18)	6.20 (0.26)	17.30 (0.21)
alternate-congruent	6.15 (0.29)	6.31 (0.23)	16.60 (.34)
simultaneous-incongruent	6.35 (0.23)	6.35 (0.29)	16.60 (.40)
alternate-incongruent	6.57 (0.18)	6.50 (0.30)	16.70(.42)
simultaneous-fixation	5.75 (0.29)	5.95 (0.31)	17.70 (.15)
alternate-fixation	6.62 (0.12)	6.60 (0.15)	16.70 (.47)
control	5.90 (0.28)	6.12 (0.20)	------

Table 2.

Adjusted means (±SE) for the EMG activation across all throws (normalized (%) to peak) at the biceps brachii, triceps brachii, flexor carpi radialis and extensor carpi radialis.

	Biceps	Triceps	Flexor	Extensor
simultaneous-congruent	48.35 (4.76)	49.45 (4.02)	46.74 (4.98)	60.46 (5.72)
alternate-congruent	52.31 (4.89)	52.4 (4.03)	53.17 (4.97)	58.47 (5.70)
simultaneous-incongruent	57.01 (4.78)	59.38 (4.06)	50.32 (5.05)	51.31 (5.70)
alternate-incongruent	40.54 (4.83)	60.90 (4.01)	57.16 (5.02)	58.41 (5.71)
simultaneous-fixation	63.12 (4.83)	66.86 (4.02)	52.38 (5.01)	52.12 (5.75)
alternate-fixation	51.20 (4.76)	55.89 (4.00)	48.11 (5.01)	46.92 (5.70)
control	50.86 (4.79)	68.31 (4.00)	59.88 (5.04)	54.33 (5.73)

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Conflict of interest

None