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Research article

Effects of physical practice on the duration of motor imagery

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A R T I C L E I N F O

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A B S T R A C T

Motor Simulation Theory proposes that imagined actions are produced using the brain's motor system, and should therefore always be temporally equivalent to physical movements. However, empirical results are not always consistent with this prediction. Studies indicate that the durations of unfamiliar imagined actions are over-estimated, whereas the durations of more familiar actions may be closer to (or even faster than) actual movement execution. We therefore examined the effects of different levels of practice on the durations of both physically performed and imagined actions. Participants (N=31) completed an initial assessment in which the durations of physically performed and imagined finger movement sequences were measured. Participants then completed three days of physical training in which different sequences received either extensive training (150 repetitions/session), minimal training (10 repetitions/session), or no training. In a subsequent assessment session, we found that the time taken to both physically execute and imagine performing sequences decreased with training. However, contrary to the predictions of Motor Simulation theory, imagined movement durations consistently over-estimated those of physically performed movements. While the difference in the timing of imagined and physically executed movements decreased between the initial and final assessment, this effect was not modulated by training. These results extend our understanding of the relationship between motor imagery and physical practice, and highlight a key limitation in the predictions of Motor Simulation Theory.

1. Introduction

Motor imagery is defined as a mental representation of an action without physically performing it. Motor imagery has been shown to be a valuable tool in the acquisition of simple and complex motor skills, for example in athletes [1,2] and in medical professionals [3], as well as being beneficial in motor rehabilitation in conditions such as stroke [4,5]. Despite these well-documented advantages of motor imagery, the mechanisms underlying motor imagery remain debated.

Motor Simulation theory [6] claims that motor imagery is functionally equivalent to motor execution. That is, the same neural, cognitive, and physiological processes underlie physically performing an action and imagining performing the same action. Motor imagery of an action is proposed to follow the same planning process as physically executing that action. However, during imagery, it is argued that inhibition and/or sub-threshold activation of the primary motor cortex prevents the action from being executed [6]. Studies using mental chronometry tasks have generally been considered to offer support for Motor Simulation theory. According to this theory, imagining an action should take as long as physically performing the same action in these tasks [6,7]. A close match between execution and motor imagery has been shown across a number of tasks including pointing [8,9], walking [10], and writing [8,11]. Several characteristics of physical execution are also present in imagined actions. For example, isochronism found during physically writing at different sizes was also found when imagining writing [8]. Fitts's law [12] is one widely studied characteristic of behaviour, which states that movement time for reaching behaviours increases as a function of task difficulty, which is usually indexed by the distance between the actor and the target, and as a function of the width of the target. Several studies have shown that Fitts's law holds true in both physical and imagined actions [9,13–15], though more recent work has challenged the generalisation of this law to all actions [16].

This temporal equivalence between motor imagery and overt actions is not always observed, and therefore calls into question the idea that motor imagery is an inhibited action. For example, when participants are asked to complete a walking task [7] or pointing and reaching actions [17] with added weight, imagined movement time was significantly overestimated compared to physical execution of the same

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movement. It should be noted that this pattern was not replicated when participants were not blindfolded and could use visual information to aid their imagined action [18]. This finding indicates that, like executed movements, force calculations and the timing of imagined actions are programmed independently. However, differences in the durations of imagined and physically executed movements are also found for rapid and difficult or complex attentionally-demanding actions, such as in tennis [19], swimming [20] and gymnastics routines [21]. These timing errors are inconsistent with the predictions of the Motor Simulation theory, which would predict imagined and executed actions to always be closely matched.

Neurophysiological work also highlights the differences in cortical activity between motor imagery and action execution. These differences are inconsistent with the Motor Simulation theory, which proposes that the same cortical areas should be recruited for both motor imagery and action execution. A meta-analysis comparing motor imagery, action observation, and action execution, [22] found that motor imagery consistently recruited the dorsolateral prefrontal cortex, which might reflect inhibition of motor plans [23] or working memory updating processes [24,25], which are required to monitor the mental image throughout imagery. The recruitment of dorsolateral prefrontal cortex in motor imagery has also recently been shown in a Transcranial Magnetic Stimulation study, where motor imagery of a tossing or placing action was slowed following the stimulation over dorsolateral prefrontal cortex, but the physical execution of the same overt action was unaffected [26]. These results indicate that motor imagery, when compared to motor execution, is unique in its recruitment of executive cognitive functions, such as attention and working memory, which are known to recruit dorsolateral prefrontal cortex [25,27]. In addition, parietal cortex, which is also involved in visuospatial [28] and motor working memory [29], was recruited during motor imagery [22,30].

1.1. Aim of current study

Motor Simulation theory predicts that motor imagery should always take approximately as long as motor execution in the absence of external perturbations, because both behaviours recruit the same networks [6]. The effects of physical practice should therefore be consistent across motor imagery and motor execution conditions, such that physical practice will decrease the amount of time needed to physically execute and mentally imagine completing an action. Critically, according to Motor Simulation theory, the duration of the imagined and executed action should remain equivalent before and after training. In contrast to this prediction, previous research has identified differences in the durations of Motor Imagery and Physical execution, and that such differences are modulated by physical experience. For example, Yoxon et al., [48,49] showed an effect whereby participants significantly over-estimated the duration of imagined movements compared to physically performed movements, and that limited physical practice (30 trials) significantly reduced this difference. Consistent with this effect, we examined the possibility that completing greater amounts of physical practice may decrease any differences between the durations of physically executed and imagined movements.

The current study therefore aimed to examine the effects of physical practice on the duration of motor imagery. Participants first completed an initial assessment which included physical and imagined execution of different digit sequences. They then completed three days of training where sequences were physically practiced at either a high amount (150 trials per day) or a low amount (10 trials per day). After these remote training sessions, participants completed a final execution and imagery assessment.

2. Methods

2.1. Participants

51 volunteers were originally recruited to participate in the study, of which 31 participants met all inclusion criteria (see below). Participants were recruited from two sources; 28 participants were recruited from the student population at UCLouvain, Belgium. These participants completed a hybrid procedure, whereby they completed initial and final sessions in the laboratory, with intervening training sessions being completed remotely. These participants were compensated with a maximum of 35€ for their time. To increase the sample size of the study, a further 23 participants were recruited via the online study participation platform 'Prolific' and completed the entire study remotely. These participants were compensated a maximum of £15 for their time. This experiment received ethical approval from the UCLouvain Psychological Sciences Research Ethics Committee (reference: Project 2023–57, Date: 17/11/2023). All procedures were performed in compliance with relevant laws and institutional guidelines. The privacy rights of participants have been observed and informed consent was obtained.

Several participants ($n = 20$) were excluded from the study based on a series of sequentially applied criteria. First, participants were excluded if sessions were not completed on consecutive days ($n = 9$). Further participants were excluded based on performance during an initial assessment (see general procedure for more details). This included 1) an average trial duration on Movement Imagery Questionnaire 3 (MIQ-3) was less than 25 seconds (i.e. insufficient for the participant to fully complete the questionnaire as instructed; to read the instruction, physically perform the task, mentally imagine performing the task, then provide a rating of their performance on a Likert scale; $n = 5$) and 2) Having a baseline average trial duration for execution/imagery trials of $\leq$2 seconds (indicative of extensive prior experience with typing tasks for physical performance, and/or failure to follow the instruction to perform motor imagery; $n = 6$). We also planned to remove participants that self-reported severely limited motor imagery ability (i.e. a score of 12, representing the minimum possible on the MIQ-3), though no participants met this criterion.

These criteria resulted in the inclusion of a final sample of 31 participants ($mean \pm SD = 25.55$ years $\pm$ 11.11, 29 right-handed, 2 left-handed, 13 females, 18 males). The average total score on MIQ- 3 was 64.9 ± 11.22 ($min = 44$, $max = 83$). In this data, 17 participants from the in-person dataset and 14 participants from the Prolific dataset were retained.

In the final sample, 14 participants reported having previous experience playing a musical instrument and/or professional typing. Preliminary analyses indicated no statistically significant effects of these factors ($p \geq .217$ for all). All participants were therefore considered as a single group in the present manuscript.

2.2. General procedure

The experiment took place across five days (see Table 1 for a summary). The study involved participants completing different 8-item movement sequences, either by physically performing the movements on a computer keyboard (see Fig. 1), or by imagining performing these sequences. On Day 1 participants completed MIQ-3 (see below), followed by a pre-training assessment test in which the time required to physically perform and imagine performing different button pressing sequences was measured. On Days 2, 3, and 4, participants performed differing amounts of physical practice on several of the sequences introduced in the pre-training assessment test. Finally, on Day 5, participants performed a post-training assessment test to measure how physical practice affected the durations of physically performed and imagined movements.

Table 1
Overview of the procedure across the five days of the study.

Day	1	2	3	4	5
Task	**MIQ−3** **Pre-training Assessment** *measurement of initial physical practice/imagery duration on all sequences*	**Training** *Physical practice of high- and low-training sequences only.* – *450 total trials per 'high' sequence* – *30 total trials per 'low' sequence*			**Post-training Assessment** *Measurement of final physical practice/imagery duration on all sequences*

2.2.1. Movement imagery questionnaire 3

On Day 1, participant's ability to generate motor imagery was assessed using an electronic version of MIQ-3 [31]. The MIQ-3 was used due to its high internal reliability when examining motor imagery. Each question asks the participant to physically complete one of four movements, then imagine performing that same movement using kinesthetic imagery, or to imagine observing the movement from a first-person (internal visual imagery) or third-person (external visual imagery) perspective. Participants then rated how easily they felt or saw the imagined movement on a seven-point scale ranging from 1 (very difficult to see/feel) to 7 (very easy to see/feel). Scores on each subscale were not required for the purposes of this study, therefore a total score was calculated for each participant.

2.2.2. Assessment sessions

On Days 1 and 5, participants completed assessments in which they both physically performed and imagined performing 6 different 8-item button-press movement sequences (for details see Stimuli and Apparatus). In each assessment session, participants completed 10 repetitions of each of the 6 sequences, split across 2 blocks. This resulted in 60 trials for both imagery and execution conditions (120 trials total). In the imagery condition, participants were instructed "Imagine that you are copying the digit sequence as quickly and as accurately as you can using F T Y J keys, where 1 = F, 2 = T, 3 = Y, 4 = J. Press S with your left index finger when you start to imagine making your response. Press S with your left index finger when you finish imagining making the sequence". Note that participants were asked to imagine producing the sequence with their dominant hand, and they pressed either the "S" or "L" key, depending on handedness.

The order of sequence presentation was randomized for all participants. However, based on research that even limited physical experience with an action can affect imagery duration (e.g., [46]), different sub-sets of participants completed physical execution and imagery trials using either a 'blocked' (n = 20) or 'alternating' (n = 11) design. In the blocked design participants first completed two blocks in which they physically executed the sequences, followed by two blocks in which they imagined performing the sequences. In the alternating design participants physically performed the sequences in blocks 1 and 3, and imagined performing the sequences in blocks 2 and 4. Note that two participants completed one extra repetition of each sequence per block during the assessment sessions due to a technical error. Training sessions were unaffected.

2.2.3. Training sessions

Across days 2–4, participants completed training in which they physically performed movement sequences, completing 10 blocks of 32 trials (320 trials total) each day. The sequences used were the same as those the participants had previously experienced in the Pre-training assessment session. During training we manipulated the amount of practice participants performed with these sequences; thus, in a final assessment session, we were able to examine the effects of differing amounts of physical practice on both physical and imagined performance. During training, each 32-trial block comprised 30 trials of 'High-trained' sequences (i.e. 2 sequences, each presented 15 times) and 2 trials of 'Low-trained' sequences (2 sequences, each presented once). The two remaining 'Untrained' sequences acted as a control; these sequences were never presented during the training sessions and were only used in the assessment tests.

2.3. Stimuli and apparatus

The experiment was created in PsychoPy 2023.2.3 [32] and output to a PsychoJS experiment, hosted on Pavlovia [33]. Participants used their own computer to access the experiment; prior work has demonstrated that this combination of PsychoPy and Pavlovia has an excellent ability to record precise timing for reaction time-based measures [33]. Stimulus presentation was programmed using PsychoPy "height units", such that the sizes and locations of the stimuli were relative to the window of the participants' devices. Thus, while this varied between-participants, all participants used the same device across

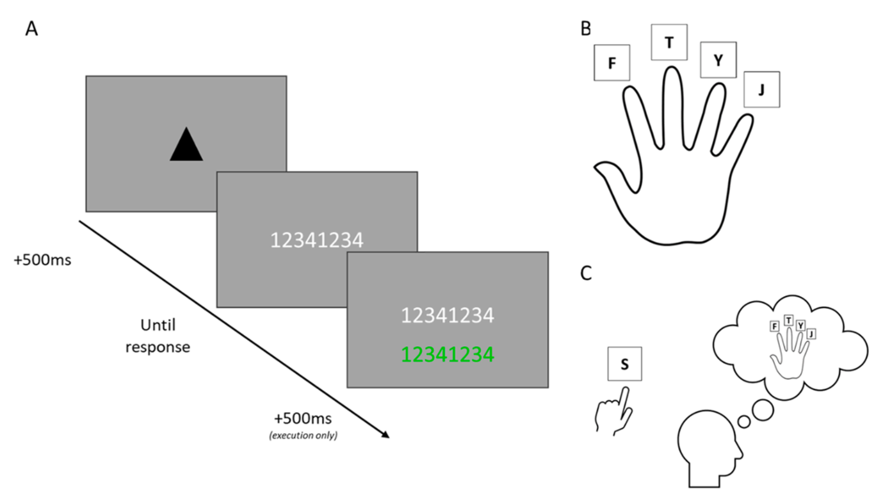

Fig. 1. (A) An example trial in the paradigm in each session. (B) Instruction image used in the physical execution condition in each session. (C) Instruction image used in the imagery condition in each session.

sessions, allowing valid within-participant comparisons.

Each sequence was preceded by a polygon (dimensions of 0.15 ×0.15 units), shown at the centre of the screen for 500 ms (Fig. 1 A). The polygon was predictive of the upcoming sequence and participants could begin to respond during the period in which the polygon was presented. The polygon-sequence association was randomised across participants. The polygons used were triangle pointing up, triangle pointing down, circle, square, diamond, and pentagon.

Each trial presented one of the six sequences at the centre of the screen. Each sequence comprised eight digits, ranging from one to four. The sequences were chosen because they met the criteria of having each digit repeated only twice in the sequence, no direct repetition of digits (e.g., 1–1), no runs (e.g., 1–2–3), and no trills (e.g., 1–2–1). The sequences chosen were: 13243124; 23142143; 24134231; 31421423; 32412431; 42312431. In this experiment, each "training" condition comprised two sequences (i.e., two high-training sequences, two low-training sequences, and two untrained sequences). Sequences were shown on screen in Arial font at a letter height of 0.15 units.

In physical execution conditions, participants performed sequences using their dominant hand on the keyboard keys F, T, Y, and J, which corresponded to the digits 1, 2, 3, and 4, respectively (see Fig. 1B). The response phase of physical execution trials ended as soon as the participant responded with eight key presses. Participants were able to see their response on screen, which was printed below the indicated sequence. If the participant's response was correct, their response turned green (Fig. 1 A). Conversely, if the response was incorrect, their response turned red. The feedback screen was shown for 500 ms.

For the motor imagery condition (Fig. 1 C), participants were instructed to imagine producing the sequence with their dominant hand. To indicate that they had started and finished imagining making the sequence, participants pressed the "S" or "L" key, depending on handedness. There was a 500 ms inter-trial interval in both imagery and physical execution conditions, which followed the feedback screen in the execution condition, or the button press to index the completion of imagery. An example trial is shown in Fig. 1 A.

2.4. Data analysis

All statistical analyses were conducted in R 4.3.2 [34] using the lmerTest [35], psych [36], brms [37,38], bayestestR [39], and emmeans [40] packages. Durations of physically performed and imagined movements were calculated as the difference in time between the first and last key press in each trial. Note that for the physical execution condition, only trials in which the sequences were correctly produced were included in the movement duration analyses. Accuracy was measured as the percentage of correct trials. Descriptive statistics are reported as mean ± SD. Degrees of freedom were calculated using Satterthwaite's method [41]. Significant effects were examined using Bonferroni-corrected post-hoc comparisons of estimated marginal means using Kenward-Roger method.

For the Assessments, linear mixed effect models were conducted to examine the duration of physical execution compared to motor imagery, and possible effects of physical training on this relationship. Within this model, modality (two levels; physical execution, motor imagery), training (three levels; high, low, untrained), and session (two levels: pre-training, post-training) were entered as fixed effects. Participant was entered as a random effect. The equation of the model was therefore: movement duration ~ training amount*modality*session + (1|Participant).

To further quantify the effect of training on imagery duration, we calculated the absolute difference (i.e. unsigned difference regardless of whether this represented under-or over-estimation) between physical and imagined execution durations. This model included only fixed effects of session and training. Participant was entered as a random effect. The equation of the model was therefore: difference ~ training*session + (1|Participant).

A similar analysis was carried out to examine the accuracy of movement sequence reproduction in the physical execution modality. Accuracy was calculated as the percentage of correctly reproduced sequences for each level of training (i.e. 20 trials per level) in each session. The equation of the model for accuracy was: accuracy ~ training*session + (1|Participant).

Motor Simulation theory argues for equivalent durations between the execution and imagination of the same action, but traditional frequentist statistics are limited in their ability to identify only differences between conditions. We therefore also report Bayesian analyses carried out on pre- and post-training movement durations. Weakly informative priors, which were normal distributions with a mean of 0 and a standard deviation of 10, were used for the fixed effects. Default priors were used for the random effect of participant. Bayesian analysis was carried out with 10 chains, with each chain being 5000 iterations. In this process 1000 "warm up" iterations were discarded per chain, leaving a total of 40,000 overall chains. Each effect was included in a model with a random effect of participant and compared to the null model, which included only the random effect of Participant. The equation of the null model was: movement duration ~ 1+(1|Participant). The inclusion Bayes Factor for each effect was then calculated across all these models and averaged to provide evidence in favour (BF_{10}) or against (BF_{01}) including that effect in the final model. Note that the Bayes Factor computed for the movement duration analysis is not carried out across matched models as all of the effects in the three-way interaction were not included in all models, and this prevented computation of the Bayes Factor for the three-way interaction.

3. Results

Movement durations during assessments are presented in Fig. 2 (for information analysis of data from training session see Supplementary Materials S1). Fig. 2 shows that physical practice reduced the durations of both physical and imagined movements, but that imagery generally overestimated the duration of physically performed actions.

3.1. Training led to faster (physical and imagined) performance

Confirming that training led to faster performance, linear mixed effects analysis identified significant main effects of session ($F(1, 330) = 530.92$, $p < .0001$, $BF_{10} = \text{inf}$), training ($F(2, 330) = 10.98$, $p < .0001$, $BF_{10} = 153.46$), and a significant interaction between session and training; $F(2, 330) = 13.44$, $p < .0001$, $BF_{10} = 343.92$. In the pre-training session, there were no significant differences between sequence durations ($p = 1.00$ for all). By contrast, after training, high-trained sequences (2.43 s ± 0.84) were significantly faster than both low-trained sequences (3.19 s ± 0.89; $p < .0001$) and untrained sequences (3.39 s ± 0.89; $p < .0001$). The difference between low-trained and untrained sequences was not significant $p = .525$.

3.2. Imagery generally over-estimated movement durations

The linear mixed effects analysis also revealed that average movement duration was quicker in physical execution compared to imagined execution (main effect of modality, $F(1, 330) = 128.51$, $p < .0001$, $BF_{10} = \text{inf}$, physical execution, 3.49 s ± 1.49 vs imagery, 4.44 s ± 1.66). While the three-way interaction between training, modality, and session was not significant ($F(2, 330) = 0.007$, $p = .993$, $BF_{01} = \text{inf}$), we examined the specific comparisons between task modalities at each session for each level of training, which showed that imagery was significantly longer than execution for all levels of training in both pre-training ($p < .0001$) and post-training ($p < .0001$) sessions (see Table 2 for further details).

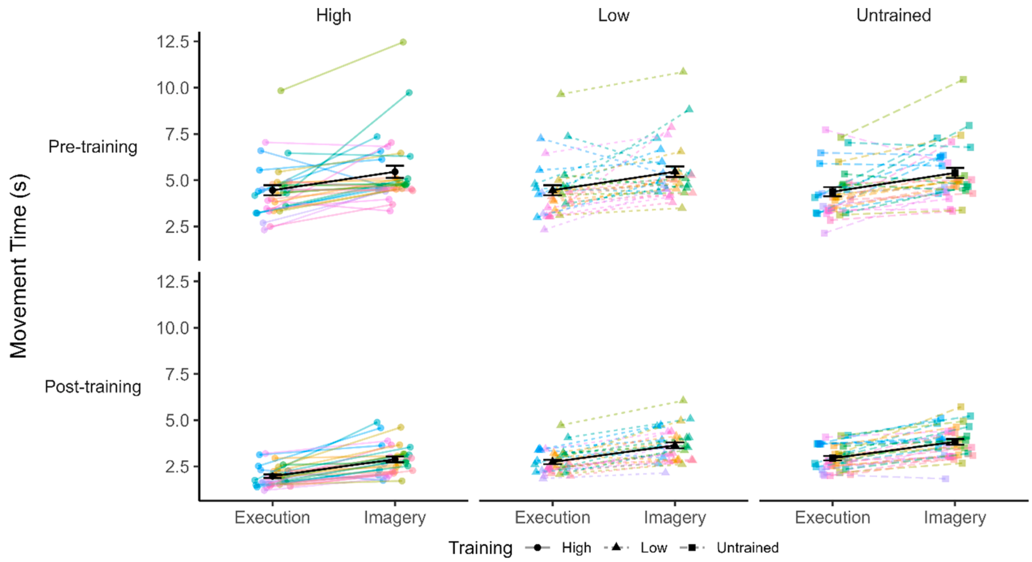

Fig. 2. Movement duration as a function of amount of practice in pre- and post-training sessions for physical and imagined execution. Mean ± SEM is represented in black.

Table 2
Means (SD) for movement duration, imagery duration, asynchrony, and accuracy in each session x training condition.

		High	Low	Untrained	Overall
Movement time (s)	**Pre-training**	4.46 (1.51)	4.46 (1.52)	4.38 (1.38)	4.43 (1.46)
	Post-training	1.98 (0.52)	2.74 (0.65)	2.95 (0.67)	2.56 (0.74)
	Overall	3.22 (1.68)	3.60 (1.45)	3.66 (1.29)	3.49 (1.49)
Imagery time (s)	**Pre-training**	5.46 (1.83)	5.46 (1.59)	5.40 (1.53)	5.44 (1.64)
	Post-training	2.88 (0.85)	3.64 (0.88)	3.83 (0.86)	3.45 (0.95)
	Overall	4.17 (1.92)	4.55 (1.57)	4.61 (1.46)	4.44 (1.67)
Absolute Difference (s)	**Pre-training**	1.21 (1.23)	1.31 (1.09)	1.22 (1.09)	1.25 (1.13)
	Post-training	0.95 (0.68)	0.94 (0.52)	0.90 (0.61)	0.93 (0.60)
	Overall	1.08 (0.99)	1.13 (0.86)	1.06 (0.89)	1.09 (0.91)
Accuracy (%)	**Pre-training**	85.67 (12.48)	81.00 (13.79)	84.87 (12.25)	83.81 (12.88)
	Post-training	92.12 (8.36)	86.43 (9.52)	74.68 (13.78)	84.41 (12.95)
	Overall	88.84 (11.04)	83.71 (12.07)	79.77 (13.91)	84.12 (12.88)

3.3. Differences between imagery and execution durations decreased between assessments

Our main analysis provided no evidence of interactions between the modality of action (i.e. imagery or execution) and other factors (no significant session by modality interaction ($F(1, 330) = 0.42$, $p = .517$, $BF_{01} = 17.24$); no significant modality by training ($F(2, 330) = 0.0002$, $p = 0.9998$, $BF_{01} = 1004.02$), no significant three-way interaction; ($F(2, 330) = 0.007$, $p = .993$, $BF_{01} = \text{inf}$). However, we note that these results may reflect an artefact of the data, which comprises both positive and negative values. We therefore conducted a further analysis of movement durations, examining the '*absolute magnitude*' (i.e. unsigned) of the difference between the durations of imagery and execution (Fig. 3). Linear mixed effects analysis confirmed that the difference between imagery and execution decreased between the assessment sessions (i.e. significant modality by session interaction, 1.25 ± 1.13 s vs 0.93 ± 0.60 s; $F(1, 150) = 12.58$, $p = .001$, $BF_{10} = 2.85$). Critically, however, this effect was not dependent on the volume of training that was performed (no significant main effect of training, $F(2, 150) = 0.18$, $p = .832$, $BF_{01} = 11834.32$), nor interaction between training and session; $F(2, 150) = 0.103$, $p = .902$, $BF_{01} = \text{inf}$. As the same changes were found for the trained and untrained sequences, this change in the difference between the durations of imagined and executed movements may represent an effect of basic familiarization with the experimental task, rather than being training-specific.

3.3.1. Accuracy varied with the amount of training

A further analysis examined the accuracy of physically produced sequences (Fig. 4).

The interaction between session and training was significant; $F(2, 150) = 14.37$, $p < .0001$, $BF_{10} = 18600$. In the pre-training session, there were no significant differences in accuracy between the sequences ($p > .198$ for all). Following training, accuracy improved significantly for both high-trained (pre-training, 85.57 %± 12.48 vs post-training, 92.12 % ± 8.36, $p = .009$) and low-trained (pre-training, 81.00 % ± 13.79 vs post-training, 86.43 % ± 9.52, $p = .029$) sequences. In contrast, untrained sequences were performed significantly less accurately in the post-training session compared to the pre-training session; pre-training, 84.87 % ± 12.25 vs post-training, 74.68 % ± 13.78, $p = .0001$. Thus, final accuracy for both the high-trained and low-trained sequences was significantly higher than for the untrained sequences (all $p<0.001$), though the difference between high-trained and low-trained sequences was not significant; $p = .067$. There was also a significant main effect of training ($F(2, 150) = 13.58$, $p < .0001$, $BF_{10} = 947.41$), but no significant main effect of session; $F(1, 150) = 0.18$, $p = .674$, $BF_{01} = 6.06$.

3.4. Summary of results

Results are summarised in Table 2, which displays the means and standard deviations for each condition.

4. Discussion

The present study examined the effects of physical practice on the duration of physically performed and imagined movement sequences. Contrary to the predictions of the Motor Simulation theory, the duration of motor imagery consistently overestimated the duration of physically

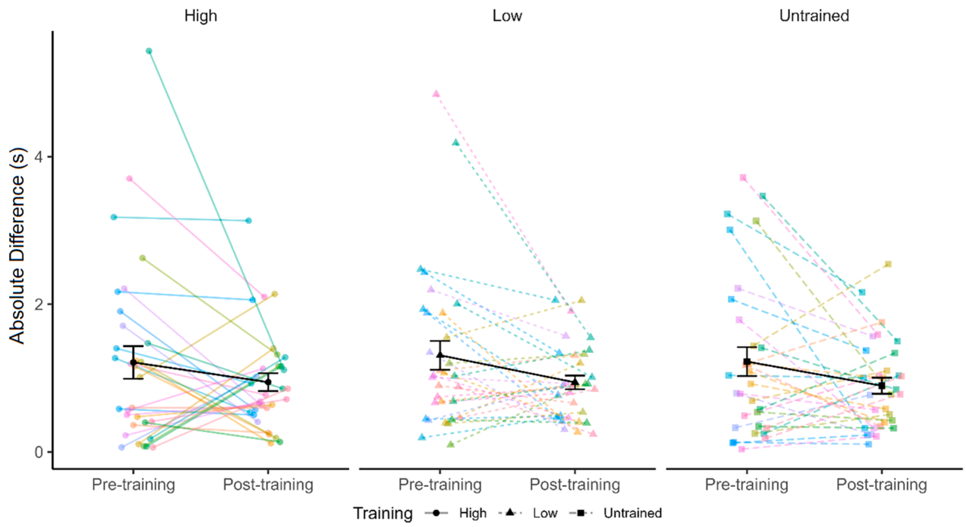

Fig. 3. Absolute differences in durations between imagined and executed durations as a function of amount of training before and after training sessions. Mean ± SEM is represented in black.

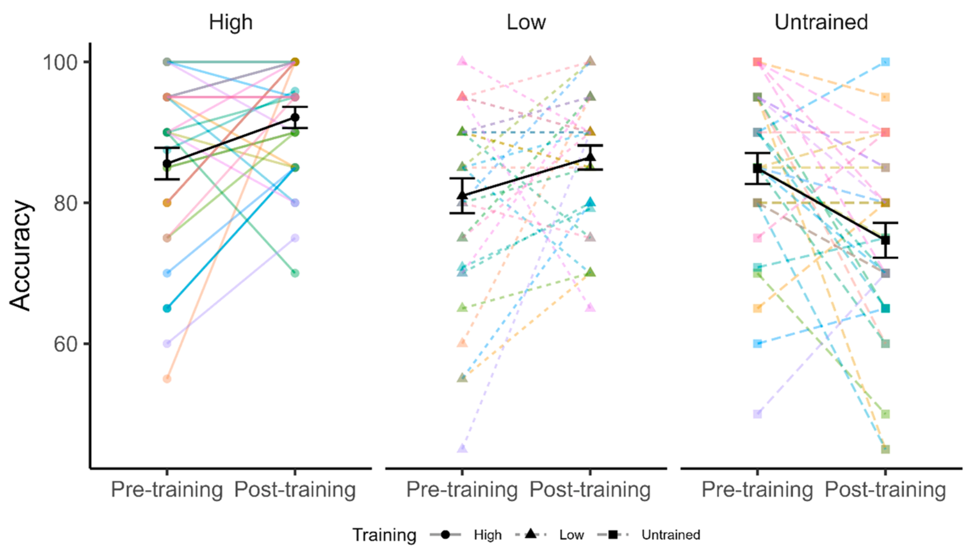

Fig. 4. Accuracy as a function of amount of training in pre- and post-training for actual and imagined execution. Mean ± SEM is represented in black.

performed sequences. When considering the absolute difference in durations of imagery and execution, we found evidence of a small improvement with practice. However, this effect was not modulated by the volume of training performed. The present results therefore challenge the predictions of Motor Simulation Theory, highlighting a gap in our theoretical understanding of motor imagery.

4.1. Main findings

4.1.1. The duration of imagery and execution are not equivalent

A primary result of this study is that the duration of motor imagery significantly overestimated the duration of physical execution across all conditions. This pattern has been reliably observed across previous studies, and has been interpreted as being generally consistent with the predictions of Motor Simulation Theory [6]. We note, however, the proposals of Motor Stimulation Theory are based on two original findings: 1) that the durations of imagined and executed movements *did not differ significantly*, and 2) that they were *strongly correlated* (for details see the analyses conducted in [7]). Notably, subsequent work has focused on the latter (correlative) result; as such, apparently contradictory results, whereby the durations of imagined movements significantly underestimate, overestimate, or do not differ significantly from the durations of executed movements, have all been proposed to support the findings of Motor Simulation theory (for a review see [19]). Given the original proposal that the durations of imagined and executed actions have similar distributions [7], a stronger test of the predictions would be to test for *equivalence* between the durations of imagined and physically executed actions. More recent research has used Bayesian frameworks [42,43] to quantify evidence both for and against equivalence of chronometric data [26,44,45]. Our results showed a significant difference between the duration of imagined and executed movements, with Bayesian analysis providing “extremely strong” evidence *against* equivalence. These results challenge a key prediction of the Motor Simulation theory, and highlight that researchers should carefully consider the evidence both for and against equivalence when using chronometric measures of motor imagery.

4.1.2. Differences between the durations of imagined and executed movements do not depend on volume of training

As noted above, we found a significant difference between the duration of imagined and physically performed movements. When the absolute magnitude of this difference was examined, we found a small but significant decrease between pre- and post-training assessment sessions. Critically, this improvement was consistent across all sequences, regardless of whether they were trained between the assessments (high- and low-trained sequences) or were only performed during the assessments themselves (untrained sequences). Bayesian analysis, again, provided extremely strong support that this effect was not modified by the volume of training, and was therefore consistent with a general improvement due to relatively minimal experience. Previous work has shown similar improvements in the relative timing of motor imagery with relatively minimal experience [46,47]. Our results replicate and extend this work, showing that after this initial small improvement, a discrepancy between the duration of imagery and execution remained, even with extensive physical training.

4.1.3. *Theoretical considerations*

A possible explanation for the discrepancy in timing between motor imagery and physical execution is that the imagery condition required attentional switching that was not required in the physical execution condition. During the imagery condition, participants were required to perform a motor response to index the beginning and ending of imagining the movement, which relies on attentional switching. According to the Motor-Cognitive model of Motor Imagery [44], attentional switching during motor imagery uses conscious executive control. The efficiency of switching between the indexing response and the imagined movement depends on the fidelity of the motor image, and therefore the need to tax central executive resources. The proposal that attentional switching may influence chronometric measures of motor imagery therefore provides a plausible framework for our present results. We note, however, that the difference between physically performed and imagined movements ranged from approximately 1200 ms before training to 900 ms after training. This difference appears to be considerably larger than those identified in comparable task-switching paradigms, which indicate voluntary or predictable task switches induce costs of approximately 100–250ms (e.g. Arrington & Longa, 2004; Rogers & Monsell, 1995). Consequently, even a highly conservative estimate of a 500 ms switching cost in the present task (i.e. 250 ms to switch from pressing the button to imagining the sequence, and 250 ms to switch back once the sequence is complete) would only partially account for the difference in the duration of the imagined and executed actions.

Another factor that might also explain the general over-estimation of movement durations during motor imagery is the complexity of the action that participants were required to imagine. For example, previous work on the Motor-Cognitive model of Motor Imagery has used arm movements involving placing or throwing an object [48], both of which represent relatively simple actions. By comparison, the sequences introduced in the current task would require more precise coordination, which may represent a more complex task. It is plausible that the general over-estimation of the time required to perform actions by imagery may relate to the relative complexity of the sequences required [49]. We note, however, that prior work with even extremely simple ballistic actions such as imagined versions of the classic Fitts' tapping task have shown that imagery typically over-estimates the duration of physically performed actions[46,47].

4.2. *Other results*

4.2.1. *Training led to faster execution and imagery*

The present results also demonstrate that physical training led to clear changes in performance, reflected in both physically executed and imagined movements. Results from the physical performance of both high and low trained sequences showed significant improvements in both speed and accuracy with training. By contrast, after training, untrained sequences were performed faster, but less accurately, than in the baseline assessment. This pattern of results demonstrates a fundamental difference between the trained and untrained sequences; participants improved both speed and accuracy for trained sequences, but only increased their speed at the *cost* of accuracy for untrained sequences. These results are consistent with prior work that conceptualizes improvements in skill through training as a change in an underlying speed-accuracy trade-off function [50,51].

Importantly, for movement durations, we found that the training effects in imagery were similar to those observed in physical execution, indexed by Bayesian analyses indicating strong evidence against interactions between modality and other factors. While our measure examined only movement duration, we note that prior work indicates motor imagery under-estimates the number of errors made in similar tasks [52]. This leads to the possibility that imagined performance may under-estimate speed, but over-estimate accuracy. Future work may wish to consider using measurements of performance that control for these two interacting variables. Evidence against modality-based interactions also indicates that the training slopes for imagery and execution were the same across training amounts, which has been argued to support a common ideomotor network for both physical and imagined action [46,47]. A consequence of physical execution improving the action-effect association is that movement durations estimated during motor imagery should be affected by training in a similar way to the actual execution time [53,54], as we found here. The reverse is also true for motor imagery-based training, which has been shown to improve physical performance in a variety of contexts, such as in cup-stacking [55] and in medicine [3]. A possible future avenue for research would therefore be to use the paradigm established here, but to have participants complete training trials using motor imagery, rather than physically executing the sequence.

In addition to this shared improvement for physical and imagined actions, improving the action-effect binding should result in the estimation of motor imagery being more temporally similar to actual execution following training. This improved ability to simulate actions has been shown in work supporting the idea of a common ideomotor code for action and imagery [46,47,54]. Again, as discussed above, we found limited evidence for this effect; our present results demonstrated that both minimal exposure and extensive training led to similar overall changes in the durations of imagined movements.

It is important to note that while the estimation of imagery duration decreased following experience of the task, the durations of imagined movements generally overestimated those of physical execution, both before and after training. Wong et al. [54] argued that this over-estimation was likely a result of limited training, as participants completed only three trials of training per condition in their task. As a result, they argued that participants would have poorly developed and integrated action-effect codes of the tested behaviours. The current findings challenge this hypothesis, as we showed that, even with increased practice (up to 450 training trials per sequence across three days of training), motor imagery consistently over-estimated the duration of movements. In addition, our sample included participants that reported no experience with similar dexterity tasks, and participants who self-reported having experience playing musical instruments or as professional/competitive typists. There was no overall difference between these participants in movement duration. We note that the present analysis did not consider the amount of previous experience, which has been associated with improvements in task performance over decades of practice [56,57]. Nonetheless, the observed pattern of results indicates that it is not necessarily the amount of physical training that affects the consistency between action execution and motor imagery.

4.3. *Limitations*

Recent work has highlighted the importance of instructions in motor imagery research [58,59]. In the present study, participants were also only instructed to imagine performing actions, without specific reference to imagining the muscle activations or the sensory/visual components of the movement. This leads to the possibility that different participants may have employed different modalities of motor imagery (i.e., using visual imagery alone, kinesthetic imagery alone, or a combination of these aspects of motor imagery). We note, however, that participants in the present study completed the MIQ-3 prior to the first assessment, which likely primed participants to consider visual and kinesthetic aspects of the movements involved in our main task. We also note that participants were presented with the same instructions in each assessment session, and therefore likely interpreted them in the same way across sessions; as such, the within-participant design of the current study reduces the likelihood of confounds related to changes in the type of imagery used between sessions. Participants were also instructed simply to "Press S (L) with your left (right) index finger when you start to imagine making your response. Press S (L) with your left (right) index finger when you finish imagining making the sequence". More precise instructions here (i.e. "press the button twice; once *synchronously* as you imagine the first press of the sequence, and once *synchronously* with the time when you imagine the last press of the sequence") may have improved the precision of our measurements. However, again, as participants were presented with the same instructions across sessions, and our study used a within-participants design, it appears unlikely that differences in the interpretation of these instructions could fully explain the present results. Nevertheless, these factors highlight the importance of clear and concrete task instructions during experiments relying on chronometric measures of imagery.

5. Conclusions

In conclusion, we examined the effects of physical practice on the durations of physically performed and imagined movement sequences. Physical practice led to the faster performance of both physically executed and imagined movements. However, contrary to the predictions of the Motor Simulation theory, the duration of imagined movements consistently differed from those of executed actions, both before and after training. While this discrepancy had reduced by the end of the study, this change was not affected by the volume of training performed. The present results demonstrate that physical training leads to changes in imagined movements. However, the overall pattern of results presents important challenges for Motor Simulation Theory.

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CRediT authorship contribution statement

Siobhan M McAteer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gautier Hamoline:** Writing – review & editing. **Andrea Denys:** Investigation. **Baptiste M Waltzing:** Writing – review & editing, Software. **Elise E Van Caenegem:** Writing – review & editing. **Marcos Moreno-Verdú:** Writing – review & editing, Software, Formal analysis. **Robert Hardwick:** Writing – review & editing, Resources, Methodology, Funding acquisition, Conceptualization.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bbr.2024.115354.

Data availability

Data and code are available through an OSF link provided in the manuscript

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