UCLouvain

Faculté des sciences de la motricité

The effects of physical practice on motor imagery

A behavioural study

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ABBREVIATION LIST

- **MST**: Motor Simulation Theory
- **MCM**: Motor Cognitive Model
- **TMS**: Transcranial Magnetic Stimulation
- **DLPFC**: Dorsolateral prefrontal cortex
- **MIQ-3**: Motor Imagery Questionnaire-3
- **ANOVA**: Analysis of variance
- ***p*-value**: Probability value
- **F**: F-statistics
- **h^2_p**: Partial eta-squared
- **M**: Mean deviation
- **SD**: Standard deviation
- **IV**: Independent variable
- **DCD**: Developmental Coordination Disorder

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I. INTRODUCTION

Motor imagery designates the mental rehearsal of a movement without executing the actual movement (Moran et al., 2012). Motor Imagery can be used to learn skills (Guillot & Collet, 2008) enhance athletic performances (Weinberg, 2008), and provide adjunct therapy in neurorehabilitation (Bello et al., 2020; Zeiler & Krakauer, 2013). For some athletes, combining motor imagery and physical execution can be used to increase performance, and is even be more beneficial than physical practice alone (Feltz & Landers, 1983). Despite considerable interest in the field of Motor Imagery, the exact mechanisms by which it works remain an open question. While many models of Motor Imagery have been proposed (for a review, see (Hurst & Boe, 2022)), their hypothesis are quite different. Among these theories, two models are most popular: the Motor Simulation Theory (Jeannerod, 2001), and the Motor Cognitive Model (Glover & Baran, 2017). Both have different ideas about the process of motor imagery and its neural similarity with action execution.

The Motor Simulation Theory holds that imagining an action and executing an action use the same mental processes and temporal organization (Decety & Michel, 1989; Jeannerod, 2001), the only difference being that the imagined movement is not physically executed. This theory predicts a close match between the duration of imagery and that of executing the same movement, as they are produced using the same processes. In the imagery task, the imagined action is stopped from being performed by an involved inhibitory process. That imagined action is normally due to subthreshold neural processes that do not meet the threshold for an actual execution of the imagined action, and so it is not executed (Hurst & Boe, 2022). Within their study, Guillot & Collet express that for some specific movements, automatic or cyclical for example, there is a correlation between the durations of both imagined or executed movements. It is not systematic, and even inconsistently reported in literature. Another study shows that for several tasks, there is a congruence between executing and imagining. Whereas, for others, the durations of physically executing and mentally imaging differ (Calmels et al., 2006).

With past research, it has been found that the imagined movement durations were closer to executed movement durations after the same movement was executed once (Yoxon et al., 2017). Looking at imagined movements that were not firstly executed, duration is not better because the planning and control of the movements is different than the ones already experienced before (Yoxon et al., 2017). Results in the same study of Yoxon et al. (2017) show that for movements of average difficulty, (e.g., modifying width and movement amplitude in contrast with the actual executed movement but within its difficulty range), execution of that movement makes it more experienced. Accordingly, imagined movements times become closer to the executed movements times when participants get some physical experience of those movements (Reed, 2002; Yoxon et al., 2017). On the opposite, if movements are more of the difficult range (outside the range of difficulty of experienced execution), pre-executing the movement does not enhance the imagination of the movement (Yoxon et al., 2017). In association with that, complex actions demand more imagining time (Guillot & Collet, 2005). This could partly relate to the difference in timing between imagined and executed movements aligning with the Motor Cognitive Model, which is talked about in the next paragraph. It is in opposition to the Motor Simulation Theory where both timings are more similar. In addition to this, according to the Fitts law, movement duration should increase linearly with the difficulty of that same movement, fitting the Motor Simulation Theory (Decety & Jeannerod, 1996). The Fitts Law is a description of the inverse relationship between speed and difficulty of the movement, it is also called speed-accuracy-trade-off (Fitts', 1954; Yoxon et al., 2017). Therefore, regarding motor imagery and the Fitts law, Decety & Jeannerod (1996) concluded that executed and imagined movements might both be governed by the same amplitude-accuracy relations.

Opposed to the Motor Simulation Theory, the Motor Cognitive Model argues motor imagery is primarily a cognitive process. While motor imagery and overt action's planning is based on mutual motor representations, their execution is sustained by different mental processes (Glover & Baran, 2017). Following this model, the predictions for executed actions are afterwards compared to sensory feedback, to control and correct the action. By comparison, during motor imagery, there is no such feedback. The model proposes these feedback processes could instead be simulated using working memory and executive functions, for example (Martel &

Glover, 2023). As such, motor imagery would be more sensitive to cognitive interference, leading it to become slower than overt actions (Martel & Glover, 2023). In their study, Martel and Glover used Transcranial Magnetic Stimulation to disturb the dorsolateral prefrontal cortex (DLPFC) during imagining or executing tasks for two experiments, to put forward the different executive functions used in motor imagery. It shows that the interference in the DLPFC activity slows down duration of motor imagery, while the execution time of overt actions is not changed. This is opposed to the Motor Simulation Theory, where both overt actions and imagined actions should both be affected by the interference on the DLPFC (Martel & Glover, 2023).

Altogether, while the Motor Simulation Theory holds that the imagery and execution duration is the same or closely matched (Jeannerod, 2001), the Motor Cognitive Model predicts on the contrary that motor imagery is longer than physical execution for unfamiliar movements, so it is overestimated, and more closely matched after practice, with action practice reducing the cognitive demands (Glover & Baran, 2017; Guillot & Collet, 2005). With practice and expertise, the motor program becomes automatic, imagery becomes similar or even quicker than execution (Jannson, 1983; Reed, 2002). This shows again that motor imagery is not always mirror of performance (Reed, 2002).

The objective of this experiment is to test the different predictions of these two models with training. In a first session, participants physically performed and imagined different movement sequences. They then practiced physically performing those sequences for three days. A final session assessed the duration of the physically executing and imagining movements sequences, to see how it differs with practice, and to test the predictions of the different models.

II. MATERIALS AND METHODS

This study was a behavioural study. It was carried out at the University of Louvain-la-Neuve in Belgium. Ethical approval was given for this study by the UCLouvain Institute of Psychology (IPSY) ethics committee.

Participants

Altogether, 36 younger and healthy adults were recruited for this study. Participants were recruited via word of mouth on the campus, via university communications, or contacted by social media, by mail, or on voluntary basis. The participants were mainly students or employees from the university of Louvain-la-Neuve.

Among those 36 participants, the data of 28 participants was used for the main effects analysis, and the data of 26 participants out of the 28 was used for the training analysis. Due to technical problems during training analysis, the data of two participants was excluded for the training data. Before that, the data of 7 participants was excluded from the study because they encountered technical problems due to bad connexion on the site given for the tasks (see *procedural details* in Methods) or forgetting a training day. Within all participants, 1 participant was excluded for not finishing the task. Overall, a total of 28 participants were kept across the study, including 11 men and 17 women. Mean age was 21 years old with a standard deviation of 1.75 (ranging from 18 to 26 years old). Participants were right-handed (n = 25) or left-handed (n = 3).

Participants were informed and provided consent in writing with agreement to participate on the first assessment day. A financial compensation of 35€ was given when they completed the entire study, comprising 10€ for the first and the final assessment sessions, and 5€ for each training day.

Selection criteria for participants was as follow: study inclusion criteria were participants aged between 18-35 years old and study exclusion criteria were inversely, participants outside the age gap and participants with known motor or coordination problems such as dyspraxia.

Protocol

The task was subdivided in three assignments and performed across 5 days (*see Figure 1)*.

The first assessment on day 1, the pre-training session, consisted in the completion of Movement Imagery Questionnaire-3 (MIQ-3), which is a basic familiarisation with the task and the measurement of initial physical and imagery duration on all sequences (*see Appendix* for full MIQ-3 instructions). Then, participants performed the key presses task. Two blocks of physically executing the sequences (10 repetitions of each sequence across 2 blocks, so 5 repetitions per block, with 6 different sequences) were performed and then followed by two blocks (10 repetitions of each sequence across 2 blocks, with 6 different sequences) of the imaginary condition. In the imaginary conditions, participants had to imagine preforming the action. Duration was about 1h and took place in a laboratory style room (quiet room with no distraction). Before starting the task, the investigator took time for a brief introduction of the task to the participant and paid attention that the participants performed the task correctly.

Across day 2-3-4, was the second part of the assignment, the training sessions. Participants were asked to train the execution task on their own computer. The tasks were done remotely in any quiet room the participant could find without any distraction. The instructions were to go as fast as they could for every attempt. If they missed, they had to continue to the next sequence.

Each training took about 30 to 45 min.

Lastly, the final assessment on day 5, the post-training session, participants were asked to perform the physical executing performance and the imagery performance for all sequences measured. It took place as the first assessment in a laboratory style room and took around 20 to 25min.

The execution and imagery performed blocks were the same sessions for day 1 pre-training and day 5 post-training. Always starting with 2 execution blocks and then with 2 imagery condition blocks. In those, there were both high and low trained sequences as well as novel sequences.

The investigator was present during the first assessment and the last assessment. For precaution to the inconvenience of fatigue, participants were allowed to take frequent breaks between the blocks of trials.

Figure 1: Task procedure

Day	1	2	3	4	5
Task	Assessment Completion of MIQ-3; Basic familiarisation with task; measurement of initial physical practice/imagery duration on all sequences	Training			Assessment Physical performance and imagery performance for all sequences measured
Location	Laboratory	Remote			Laboratory
Duration (approx.)	1h	30-45min			20-25min

General procedures and procedural details

The participants used their own laptop for the experiment with a modified version of the program for them to access (via a link to the website). All the experiment units were reported in Psychopy screen units.

For the tasks, sequences of numbers were shown on the participant's computer screen. These sequences were all preceded by various figures (pentagon, triangle pointed up, triangle pointed down, square, circle, diamond) *see figure 2*. Each different sequence was associated to one figure. The figure-sequence association was randomized in between the participants and varied across 6 orders for the experiment. Figure-sequence association for each order is summarized in the *Appendix.* Those figures appeared for 500ms in the centre of the screen with a cue shape of 0.15x0.15.

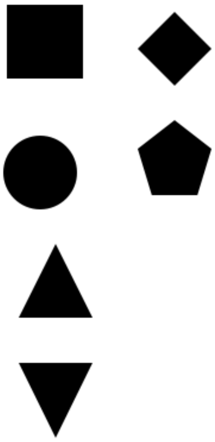

Figure 2: cue images/shapes

13243124
23142143
31421423
32412431
24134231
42312431

*Figure 3: s*equences used

Each sequence is composed by 8 numbers. Those numbers go from 1 to 4 *see figure 3*. The numbers 1-2-3-4 are each associated to a specific computer key: 1=>F, 2=T, 3=>Y, 4=>J. Those specific letter keys are used instead of the number keys on the computer keyboard. They also offer an ideal position for each finger of the dominant hand. The 4 letter keys chosen (F, T, Y, J) are each associated to one finger of the participant's dominant hand (either index, middle finger, ring finger or little finger) *see Figure 4.*

Figure 4

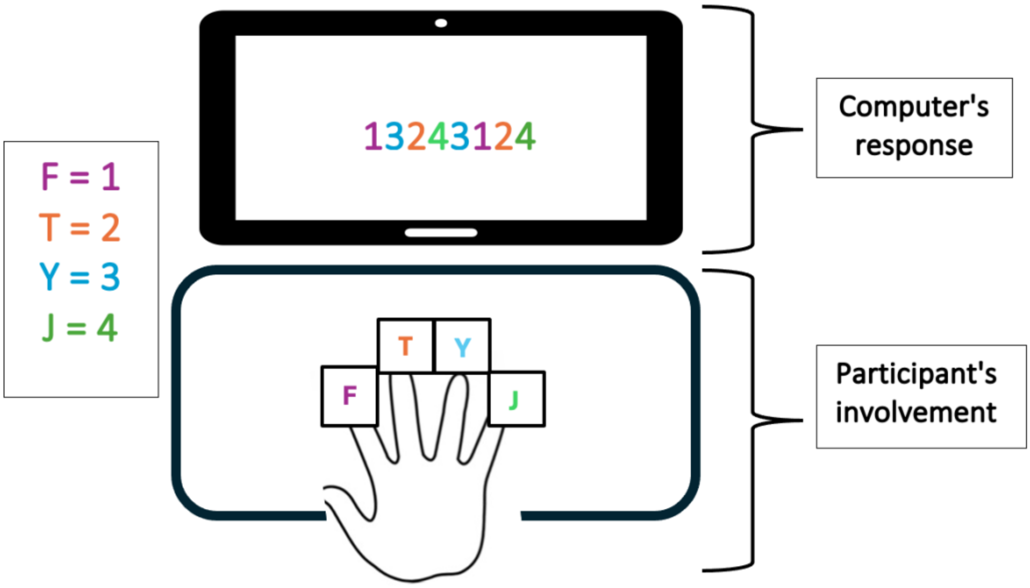

Figure 4: Summary of task set up with the number-key-finger association.

Different sequences were used for the key presses task *see figure 3*. Those sequences were differentiated into novel, low and high trained sequences:

- High practice = trained 150 times per practice session (total of 450 trials training per sequence).
- Low practice = trained 10 times per practice session (total of 30 trials training per sequence).
- Novel sequences = never trained in practice sessions.

For the experiment, the training amount for each sequence varied between 2 high trained sequences, 2 low trained sequences and 2 novel sequences. Participants had to train on 4 sequences in total, the novel sequences not being trained. The way in which a sequence was decided as high/low/novel was counterbalanced across 6 orders. Participants were randomly allocated to 1 of these orders. The cue-sequence associations also varied across these 6 orders. The size of the sequences was in Arial font at a letter height of 0.15. These sequences were chosen based on three criteria: no repetition of digits (e.g. 1-1-2), no runs of more than two consecutive digits (e.g. 1-2-3), no trills (e.g. 1-2-1).

Assessment sessions tested each sequence equally in both imagery and execution.

During the action execution condition, participants had to keypress 8 characters dependent on the sequence given on screen *see figure 4.* When the 8 characters were key pressed, the trial ended *see figure 5.* During the imagery condition, 8 characters dependent on the sequence are still shown on screen, but participants had to imagine key pressing these 8 characters. When starting imagining the sequence, they had to press the S key for right handed or L key for left handed. When finishing imagining the sequence, they had to press a second time the S key or L key depending on their handedness, to end the trial. Here, the dominant hand used for the imagery task, the other doing the key presses. The key presses had to be done with the same hand each time.

Figure 5

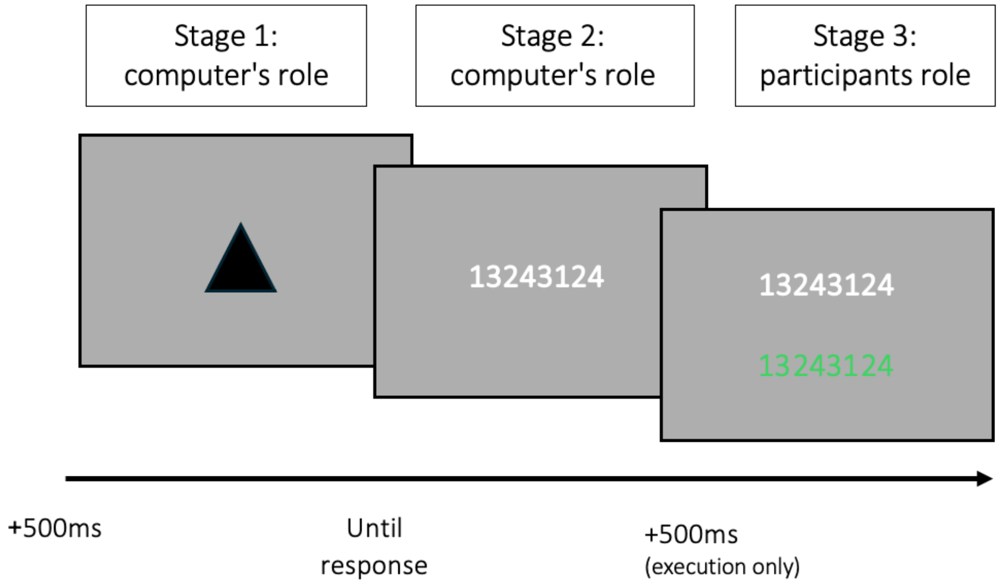

Figure 5: An example trial in the paradigm.

For each trial, the participants could see their response with a red or green feedback in the centre of the screen *see figure 5*. Red negative feedback was shown for an incorrect response from the participant and green feedback for correct response. The colour feedback screen was also shown for 500ms then went to the next trial *see figure 5.*

The time to imagine or physically execute the sequences was recorded and collected to see how the training affected the relationship between imagery and execution. Participants required around 5 sec to complete the sequence. Following hypothesis, that time should reduce with the training sessions. The initial time was measured on day 1 and the final time on day 5.

On day 1 and 5, for both pre-training and post-training participants had to perform 10 repetitions of each sequence across 2 blocks. In total 60 repetitions for both imagery and execution. For the training days, day 2 to day 4, 10 blocks were performed and physically executed. Each block had 32 trials with a small number of trials for the low trained sequences (1 trial for each of the low trained sequence) and a high number of trials for the high-trained sequences (15 trials of each of the high trained sequence).

Again, there was a 500ms time interval between trials as it was for the execution conditions *see Figure 5.*

MIQ-3 task

The Motor Imagery Questionnaire 3 (Williams et al., 2012) was used to measure the motor imagery clearness with three different subscales. Full instructions are displayed in the *Appendix*. The mentally executed task was asked with those measuring subscales from different point of views: (1) with internal visual perspective, (2) external visual perspective, (3) feeling the sensation of the movement (kinaesthetic imagery).

Participants were asked to execute physically and mentally 4 different movements and rate the difficulty to imagine mentally those movements. The rating goes from 1 (very hard) to 7 (very easy). The movement was always first physically executed before doing the mental exercise.

Data analysis

For the first data analysis, the baseline and test data, ANOVA* repeated measures 2x2x3 was used with factors modality (imagery/execution condition), sequence (high, low, novel sequence) and session (baseline/pre-training, test/post-training). The effects of modality (imagery/execution condition), sequence (high, low, novel sequence) and session (baseline/pre-training, test/post-training) on movement duration were examined. The movement durations of the participants for each condition (execution and imagery) were recorded for each block of the experiment. Secondly, follow-up analysis with Post-Hoc tests (Bonferroni-Holm) was conducted to test and check the significant differences between each level.

For the next data analysis, the training data, ANOVA* repeated measures 2x2 was used to examine the effects of training sessions (training session 1,2 and 3) and sequence (high, low, novel sequence) on movement duration. Factors were sequence (high, low, novel sequence) and training session (training session 1,2 and 3). Movement durations of each participant was recorded for each training block and session of the experiment. Again, after that, follow-up analysis was conducted with Post-Hoc tests (Bonferroni-Holm) to test and check the significant differences between each level.

*Repeated measures ANOVA is used when the same measurements are taken on the same subjects over multiple time points or conditions. It accounts for the within-subject correlation and allows for the analysis of changes over time or differences across conditions.

III. RESULTS

Baseline and test data:

Data analysis of baseline and test data examined the effects of the factors modality, training amount and session on the movement duration. A summary of the results can be found in the tables in the *Appendix.* For the data analysis, results were considered **significant** when ***p* < 0.005** or when ***p* < 0.001**.

Linear effects analysis revealed significant results for the main factors of session; [$F(1,27) = 78.968$, $p < 0.001$, $\eta^2_p = 0.745$]. With $p < 0.001$, it confirms movement duration decreases between baseline ($M = 4.97$s, $SD = 1.83$) and test session ($M = 3.10$, $SD = 1.25$; $p < 0.001$). For the factor sequence, the main effect of training amount is significant; [$F(2,54) = 24.519$, $p < 0.001$, $\eta^2_p = 0.476$]. A significant main effect was also found for modality: [$F(1,27) = 9.644$, $p < 0.005$, $\eta^2_p = 0.263$], such that comparing imagery and execution, imagery is always slower than execution. The interaction between session and sequence was also significant; [$F(2,54) = 27.748$, $p < 0.001$, $\eta^2_p = 0.507$]. For this interaction, the assumption of sphericity with Mauchly's test, was violated for this effect so the results should be interpreted with a degree of caution.

There were no significant results, neither the interaction between session and modality; [$F(1,27) = 1.679$, $p = 0.206$, $\eta^2_p = 0.059$] nor modality and sequence; [$F(2,54) = 0.158$, $p = 0.854$, $\eta^2_p = 0.006$] or the three-way interaction between modality, session and sequence; [$F(2,54) = 1.153$, $p = 0.323$, $\eta^2_p = 0.041$], for all, $p > 0.005$.

The plots below show the difference between baseline and test (session) more clearly. An improvement in movement duration between baseline and test sessions can be clearly seen for both imagery and execution modalities. Still, improvement is more important for physical execution and is shown to be slower in imagery conditions. Either way both modalities' movement duration decreases towards the test session, even after the training period. This shows that there is an improvement in the task with training in both the imagery and execution conditions. Movement durations for imagery and execution task between baseline and test session are displayed in *Figure 6a and 6b.*

Figure 6a

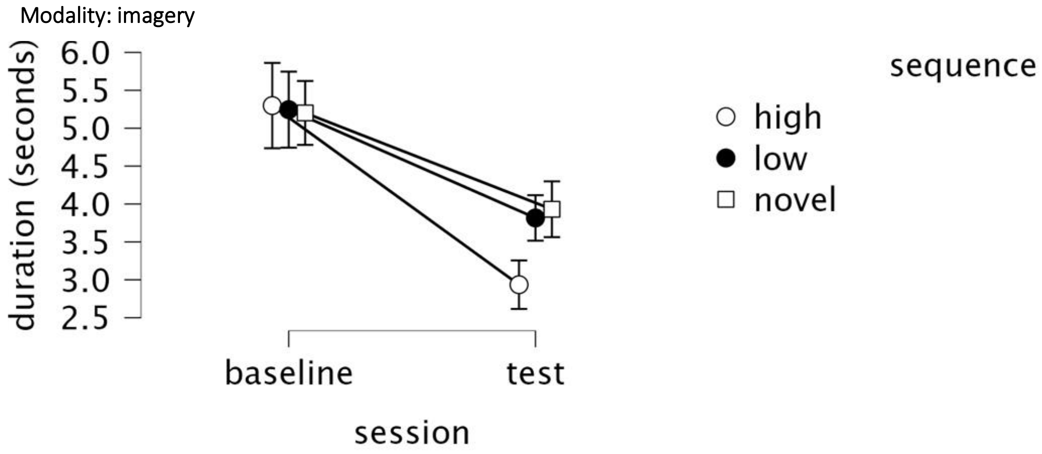

Figure 6b

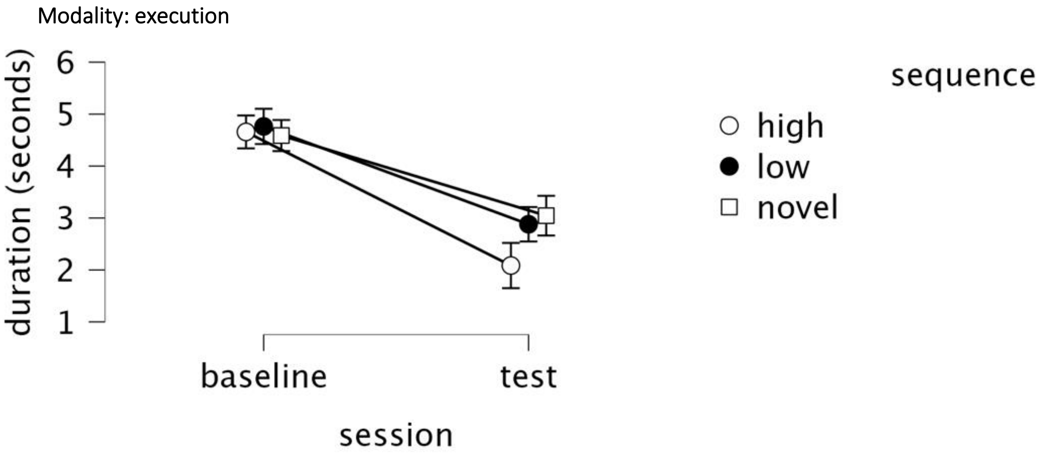

Figure 6a: Movement durations between baseline and test session for high, low and novel sequences in imagery conditions (the three-way interaction). *Figure 6b:* Movement durations between baseline and test session for high, low and novel sequences in execution conditions *(*the three-way interaction).

A difference between the high sequences and low/novel sequences is also displayed in *Figure 6a and 6b.* There appears to be no difference between the sequences at baseline session, but the movement duration for high-practice sequences is shorter than for low-practice and novel sequences during the test session. This highlights that training has an effect which tends to decrease the duration as the high-practice sequences show significantly in both modalities. It might be noted that the low practice sequences seem to face the same trends, but it is unsignificant compared to novel sequences and thus not considered here.

Other descriptive plots:

Figure 7a

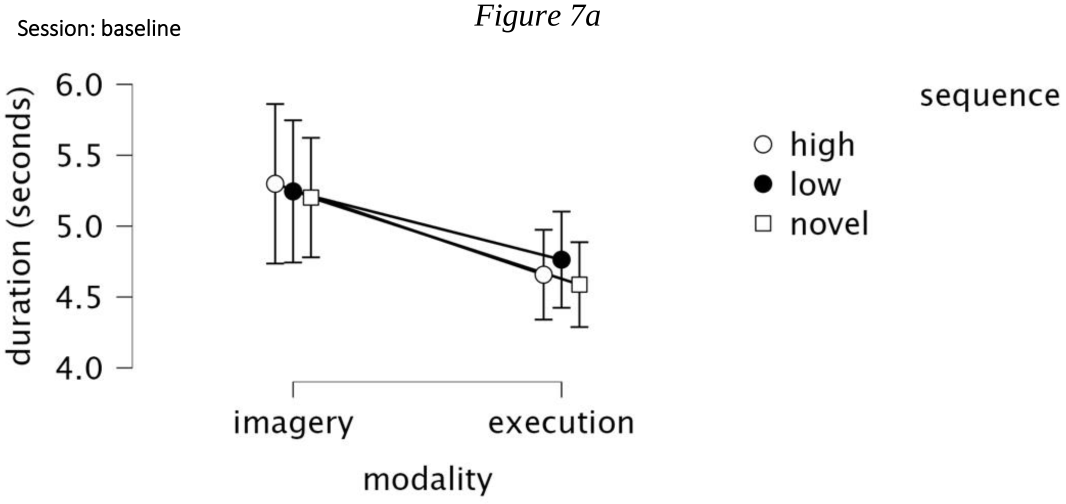

Figure 7b

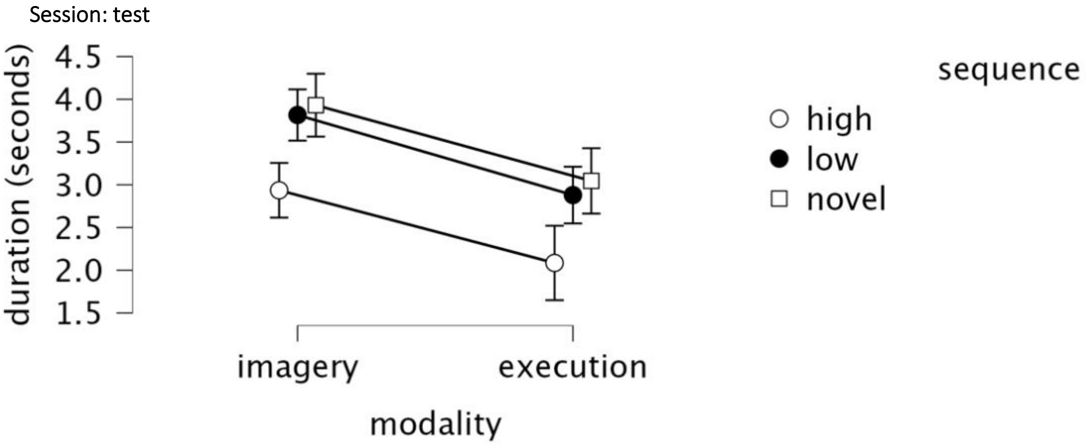

Figure 7a: Movement durations between imagery and execution for high, low and novel sequences on baseline session. *Figure 7b:* Movement duration between imagery and execution for high, low and novel sequences on test session.

Here, a clearer difference between imagery and execution can be seen. The difference between high sequences and low/novel sequences stays clear between imagery and execution, especially for the test session *see Figure 7b*.

Secondly, follow-up analysis has been done for those significant effects. For the significant main effects of session, sequence, modality and the interaction between session and sequence, Bonferroni-Holm corrected Post Hoc tests is used to test and check for any significant differences between each level of the IVs.

For the factor session, the Bonferroni-Holm corrected comparisons revealed a significant difference between baseline (*M* = 4.97s, *SD* = 1.83) and test session (*M*

= 3.10s, *SD* = 1.25; $p < 0.001$). For factor sequence, there was a significant difference between high and low sequences, but not between low and novel sequences. Post-Hoc Bonferroni-Holm corrected comparisons revealed a significant difference between high (*M* = 3.74s, *SD* = 1.99) and low (*M* = 4.17s, *SD* = 1.80) sequences ($p < 0.001$), and between high and novel (*M* = 4.18s, *SD* = 1.66) sequences ($p < 0.001$). The difference between low and novel sequences was not significant with $p = 0.833$ (because *p* is higher than 0.005/0.001). For high sequence, mean deviation *M* = 3.737s and standard deviation *SD* = 1.985. For low sequence *M* = 4.174s and *SD* = 1.797. For novel sequence, *M* = 4.183s and *SD* = 1.660. The follow up analysis for factor modality showed a significant difference between execution (*M* = 3.69s, *SD* = 1.48) and imagery modality (*M* = 4.38s, *SD* = 2.06; $p = 0.004$) with $p < 0.005$.

Some interactions between session and sequence showed that the differences between baseline high (*M* = 4.988s and *SD* = 1.954) and test high (*M* = 2.486s and *SD* = 0.973), between baseline low (*M* = 5.014s and *SD* = 1.862) and test low (*M* = 3.334s and *SD* = 1.271), as well as between baseline novel (*M* = 4.901s and *SD* = 1.702) and test novel (*M* = 3.465s and *SD* = 1.272), were significant, $p < 0.001$.

On the contrary, there are some non-significant differences in the follow up analysis within the interaction between session and sequence, which are the interactions between baseline high and baseline low ($p = 0.882$), baseline high and baseline novel ($p = 0.882$), baseline low and baseline novel ($p = 0.882$), as well as test low and test novel ($p = 0.720$).

Although the three-way interaction was not significant, [$F(2\text{-}54) = 1.153$, $p > 0.001$, $\eta^2_p = 0.04$], the differences between imagery and execution were examined and compared for each session and training. There was no difference between imagery and execution in pre-training for high sequences because $p > 0.005$ (p = 0.472). For low training sequences in pre-training, there was also no difference between imagery and execution ($p = 1.00$). Novel-trained sequences result in pre-training also showed no difference between imagery and execution ($p = 0.538$). The differences in pre-training (baseline session) between sequences were not significant, for all, p > 0.005.

With post-training, still no difference between imagery and execution for high trained sequences was seen ($p = 0.088$). Also, for novel-trained sequences (*p* =

0.064). The difference was only significant if $p < 0.005$. But, for low-trained sequences ($p = 0.039$) there was a significant difference, $p < 0.005$. This difference was an overall pattern of imagery being longer than execution.

To conclude, there was a main effect whereby imagery was always taking longer than execution, but however, it was not specific to some interaction between our conditions.

Training data:

Training data analysis examined the effects of sequence and training session on the movement durations. Again, a summary of the results can be found in the tables in the *Appendix.* For the data analysis, results were considered **significant** when $\boldsymbol{p < 0.005}$ or when $\boldsymbol{p < 0.001}$.

Within subjects effects, significant results were found for session: [$F(1,20) = 28.965$, $p < 0.001$, $\eta^2_p = 0.609$], for sequence: [$F(1,20) = 25.227$, $p < 0.001$, $\eta^2_p = 0.558$] and between session and sequence: [$F(1,20) = 11.470$, $p < 0.005$, $\eta^2_p = 0.364$].

Between the first practice and the last practice, movement duration decreases. Movement duration also decreases for both high and low sequences. This is displayed in *figure 8.* Training decreases movement durations. It is greater for high sequences then for low sequences. For the high sequences, there was a larger decrease in duration between first and last session. For the low sequences, there was also a smaller decrease in duration. This shows the effects of the amounts of practice. The novel sequences are not trained.

Figure 8

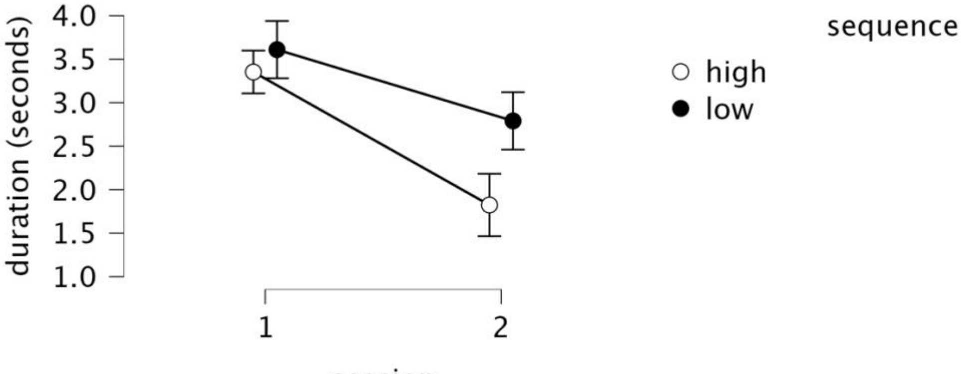

Figure 8: Descriptive plot of the interaction session and sequence.

In the follow-up analysis for training data, Bonferroni-Holm corrected Post-Hoc test was used for the significant main effects. For session, Post-Hoc Bonferroni-Holm corrected comparisons revealed a significant difference between: (1) first training on day 2 (*M* = 3.484s, *SD* = 1.122), and (2) last training on day 4 (*M* = 2.313s, *SD* = 0.784), $p < 0.001$, *see figure 8.*

For sequence, there was a significant difference between high (*M* = 2.621s, *SD* = 1.057) and low sequences (*M* = 3.242s, *SD* = 1.135), $p < 0.001$.

For the interaction between session and sequence, there was a significant difference between the first practice with high sequences (*M* = 3.331, *SD* = 1.011) and the last practice with high sequences (*M* = 1.911, *SD* = 0.457), $p < 0.001$. There was also a significant difference between the last practice high sequence (*M* = 1.911, *SD* = 0.457) and the first practice low sequence (*M* = 3.643, *SD* = 1.227), $p < 0.001$. Lastly, there was significant difference between last practice high sequence (*M* = 1.911, *SD* = 0.457) and last practice low sequence (*M* = 2.787, *SD* = 0.831), with $p < 0.001$.

IV. DISCUSSION

In this study, the different predictions of the two most common models of motor imagery, the Motor Simulation Theory and the Motor Cognitive Model were tested. Hypothesis for the Motor Simulation Theory is that imagery and execution action would be affected similarly with training. Whereas for the Motor Cognitive Model, motor imagery duration would be longer than execution pre-training, and closer to or shorter than execution post-training. With these results, it has been observed that imagery duration is always over-estimated compared to action execution. Notably, as the three-way interaction was not significant, this means that the amount of training does not affect the improvement in the estimation and performance of the task.

Following the results, they show some links towards both the Motor Simulation Theory and the Motor Cognitive Model. Looking at the interaction between training session (baseline/test) and modality (imagining/executing), it shows that with training, for both execution and imagery, duration decreases. There is an improvement from pre-training to post-training. This disentangles the predictions of the Motor Cognitive and the Motor Simulation models. Results lean more towards the Motor Simulation Theory, though some arguments favour the Motor Cognitive Model. When the results were significant, although the three-way interaction was not, the Post-Hoc tests checked for all the hypothesises.

The main point to look at was the three-way interaction between modality (imagery or execution), sequence (high, low, novel) and session (baseline/pre-training and test/post-training). Was there a difference between imagery and execution pre and post training and how it changed between high, low and novel sequences? The two models had different predictions about this interaction. The Motor Simulation Theory would predict there would not be a three-way interaction, imagined and execution actions durations should always closely match both before and after training. On the other hand, the Motor Cognitive Model would predict a three-way interaction between the 3 factors. This means a low correspondence between imagery and execution durations before training and for post-training, durations should be closer, the amount of training affecting that closeness. So, imagery would be slower on pre-training session for all sequences. Moreover, for the after-training session, that difference would be expected to be minimised or ideally that the imagery be quicker than execution for the high trained sequences. The difference between imagery and execution is less for the low trained sequences and execution is quicker than imagery for novel sequences.

In these results, the three-way interaction is not appearing. The Motor Simulation Theory can be supported, also referred as functional equivalence for which it was expected that regardless of training, regardless of time point, imagery and execution will always be similar. There would be no significant differences between imagery and execution for high/low/novel sequences between pre- and post-training, this means there would be no three-way interaction just like in the present results. In addition to this, results show that there was a decrease in the movement duration for both imagined and physically executed actions between pre- and post-training.
Still, evidence for that model is somewhat limited. Results show that imagery and execution are significantly different at every time point and for every sequence and that it does not improve with practice. While the Motor Simulation Theory predicts these times should closely match, the results reveal there is always about 1 second of difference between them. It is debatable to say this is a close match.
As said before and in the study by Decety and Jeanrod (1995), motor imagery is "a dynamic state during which we mentally stimulate a given action". So, executing a task and experiencing its consequences, amplifies the associations between the various codes. This shows that training and executing the movement would improve the imagination's task duration and so time of imagining should be more similar to the actual executing task (Yoxon et al., 2015).

Secondly, there is quite an important relation for which no interaction was highlighted by the results. This is good thing. It is the interaction between modality and session. Because the interaction is not significant, it means regardless of, if the training is done a lot of time or not, the effect of training on imagery and execution is the same. With training, imagery and execution time decrease between pre- and post-training. That is an important result regarding the Motor Simulation Theory because the fact that training has a similar effect on execution and imagery, that might indicate that at some point they would rely on the same neural pathways which is shown in various other studies (Wong et al., 2013; Yoxon et al., 2015, 2017).

Lastly, looking at the effect of modality (imagery/execution), the fact that regardless the time point, regardless of the session and training, imagery is always overestimated and significantly longer compared to execution. This effect has been shown repeatedly in studies of *Wong et al (2013)* and *Guillot and Collet (2005)* review. Previous studies have been used to support the Motor Simulation Theory, but the fact that imagery is always overestimated is a challenge to the key prediction of the temporal equivalence in that model. With this overestimation result, Motor Cognitive Model can be supported because there would be a cognitive process that is stepping in and doing something to out the mental image of the action. But if that prediction was true, it would be expected it is because of the training, durations improve, and it would give a better representation of the action and the sensory consequences of that action in this study. It can be expected that imagery would become closer to the execution time with training. But again, that has not been seen in the present results. In the meanwhile, the imagery time decreases with training but not at the same extend as the execution time. That leads us to ask ourselves why would execution still always be quicker than imagery? Following the Yoxon study, many processes, in which execution and imagination are found, share common networks or neural codes and so have links in between them. Mainly perceiving a movement and imagining a movement would have a common ideomotor network and so they would have to activate the same code for that movement (Yoxon et al., 2017). Executing and imagining would also have same temporal organisation. For cyclical movements, executing and mentally simulating, are assumed to be based on same kind of mechanisms. This would put forward more the Motor Simulation Theory (Guillot & Collet, 2005) like in the present results with imagery and execution duration both decreasing with training. It is although not consistent in the literature.

Previous research reveals that motor imagery and execution have a lot in common in the activation and stimulation of similar brain structures (Sirigu et al., 1995; Williams et al., 2012). With those similarities, one can only suppose one same network would be used for both processes (imagining and executing) but also others, e.g., the perception process. More and more studies put forward suppositions that the processes execution, imagination and perception depend on the same coding system. Humans are as much able to select, plan and execute movements and actions as they can imagine and perceive those same movements. This puts again forward that they might follow similar neural coding and network. The only difference would be that these codes are somehow unconnected, offline at some point for action imagination and perception. There is other evidence showing and supporting the activation of the motor system during the observation of other people performing an action for example (Wong et al., 2013). Within their study, Wong et al. believe that the common coding hypothesis of those processes is supported with three observations: the relation between difficulty and movement remained consistent across the task, experience influences imagination and gives shorter duration of the task and closer to the actual executing task, finally, the motor overflow in the imagination condition is linked to the amplitude and challenge of the imagined movement. In the meanwhile it is still quite unclear why the imagined movements are still taking more time than the actual execution (Wong et al., 2013).

Besides this information and the present results, scientific evidence also shows that motor imagery can be used for neurorehabilitation and recovery in different neurological pathologies (Martel & Glover, 2023) as well as for increasing performance used by athletes (Weinberg, 2008). For example, the first 3 months post-stroke accident, called "acute phase", are the most important for recovery (Vleugels et al., 2020; Xu et al., 2017). During that period, the motor imagery could help the brain reorganize the new neural pathways via neuroplasticity and improve the recovery period overall with motor skill learning (Vleugels et al., 2020; Zeiler & Krakauer, 2013). The Motor Cognitive Model could be used as part of a treatment for Developmental Coordination Disorder (DCD) because they present lower motor imagery abilities with deficits in executive functions. It could help strengthen those limitations. Patients with DLPFC damage could also benefit form including Motor Cognitive Model in their rehabilitation treatment as it is shown previously that the DLPFC is rather important structure for motor imagery (Martel & Glover, 2023).

However, our understanding of how the brain realizes Action Simulation is limited. Traditional views propose Action Simulation primarily recruits the motor system, but the recent “Motor Cognitive Model” argues we instead use prefrontal cognitive resources to generate motor simulations. A good understanding of how it works, both execution and imagery will probably improve these practical applications in the future.

STRENGTHS AND LIMITATIONS:

Strengths: In this study, much more training has been done than in previous ones like the Yoxon et al. study or the Wong et al. study for example. They used 1 to 3 trials of experience only.

Participants had to answer a MIQ test to indicate what knowledge they had about motor imagery. Results of that test showed mostly that participants find it quite easy to see or feel the movement because the results are not broadly spread (SD = 9.77). This would mean they had not too much difficulty for the imaging task. A within subject's design was used, so participants acted as their own controls, and all do the same.

Limitations: This study has also limitations and points that need to be improved in the future. First limitation, it is supposed that the training effects become more strongly evident after much more "years" of training in contrast with "only" five days of experience that has been done here (see Reed 2002 and Calmels et al. 2006 papers).

Even though the experiment was performed in a laboratory style room with no distractions, the second limitation concerns the training sessions which were done at each participant's home. Thus, there is no proof of any distraction during those training sessions, results could be less accurate.

The results show differences between both modalities but also some similarities. It can be seen as a limitation that most of them point to a certain interpretation direction but none which have a 100% final answer to it.

V. CONCLUSION

In this study, the predictions of the Motor Simulation Theory and the Motor Cognitive Model were examined by investigating the effects of practice on motor imagery with physical execution conditions and imagery conditions. The results provide mixed evidence for either of these theories. It is found that regardless of the amount of training, imagery was always slower than execution. In the meanwhile, both imagery and execution durations improved with training. Through these results, links are highlighted towards the Motor Simulation Theory, the fact that both improve with training and mainly that there is no three-way interaction could show some evidence for that model. But they also show links towards the Motor Cognitive Model because imagery and execution are significantly different regardless time point or the training. Because movement durations were always overestimated for imagery, it was not possible to follow completely that theory either, imagery does not become quicker than execution in the present results. Further research about those two models needs to be done, as well as a good understanding of execution and imagery.

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VII. APPENDIX

Cue-sequence association:

Participants were randomly allocated to 1 of the 6 orders. The cue-sequence associations also varied across these 6 orders.

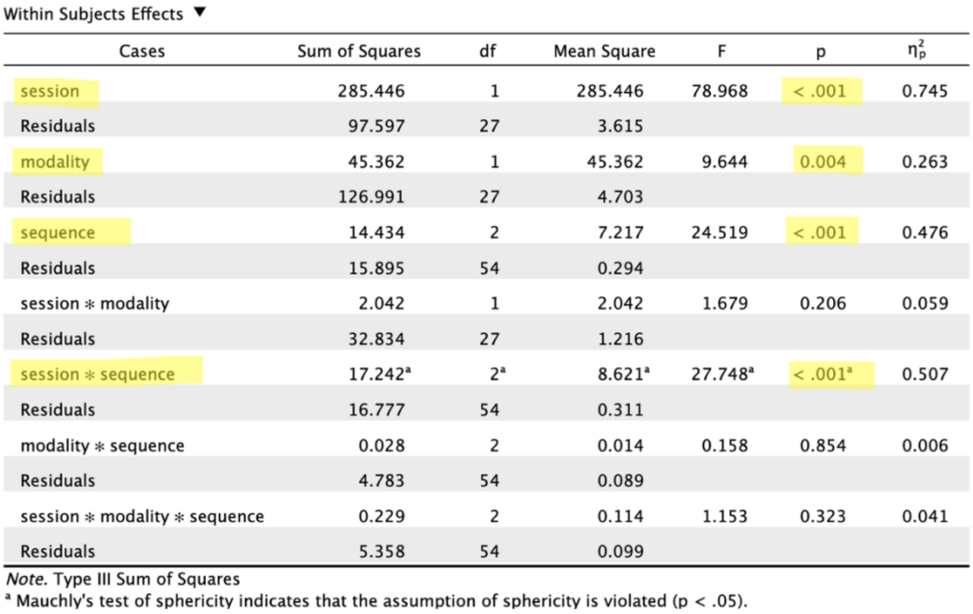
Shape	Associated sequence (depending on the order)
	**Order 1:** 42312431 **Order 2:** 13243124 **Order 3:** 23142143 **Order 4:** 31421423 **Order 5:** 42312413 **Order 6:** 32412431
	**Order 1:** 24134231 **Order 2:** 42312413 **Order 3:** 32412431 **Order 4:** 24134231 **Order 5:** 31421423 **Order 6:** 13243124
	**Order 1:** 31421423 **Order 2:** 32412431 **Order 3:** 42312413 **Order 4:** 13243124 **Order 5:** 24134231 **Order 6:** 23142143
	**Order 1:** 23142143 **Order 2:** 24134231 **Order 3:** 13243124 **Order 4:** 32412431 **Order 5:** 13243124 **Order 6:** 42312413
	**Order 1:** 32412431 **Order 2:** 31421423 **Order 3:** 31421423 **Order 4:** 23142143 **Order 5:** 23142143 **Order 6:** 24134231

	**Order 1:** 13243124 **Order 2:** 23142143 **Order 3:** 24134231 **Order 4:** 42312413 **Order 5:** 32412431 **Order 6:** 31421423

Results tables:

1. Baseline and test data

   a. Repeated measures ANOVA



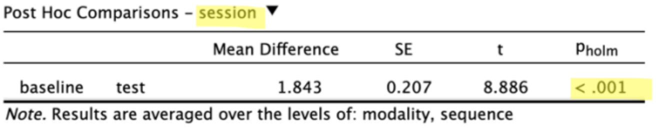
Within Subjects Effects ▼

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
session	285.446	1	285.446	78.968	< .001	0.745
Residuals	97.597	27	3.615			
modality	45.362	1	45.362	9.644	0.004	0.263
Residuals	126.991	27	4.703			
sequence	14.434	2	7.217	24.519	< .001	0.476
Residuals	15.895	54	0.294			
session ∗ modality	2.042	1	2.042	1.679	0.206	0.059
Residuals	32.834	27	1.216			
session ∗ sequence	17.242ᵃ	2ᵃ	8.621ᵃ	27.748ᵃ	< .001ᵃ	0.507
Residuals	16.777	54	0.311			
modality ∗ sequence	0.028	2	0.014	0.158	0.854	0.006
Residuals	4.783	54	0.089			
session ∗ modality ∗ sequence	0.229	2	0.114	1.153	0.323	0.041
Residuals	5.358	54	0.099			

Note. Type III Sum of Squares

ᵃ Mauchly's test of sphericity indicates that the assumption of sphericity is violated (p < .05).

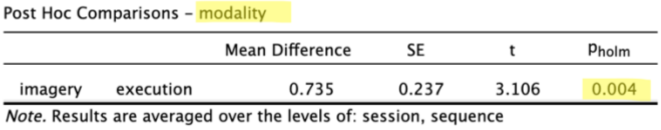
   b. Post-Hoc tests



Post Hoc Comparisons – session ▼

		Mean Difference	SE	t	p_{holm}
baseline	test	1.843	0.207	8.886	< .001

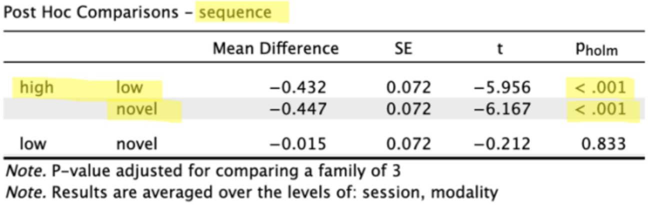
Note. Results are averaged over the levels of: modality, sequence



Post Hoc Comparisons – modality

		Mean Difference	SE	t	p_{holm}
imagery	execution	0.735	0.237	3.106	0.004

Note. Results are averaged over the levels of: session, sequence

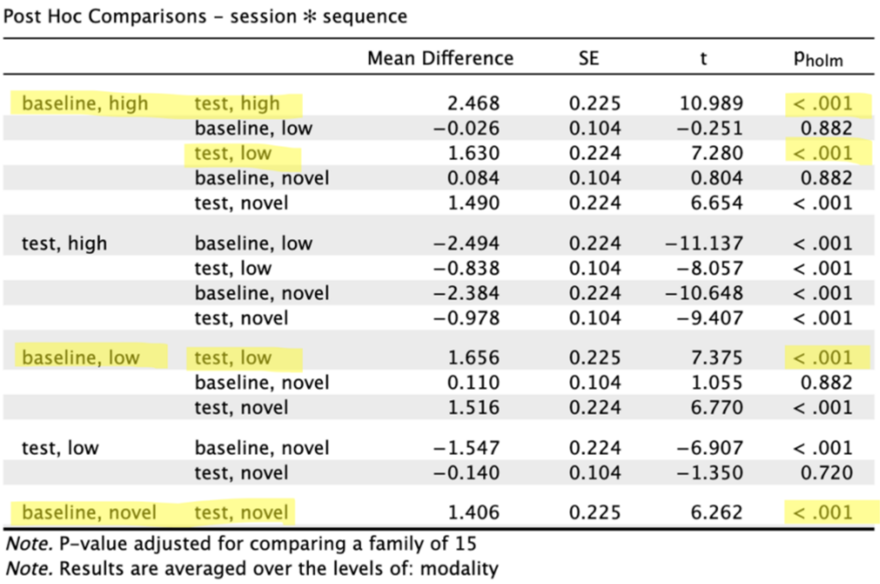


Post Hoc Comparisons – sequence

		Mean Difference	SE	t	p_{holm}
high	low	−0.432	0.072	−5.956	< .001
	novel	−0.447	0.072	−6.167	< .001
low	novel	−0.015	0.072	−0.212	0.833

Note. P-value adjusted for comparing a family of 3

Note. Results are averaged over the levels of: session, modality



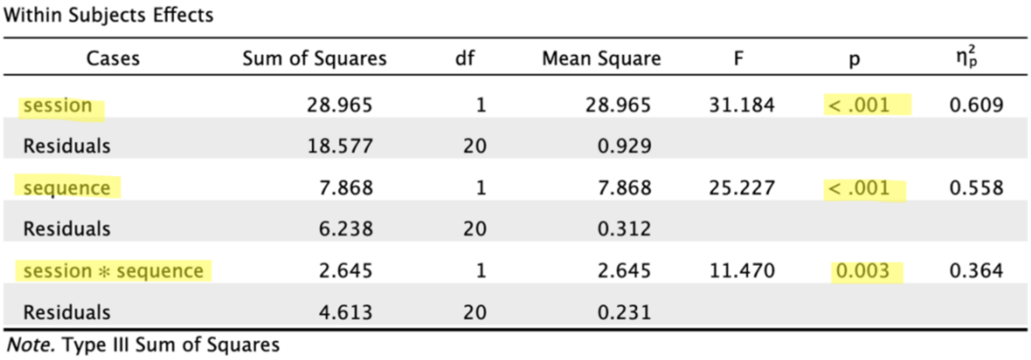
Post Hoc Comparisons – session ✻ sequence

		Mean Difference	SE	t	p_{holm}
baseline, high	test, high	2.468	0.225	10.989	< .001
	baseline, low	−0.026	0.104	−0.251	0.882
	test, low	1.630	0.224	7.280	< .001
	baseline, novel	0.084	0.104	0.804	0.882
	test, novel	1.490	0.224	6.654	< .001
test, high	baseline, low	−2.494	0.224	−11.137	< .001
	test, low	−0.838	0.104	−8.057	< .001
	baseline, novel	−2.384	0.224	−10.648	< .001
	test, novel	−0.978	0.104	−9.407	< .001
baseline, low	test, low	1.656	0.225	7.375	< .001
	baseline, novel	0.110	0.104	1.055	0.882
	test, novel	1.516	0.224	6.770	< .001
test, low	baseline, novel	−1.547	0.224	−6.907	< .001
	test, novel	−0.140	0.104	−1.350	0.720
baseline, novel	test, novel	1.406	0.225	6.262	< .001

Note. P-value adjusted for comparing a family of 15
Note. Results are averaged over the levels of: modality

2. Training data

a. Repeated measures ANOVA

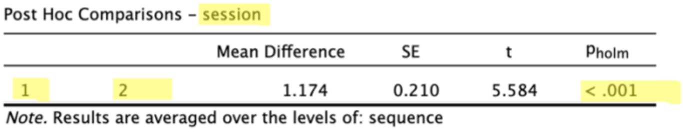


Within Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
session	28.965	1	28.965	31.184	< .001	0.609
Residuals	18.577	20	0.929			
sequence	7.868	1	7.868	25.227	< .001	0.558
Residuals	6.238	20	0.312			
session ✻ sequence	2.645	1	2.645	11.470	0.003	0.364
Residuals	4.613	20	0.231			

Note. Type III Sum of Squares

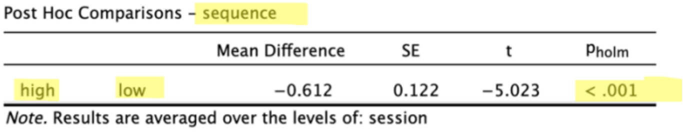
b. Post-Hoc tests



Post Hoc Comparisons – session

		Mean Difference	SE	t	p_{holm}
1	2	1.174	0.210	5.584	< .001

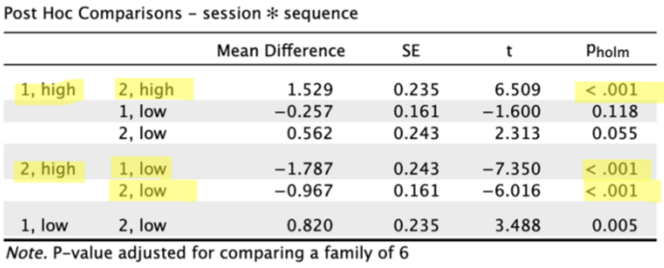
Note. Results are averaged over the levels of: sequence



Post Hoc Comparisons – sequence

		Mean Difference	SE	t	p_{holm}
high	low	−0.612	0.122	−5.023	< .001

Note. Results are averaged over the levels of: session



Post Hoc Comparisons – session ✻ sequence

		Mean Difference	SE	t	p_{holm}
1, high	2, high	1.529	0.235	6.509	< .001
	1, low	−0.257	0.161	−1.600	0.118
	2, low	0.562	0.243	2.313	0.055
2, high	1, low	−1.787	0.243	−7.350	< .001
	2, low	−0.967	0.161	−6.016	< .001
1, low	2, low	0.820	0.235	3.488	0.005

Note. P-value adjusted for comparing a family of 6

MIQ task instructions:

This questionnaire considers two ways of mentally representing movements. These are used by some people more than others and are more applicable to some types of movement than others. The first is to try to form a visual image or picture of the movement in your mind. The second is to feel the representation of a movement without performing it. In this questionnaire, you are asked to perform either of these tasks mentally for a variety of movements and then to rate how easy or difficult you find these tasks. The estimates you give are not designed to assess how well or badly you perform these mental tasks. They are intended to highlight the ability of subjects to represent these tasks in different movements. There are no good or bad estimations, or estimations that are better than others.

Each of the following statements describes a specific action or movement. Read each statement carefully and perform the movement as described. Perform the movement only once. Return to the starting position of the movement as if you were going to perform the action a second time. Then, depending on what you've been asked to do: (1) either form as clear and vivid a visual mental image as possible of the movement you've just performed from an internal perspective (i.e., from a 1st-person perspective, as if you were inside your own body and seeing the actions with your own eyes), (2) form as clear and vivid a visual mental image as possible of the movement you've just performed from an external perspective (i.e., from a 3rd-person perspective, as if you were watching yourself on a DVD), or (3) try to feel yourself performing the movement without actually doing it.

After completing the required mental task, estimate the ease or difficulty with which you were able to perform it. Make your estimate using the following scales. Be as precise as possible and take the time you need to arrive at the right estimate for each movement. You will choose the same estimate for each "visualized" or "felt" movement, and it is not necessary to use the full length of the scale.

Evaluation scale: motor imagery scale

1	2	3	4	5	6	7
Very hard to visualize	Hard to visualize	Quite hard to visualize	Neutral (not hard/not easy)	Quite easy to visualize	Easy to visualize	Very easy to visualize

Evaluation scale: kinaesthetic imagery scale

1	2	3	4	5	6	7
Very hard to feel	Hard to feel	Quite hard to feel	Neutral (not hard not easy)	Quite easy to feel	Easy to feel	Very easy to feel

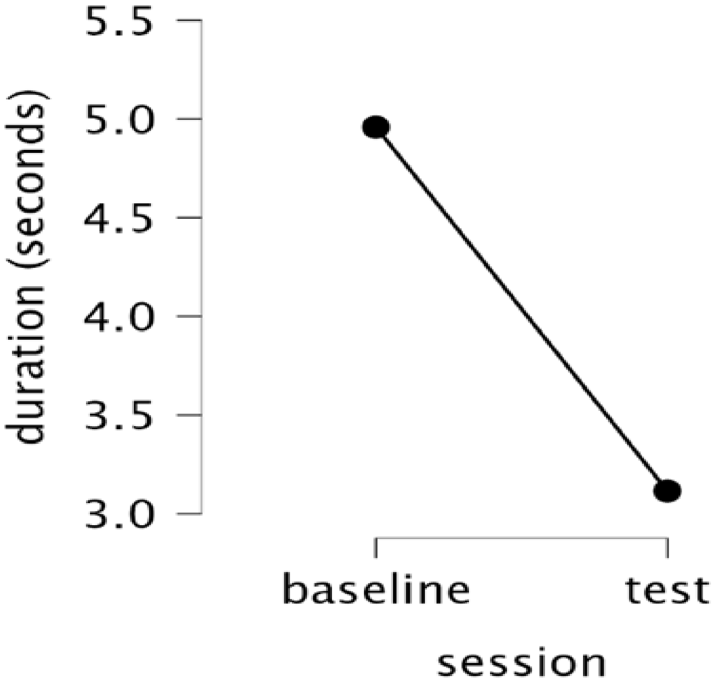
<u>Descriptive plots for each factor:</u>

1. Modality = x, duration (sec) = y: Imagery duration is higher than execution duration.
2. Session = x, duration (sec) = y: baseline session duration is higher than test session duration. Duration decreases during the 5 days test.
3.Sequence = x, duration (sec) = y: duration of high sequences is lower than low/novel sequences which are very similar.

A.

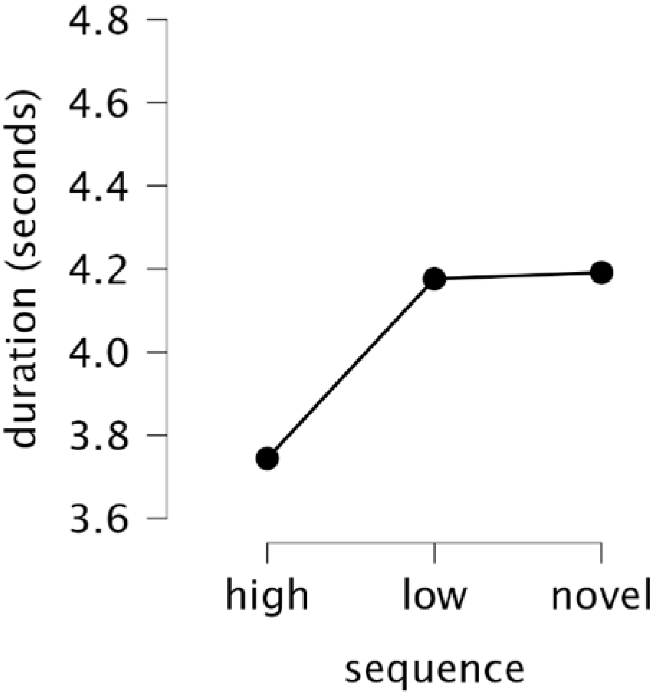
A. Descriptive plot of factor modality

B.



B. Descriptive plot of factor session

C.



C. Descriptive plot of factor sequence

ABSTRACT

Motor imagery is the mental imagination of an action or movement without executing that action or movement. Despite previous research about motor imagery and different models of its function, it is still unclear to how it works. The two most common models are the Motor Cognitive Model and the Motor Simulation Theory. They put forward different ideas: motor imagery and execution are similar between pre-training and post-training, for the Motor Simulation Theory. In contrast, motor imagery and execution are different between pre-training and post-training with imagery that becomes quicker post-training, for the Motor Cognitive Model. The purpose of this study was to examine the effects of physical training on motor imagery. The experiment was performed over 5 days with 28 participants, aged between 18 and 26 years old. After a first baseline session day 1, they were trained on an execution typing task for 3 days and ended the experiment with a test session day 5. Baseline and test sessions included imagery and execution tasks while training sessions included only an execution task. Consistent with previous findings, with training, both imagery and execution durations decrease, which could lead us to both models. As there was no three-way interaction found in the present results, it showed evidence for the motor Simulation Theory. Nevertheless, regardless of time point and training, it is found that imagery and execution are always different, and that imagery is always overestimated. This shows some evidence of the Motor Cognitive Model.

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