Testing the Motor-Cognitive Model of Motor Imagery with an On-Screen Pointing Task

Evelyn M.A.J. Karelse

Faculty of Behavioral, Management and Social Sciences, University of Twente

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First supervisor: dr. R.H.J. van der Lubbe

Second supervisor: dr. S.M. van den Berg

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Abstract

Motor imagery is an important area in psychology which is still theoretically underdeveloped. In this paper the currently prevalent view, the functional-equivalence model of motor imagery, was presented and contrasted with the motor-cognitive model of motor imagery. In an experiment, the predictions of both models were tested against each other by manipulating the precision of movements and by introducing a memory task with the intent to tax executive resources of the participant. The effects of the precision of the movement and the presence of a memory task were compared with overt actions and mental movements. In the experiment, the participants in the motor imagery group were expected to show a larger delaying effect due to increasing precision in movement and due to the execution of a memory task; this prediction was upheld. None of the results could be explained by a version of the functional-equivalence model of motor imagery. It was concluded that the motor-cognitive model of motor imagery might represent a workable and feasible step forward in understanding motor imagery.

Keywords: motor imagery, motor-cognitive model, pointing task

Introduction

Practicing imaginary movements has been proven to be useful in learning processes of professional musicians and athletes, and beneficial for the neurorehabilitation process of patients with motor disorders (e.g., Adams, Lust & Steenbergen, 2017; Feltz & Landers, 1983). The mental simulation of movements, also known as motor imagery, is a cognitive ability that allows individuals to consciously perform and experience a motor action without using and activating the corresponding muscles (e.g., Van der Lubbe, Sobierajewicz, Jongsma, Verwey & Przekoracka-Krawczyk, 2021; Rieger & Massen, 2013; McAvinue & Robertson, 2008; Decety, 1996; Jeannerod, 1994). In addition, motor imagery allows individuals to consciously access the content of a motor image, which otherwise might not be consciously accessed during an overt action (Lotze & Halsband, 2006).

In the present study an attempt will be made to test the motor-cognitive model of motor imagery, as proposed by Glover & Baran (2017). Recent studies have shown that the behavioral outputs and neural counterparts of motor imagery and overt action show various discrepancies under certain conditions (Glover, Bibby & Tuomi, 2020; Glover & Baran, 2017). The motor-cognitive model has two main theoretical advantages over the functional-equivalence model. First, the motor-cognitive model explains behavioral and neurological differences and similarities between motor imagery and overt action. Secondly, the motor-cognitive model offers testable predictions regarding the circumstances under which motor imagery and overt actions might either functionally match or differ (Glover & Baran, 2017).

There are various ways in which individuals can visualize motor imagery. Two different kinds of motor imagery are kinesthetic motor imagery and visual motor imagery, from a first-person perspective and a third-person perspective respectively (e.g., Van der Lubbe, et al., 2021; Rieger & Massen, 2013; Guillot, Nguyen, Malouin, Richards & Doyon, 2009; Decety, 1996). In the current study, the focus will be on kinesthetic motor imagery, which requires participants to “feel the movement and perceive muscle contractions mentally” (Guillot, et al., 2009, p. 2159), and also requires participants to “sense their own motions and experience realistic kinesthetic sensations” (Van der Lubbe et al., 2021, p. 72; Ridderinkhof & Brass, 2015).

The experiment used in the current study will be reported after a brief explanation of the functional equivalence model, and an elaboration on behavioral and neurological evidence for the motor-cognitive model. The functional equivalence model of motor imagery assumes that motor imagery and overt action are behaviorally and neurologically equivalent.

The motor-cognitive model of motor imagery, as proposed by Glover and Baran (2017), assumes that motor imagery and overt action are functionally distinct. The results of the experiment showed that participants were overall slower when executing motor imagery, compared to when executing overt actions. Furthermore, the results suggest that a memory task has a larger delaying effect while executing motor imagery than while executing overt actions.

The Functional-Equivalence Model of Motor Imagery

The functional-equivalence model holds that motor imagery and overt action are functionally equivalent, both behaviorally and neurologically. This model assumes that motor imagery, or a continuous motor image, is merely an internal visualization representing a movement simply without corresponding overt action or activation of the corresponding muscles (Decety, 1996; Jeannerod, 1994). According to this view, both motor imagery and overt action strictly rely on the antecedent generation of a motor image after which the execution of the overt or mental movement follows. This predicts that there is no need for executive control to consciously generate motor images for mental movements or motor imagery tasks. Furthermore, this model suggests that motor imagery should be able to accurately simulate overt action over a range of circumstances, and that there should be no systematic timing errors or systematic neural differences between motor imagery and its overt counterpart (Decety, 1996; Jeannerod, 1994).

The Motor-Cognitive Model of Motor Imagery

The motor-cognitive model of motor imagery contrasts with the functional-equivalence model. It assumes both systematic behavioral and neural differences between motor imagery and overt action in particular circumstances. This difference is caused by the increased use of executive resources during the execution of a mental movement compared to the execution of an overt action.

Comparable to overt action, motor imagery has two stages (Glover & Baran, 2017). The first stage is a pre-planning stage, which happens before the initiation of a simulated action. In this pre-planning stage, a motor image is generated which results in similar visualizations to the images that are generated for overt actions. Up until the completion of this pre-planning stage, motor imagery and overt action are the same (Van der Lubbe et al., 2021; Glover & Baran, 2017). The second stage is the point at which the movement is either covertly or overtly executed and is also the point at which overt action and motor imagery seem to diverge functionally (Glover & Baran, 2017).

During the execution of an overt action, the movement is monitored by automatic and unconscious visual and proprioceptive feedback systems. These feedback systems oversee and make small adjustments to ongoing movements in real-time (Glover, Bibby & Tuomi, 2020; Glover & Baran, 2017). Contrary to overt action, mental movements do not have access to these feedback systems because of the absence of muscle movements during motor imagery. The motor-cognitive model assumes that motor imagery relies more on executive resources and conscious elaboration than overt actions do, which is assumed to be the result of the absence of automatic feedback systems in mental movements. Additionally, reliance on executive resources during mental movements is what is assumed to lead to differences in behavioral en neural outputs in numerous and varying circumstances, according to the motor-cognitive model of motor imagery.

Behavioral Evidence for the Motor-Cognitive Model of Motor Imagery

Systematic timing differences as behavioral output of motor imagery between motor imagery and overt action can be explained by the motor-cognitive model of motor imagery, but not by the functional-equivalence model. Research has shown that when simulating movements that are more composed or are new to the individual executing the task, motor imagery often takes longer than its overt counterpart (Glover, Bibby & Tuomi, 2020; Glover & Baran, 2017; Rieger & Massen, 2013; Grealy & Shearer, 2008; Guillot & Collet, 2005). Additionally, practicing composed and novel movements has shown to systematically decrease the delay between motor imagery and overt action. In other circumstances, motor imagery can also be faster than its overt counterpart. According to research, one of these circumstances is the simulation of actions that are highly practiced or overlearned by the individual executing the mental movements (Glover & Baran, 2017).

The motor-cognitive model suggests that there are timing differences between highly practiced and novel mental movements, due to the fidelity of the motor image that is generated. When a movement is novel, the generated motor image is assumed to be less detailed than a motor image that is generated for a highly practiced movement. When a motor image is less detailed, more conscious online control, executive resources and time will be needed to generate a motor image that enables the image to be simulated. On the other hand, highly practiced actions provide a clear and detailed mental image of the task, which means that there is less need for the conscious generation of a motor image. This enables the image to be simulated at a similar, or even greater speed than the corresponding movement is executed. Systematic timing differences, whether motor imagery is sped up or delayed compared to its overt counterpart, are in line with the motor-cognitive model of motor imagery (Glover & Baran, 2017).

In a study done by Glover and Baran (2017), they found evidence that mental movements that required more precision from the participants, also taxed the participants' executive resources more than with mental movements that required less precision. The participants who executed a motor imagery task showed delayed reaction times because of increase of the required precision of a task, more so than participants who overtly executed the action. The second part of the experiment by Glover & Baran (2017) consisted of either a mental movement or an overt movement, and an interference task with the goal to tax the executive resources of the participants. The interference task had a significantly larger delaying effect on the group that mentally executed the movement, compared to the group that overtly executed the movement. The delay due to the interference task in the motor imagery condition, suggests that motor imagery taxes executive resources more than overt action (Glover & Baran, 2017). Additionally, the results suggest that cumulative effects of the interference task will increase the overall use of executive resources, which is also reflected in the systematic timing differences between both groups. These systematic timing differences between the motor imagery group and the overt action group are also in line with the general hypothesis of the motor-cognitive model of motor imagery.

In a later study, done by Glover, Bibby and Tuomi (2020), they found evidence that switching attention between motor imagery and indexing responses resulted in longer reaction times compared to switching attention between overt action and indexing responses. Comparable to the earlier study by Glover & Baran (2017), they also found that the participants in the motor imagery group showed a larger delay in reaction time because of the addition of an interference task compared to the participants in the overt action group. This delay in reaction time for the motor imagery group is assumed to be the result of a larger engagement of online executive control for participants in the motor imagery group compared to a lesser engagement of online executive control for participants in the overt action group. Furthermore, they state that the exact type or nature of the interference task does not matter, as long as it taxes executive functions. The results of this study are again also in line with the general hypothesis of the motor-cognitive model of motor imagery.

Neurophysiological Evidence for the Motor-Cognitive Model of Motor Imagery

During motor imagery neural activity also occurs outside of classic motor areas (Guillot, et al., 2009). Areas that are distinct to motor imagery are the ventral visual stream, occipital lobes, and the inferior frontal gyrus (Jiang, Edwards, Mullins & Callow, 2015; Guillot et al., 2009). The ventral stream and occipital lobes are pathways that carry visual information with the goal to recognize and identify objects and is argued to be used in the execution stage of motor imagery to help elaborate on the visual elements of a motor image. The inferior frontal gyrus is an area largely tasked with language processing and speech production. Individuals who are less skilled at motor imagery, or individuals executing novel mental movements seem to have higher levels of activity in the inferior frontal gyrus than individuals who are more skilled at motor imagery or individuals who are executing highly practiced or overlearned movements (Olsson & Nyberg, 2011; Guillot et al., 2009).

An additional area in the brain which is argued to be particularly involved in motor imagery is the dorsolateral prefrontal cortex (DLPFC). Glover, Bibby and Tuomi (2020), argued that processes involved in switching attention and mental operations are visible in activity in the DLPFC. Research shows that the DLPFC is more active during motor imagery than during overt actions and shows an additional increase in activity for novel mental movements (Guillot et al., 2009). Additionally, the assumed role of executive online functions in motor imagery tasks, seems to be consistent with the supposed role of the DLPFC in executive online functions (Van der Lubbe, et al., 2021; Yuan & Raz, 2014; Niendam et al., 2012).

Current Study

The current study aims to test the motor-cognitive model of motor imagery with an on-screen pointing task. To do this, there will be two groups in which participants are either asked to imagine or to execute the prescribed movement. Both groups have four within conditions. First, there are two conditions in which the participant is requested to do a movement that requires higher precision and another condition in which the participant is requested to do a movement that requires lower precision. In line with the results shown by Glover & Baran (2017) and in line with the general hypothesis of motor-cognitive model, participants are expected to show a stronger delay while executing the higher precision movement compared to the lower precision movement in the motor imagery group compared to the overt action group.

Two of the within conditions are a higher precision pointing task with a memory task, and a lower precision pointing task with a memory task. Also, in line with the motor-cognitive model of motor imagery, and the results shown by Glover & Baran (2017) and Glover, Bibby and Tuomi (2020), the participants in the motor imagery group are expected to show a larger delay in reaction time while executing the higher precision pointing task as opposed to the overt action group. Furthermore, participants are expected to have a delay in reaction time caused by the memory task, compared to trials without a memory task. Participants in the motor imagery group are expected to show a larger delay in reaction time due to the memory task than participants in the overt action group.

Methods

Participants

A total of forty-three participants took part in the experiment. Thirty-five participants were recruited via an internal system at the University of Twente, in which students from the Psychology program are recruited and receive points for their participation in the study. Eight participants were recruited by sampling among the researcher's personal contacts.

Of these forty-three participants, three took part in the pilot testing of the study, after which their data was discarded. Of the remaining forty participants, twenty-nine participants were female, ten participants were male, and one participant chose not to disclose their gender. Thirty-three participants were between eighteen and twenty-two years of age and seven participants were between twenty-three and twenty-six years of age. and thirty-eight participants were currently doing or had graduated from their university or higher-vocational education bachelors' degree, and two of the participants were currently doing or had graduated with a university masters' degree. Thirty-seven out of forty participants reported to be right-handed.

Materials and Stimuli

All the experimental trials took place in a 'flexperiment' cubicle, made available by the BMS Lab at the University of Twente, which is a controlled environment in which the experimenter could monitor the participant from a distance throughout the experiment. Participants sat at a desk, on which a monitor, keyboard and mouse was placed. The participants could either put the mouse to the right-hand side of the monitor if they were right-handed or place the mouse at the left-hand side of the monitor if they were left-handed. The experiment was programmed in OpenSesame with Python inline code.

There were five basic types of stimuli presented throughout the experiment, which were (1) the start button, (2) a small target, (3) a large target, (4) the four digits that are presented for the memory task, and (5) the prompt to complete the memory task by filling in the four digits. These stimuli are used throughout the experiment but are not present in every trial.

The start button, as illustrated in Figures 1 and 2, has different functions depending on the group that the participants are in. For the experiment in the overt action group, the start button simply serves as a point on which participants can click to make the target appear on-screen. For the experiment in the motor imagery group, the start button also has the initiation function, but also serves as an indexing point at which participants can indicate that they have completed the mental movement task at hand.

The targets, also illustrated in Figures 1 and 2, were presented when a participant clicked the start button. The small targets were presented in the (1) higher precision pointing task without the memory task, and (2) the higher precision pointing task with the memory task. The smaller targets were 32 by 32 pixels in size, to elicit a higher precision movement than the larger targets. The large targets were presented in the (3) lower precision pointing task trials without memory task, and (4) the lower precision pointing task trials with memory task. The larger targets were 64 pixels by 64 pixels, to elicit a lower precision movement than the smaller targets. The movement task for the participants was to click on the target presented on screen for the overt action group or imagining moving the mouse to click on the target and then indexing the completion of this movement through clicking on the start button for the motor imagery group. All the targets mentioned above were black squares presented on a white background, to enable any participants experiencing color-blindness to take part in the experiment. Additionally, the targets were all presented at random distance from the start button. An illustration of a low precision pointing task without a memory task can be found in Figure 1.

The four digits presented for the memory task and the prompt to complete the memory task by filling in the four digits as presented in the experiment, are presented in Figure 2. The memory task consisted of four random digits which were presented to the participant. The participant had 60 seconds to memorize the digits, or the participant could indicate that they wanted to continue if they had memorized the digits within these 60 seconds. After completing one pointing task trial, either with a small or a large target, the participants were prompted to fill in the four digits they had memorized right before the corresponding trial. Like the memorization prompt, the participants had 60 seconds to fill in the digits or could continue if they had filled in the digits within this time. The memory task and the prompt to answer were presented in (2) the high precision pointing task trials with memory task, and (4) the low precision pointing task trial with memory task. An illustration of a high precision pointing task with a memory task can be found in Figure 2.

Additionally, the Vividness of Movement Imagery Questionnaire-2 (VIMQ-2) was used to assess the individual differences between subjects' ability to imagine themselves while executing twelve simple motor tasks from an internal imagery perspective, and external imagery perspective, and a kinesthetic imagery perspective (Roberts, Callow, Hardy, Markland & Bringer, 2008). The VIMQ-2 is a revised version of the original Vividness of Movement Imagery Questionnaire as presented by Isaac, Marks & Russel (1986).

Figure 1

Exa*mple of a Pointing Task Trial with a Large/Low Precision Target without a Memory Task*

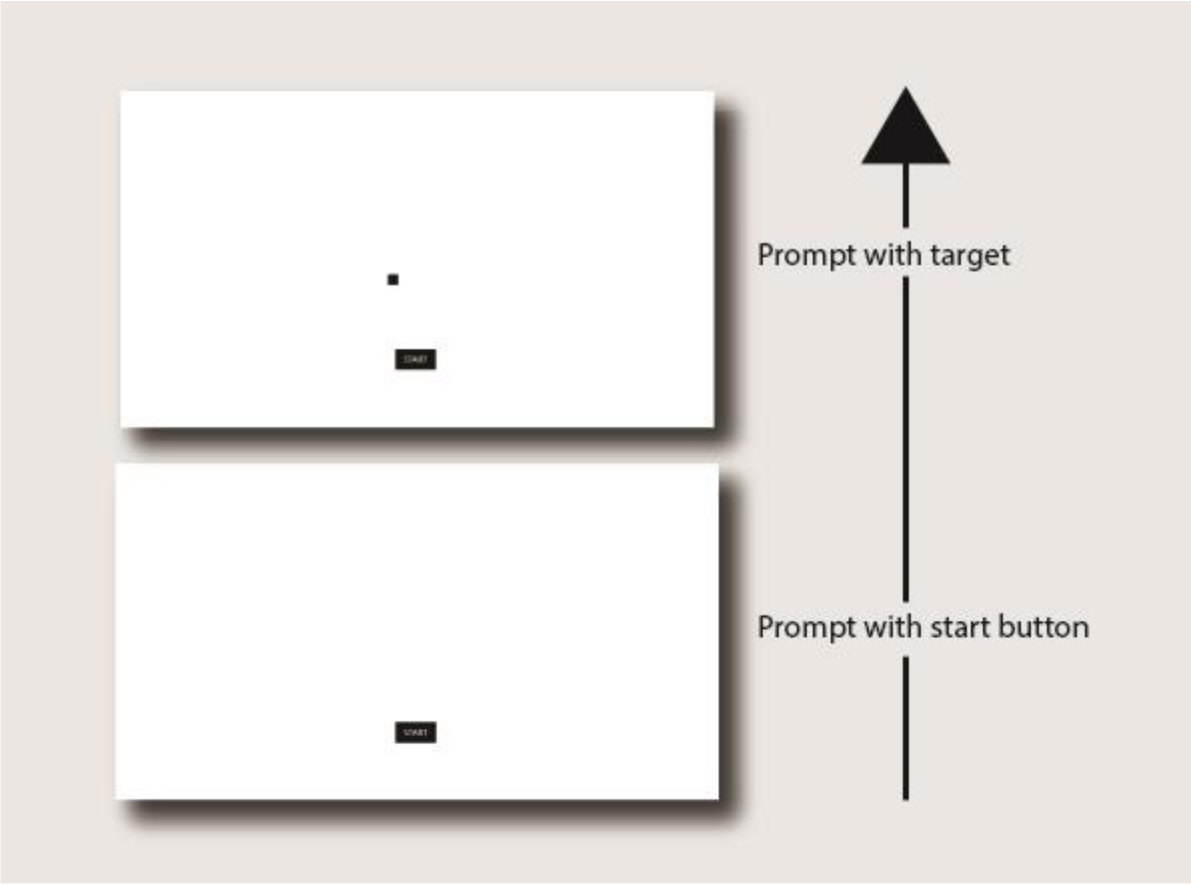
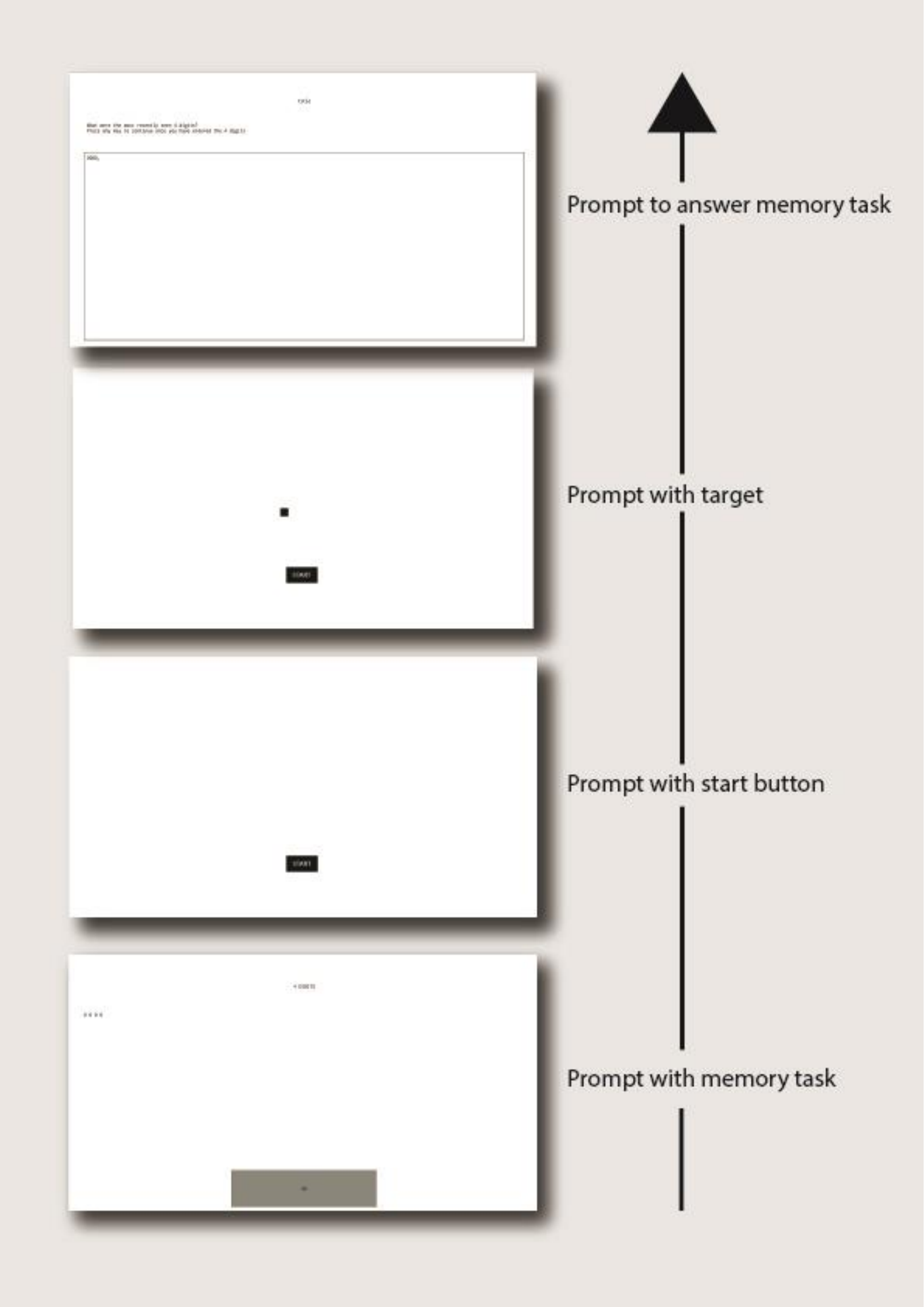


Figure 2

Example of a Pointing Task Trial with a Small/High Precision Target and a Memory Task



Procedure

Starting the experiment, the participant received instructions from the experimenter. Participants were also asked to put their mobile phones on silent and put them out of sight, to avoid any possible distractions. They were instructed to read through the informed consent form and sign it if they agreed to participate. After the participants signed the informed consent form, they were instructed to continue to the experiment which was presented on the monitor in front of them. Starting the experiment, instructions (presented in Appendices A and B for the motor imagery group and the overt action group respectively) were given to the participants with crucial information they need for the tasks. The instructions were different for the overt action and the motor imagery group but were as similar as possible to avoid any possible differences between groups due to differences in the instructions. The experimenter was always accessible to the participants in the case that the participants had any questions throughout the experiment. All the participants were debriefed after they had completed their participation.

After the instructions, the participants were presented with three practice trials in which they could practice the task. The practice trials consisted of 3 trials of the low precision pointing task, with the memory task. Once they had completed the practice trials they could continue to the experimental trials. The experimental trials consisted of three trials of the (1) lower precision pointing task without the memory task, three trials of the (2) higher precision pointing task without the memory task, three trials of the (3) the lower precision pointing task with the memory task and three trials of the (4) the higher precision pointing task with the memory task. In short, participants had twelve trials in which they click on a target of which six trials included a memory task. Per group each of the within conditions were presented, but were not presented in the same order for all participants. The presentation of the within conditions were counterbalanced to exclude any confounding effects due to sequence or order of trials.

Data Analysis

To prepare, the reaction times per participants had to be standardized as the distance of the target was randomly chosen per trial. To do this, the distance from the start button to the target (in pixels) was divided by the reaction time, which was then multiplied by 100.

This resulted in a standardized time measuring how long it took to move to 100 pixels on the screen. Additionally, participants who scored a total of zero percent on the six memory tasks that were presented, were excluded due to failure to follow the instructions. This resulted in excluding three participants in the motor imagery condition and two participants in the overt action condition. Furthermore, participants who had outlying scores (three or more standards deviations away from the mean) in two or more of the within conditions were excluded as well. This resulted in the exclusion of an additional two participants in the motor imagery condition, and the exclusion of an additional two participants in the overt action condition. After this, the analyses were conducted on data of fifteen participants in the motor imagery group and sixteen participants in the overt action group.

As for analysis of the data, three sets of statistical analyses were conducted. To measure the effects of target size (small vs. large), the memory task (with vs. without) and the between group (overt action vs. motor imagery) on reaction time for the pointing task trials, a three-way repeated measures analysis of variance was used. In this analysis, target size and the memory task were within factors, and group was a between-subjects factor. Second, the effects of target size (small vs. large) and group (overt action vs. motor imagery) on the time it took participants to answer the interference task were analyzed using a two-way measure of analysis of variance. Additionally, a two-way measure of analysis of variance was used to analyze the effects of target size (small vs. large) and group (overt action vs. motor imagery) on scores for the motor imagery task. Third and last, an independent samples t-test was used to determine if there are any differences regarding the scores of the VIMQ-2 questionnaire between groups (overt action vs. motor imagery).

Results

A two-way repeated measure of analysis of variance showed that there was no significant main effect of target size on reaction time for the pointing task $(F(1, 31) = 0.20, p = 0.66, \eta_\rho^2 = 0.006)$. Additionally, there is no main effect of the memory task on reaction time $(F(1, 31) = 1.445, p = 0.24, \eta_\rho^2 = 0.045)$. There were also no significant interaction effects between target size and group $(F(1,31) = 0.41, p = 0.84, \eta_\rho^2 = 0.001)$, or between interference and condition $(F(1, 31) = 2.86, p = 0.10, \eta_\rho^2 = 0.0855)$.

However, there was a significant interaction effect between precision and interference $(F(1,31) = 11.34, p = 0.005, \eta_\rho^2 = 0.227)$ on reaction times for the pointing tasks.

Participants in the mental imagery group showed a delay in reaction time when the mental movement required more precision, and their reaction time delayed even more when a memory task was added. In addition to this, there was also a significant interaction effect between target size, interference, and group ($F(1, 31) = 4.838, p = 0.035, \eta_\rho^2 = 0.135$). Finally, there was also a significant main effect of group on reaction time ($F(1, 31) = 30.44, p < 0.001, \eta_\rho^2 = 0.569$). Participants in the mental imagery condition were faster in the pointing task trials with a large target without a memory task, compared to the pointing task trials with a memory task. However, participants in the same group were slower in the pointing task trials with a small target without a memory task, compared to the same trials with a memory task. Furthermore, participants in the overt action group were overall faster than participants in the motor imagery group. Participants in the overt action group showed no delay with the addition of a memory task in the pointing trials with a large target, compared to the pointing task trials with a large target without a memory task. Furthermore, participants in the overt action group showed a very slight delay in the pointing task trials with a small target with a memory task.

Figure 3

Average Reaction Times of the Overt Action Group and the Mental Imagery Group of Trials With and Without a Memory Task

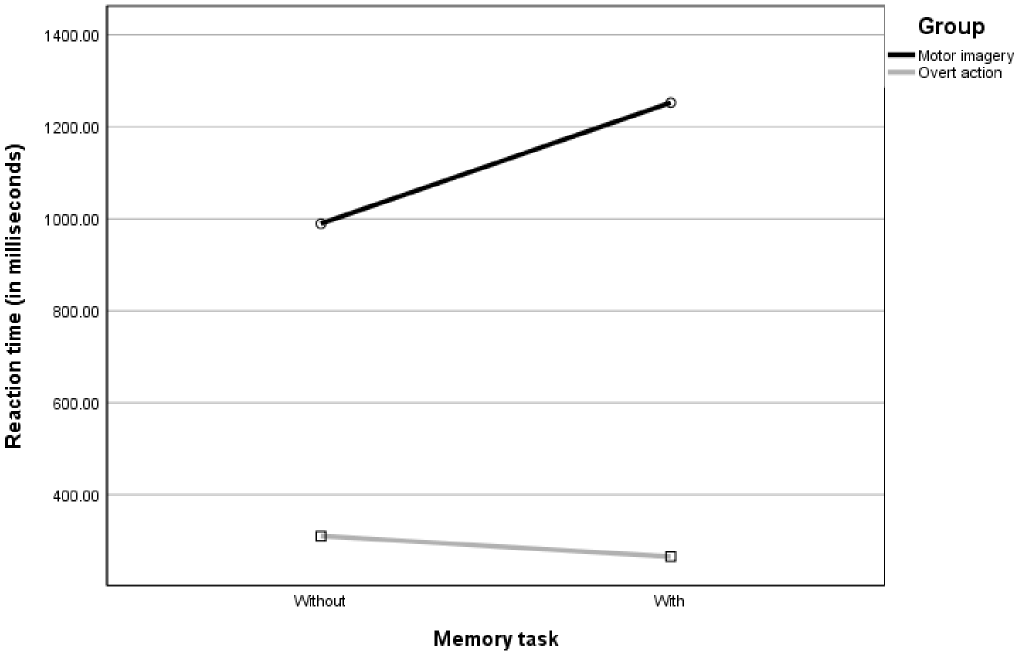


Table 1

Descriptive Statistics of the Reaction Times of the Pointing Tasks for the Motor Imagery Group and for the Overt Action Group.

Group	N	Target size	Memory task	Mean	Standard error	(95% CI) Lower bound	(95% CI) Upper bound
Motor imagery	15	Large	No	1124 ms	99 ms	920 ms	1327 ms
	15	Large	Yes	1083 ms	116 ms	846 ms	1320 ms
	15	Small	No	854 ms	88 ms	674 ms	1034 ms
	15	Small	Yes	1421 ms	172 ms	1070 ms	1773 ms
Overt action	16	Large	No	327 ms	102 ms	117 ms	536 ms
	16	Large	Yes	235 ms	119 ms	-9 ms	479 ms
	16	Small	No	292 ms	91 ms	106 ms	487 ms
	16	Small	Yes	295 ms	177 ms	-66 ms	657 ms

A one-way measure of analysis of variance for reaction time of answering the memory task showed that there were no significant effects of target size between groups for the tasks with a small target *($F(1, 31) = 1.96, p = 0.17$),* or with a large target *($F(1, 31) = 0.01, p = 0.91$).* However, participants in this experiment in the motor imagery were on average slower when answering the memory task with a pointing task with a small target, compared to participants in the overt action condition. The same was true for the tasks with a large target. Furthermore, a one-way measure analysis of variance showed that there were no significant effects of group on the percentage of correct answers for the memory task for the trials with a large target *($F(1, 31) = 0.12, p = 0.92$)* or the small target *($F(1, 31) = 1.12, p = 0.156$).*

Finally, an independent samples *t*-test showed that there were also no significant differences between conditions regarding the VIMQ-2. There were no significant differences between the overt action condition and the motor imagery condition regarding the subjects' ability to imagine through an external imaging view *($t(29) = -0.45, p = 0.66$),* an internal imaging view *(t(29) = 0.26, p = 0.80)* or a kinesthetic imaging view *(t(29) = 0.29, p = 0.78).* Further, there were no significant difference between conditions between subjects preferred imaging style *(t(28) = -0.92, p = 0.37),* switching imaging styles while using external imaging *(t(29) = -1.76, p = 0.09),* switching imaging styles while using internal imaging *(t(29) = -0.004, p = 0.99),* combining kinesthetic imaging and external imaging *(t(29) = -0.63, p = 0.54),* or combining kinesthetic imaging and internal imaging *(t(29) = 0.86, p = 0.40).*

Figure 4
Average Reaction Time of the Overt Action Group and the Mental Imagery Group for Pointing Task Trials with Large/Low Precision Targets and Small/High Precision Targets with a Memory Task

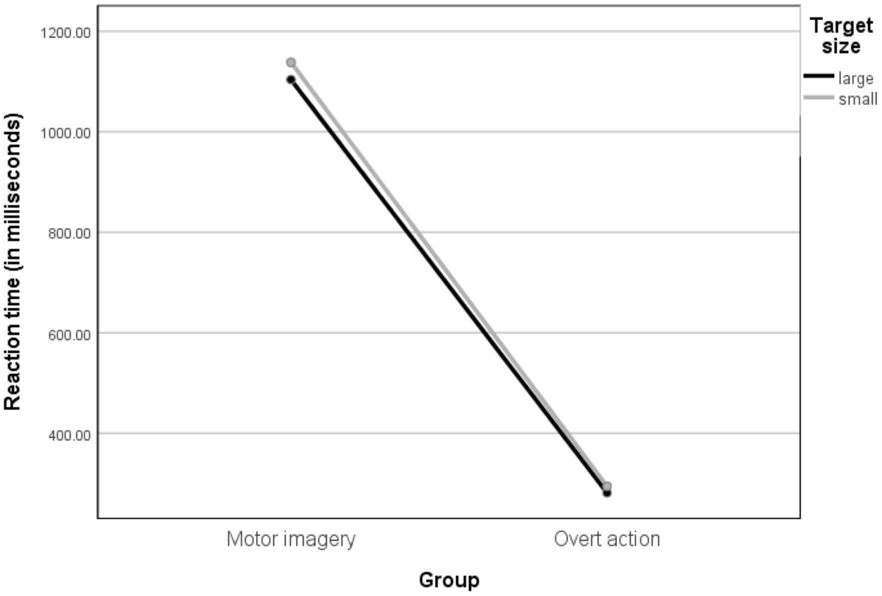


Table 2
Descriptive Statistics of the Reaction Times of Answering the Memory Tasks for the Motor Imagery Group and for the Overt Action Group.

Group	N	Target size	Mean	Standard error	(95% CI) Lower bound	(95% CI) Upper bound
Motor imagery	15	Large	1993 ms	331 ms	1229 ms	2636 ms
	15	Small	2001 ms	242 ms	1487 ms	2515 ms
Overt action	16	Large	1883 ms	286 ms	1269 ms	2497 ms
	16	Small	1757 ms	182 ms	1385 ms	2128 ms

Discussion

The current study sought to test the general hypothesis of the motor-cognitive model of motor imagery against the functional-equivalence model of motor imagery by using en experiment designed to task executive functions of the participants while they were executing a mental movement or an overt action, and to distinguish between higher and lower precision movements. The findings of the experiment show evidence suggesting that motor imagery is not functionally equivalent to overt actions as suggested by, for example, Decety (1996), Holmes & Collins (2001), and Jeannerod (1994). These findings rather show that motor imagery is in at least some respects different from overt action, as suggested by the motor-cognitive model of motor imagery proposed by Glover & Baran (2017).

The results as reported here demonstrated that taxing executive functions interfered with the timing of motor imagery. In the motor imagery condition, the participants showed a strong delay between the target pointing task that required a high precision movement when a memory task was added. This delay was not present in the participants who were in the overt action group. This discrepancy in timing between the motor imagery group and the overt action group, especially when adding a memory task in the motor imagery group is in line with the motor-cognitive model.

Interestingly, when the participants in the motor imagery group did the pointing task with a memory task their reaction times were lower when the memory task is added. This can potentially be attributed to the fact that the larger target task was a more familiar and more practiced movement to the participants, as suggested by for example Glover, Bibby & Tuomi (2020). This timing difference is also in line with the motor-cognitive model.

In research done by Glover and Baran (2017), similar results were found in their second experiment. The results showed that the addition of a task to interfere with executive resources results in a significantly larger delay when executing a mental movement, compared to executing an overt action. Furthermore, Glover, Bibby and Tuomi (2020) also found similar results to their second and third experiment. In these experiments, participants executing a mental movement also showed a larger delay in reaction time because of the addition of a task to task the executive resources.

A proponent of the functional-equivalence model might argue that the timing difference between both group can also be attributed to the assumption that participants in the motor imagery group were able to engage more in the memory task because of the absence of physical attributes, in this case holding the mouse. However, participants in the motor imagery group in this condition were in the same posture as the overt action group where both participants held a mouse. If the participants in the motor imagery task could be more engaged in the memory task, it might be argued that they were quicker with answering the task compared to the overt action group. Nonetheless, the results showed that there were no differences between groups for the time it took participants to answer the memory task.

For the functional-equivalence view to be upheld, the experiment should have shown no difference between groups, between target size, or between the presence of a memory task. The current study showed evidence that taxing the executive resources, results in timing differences between mental movements and overt actions. As such, the motor-cognitive model appears to give more weight to the results of this study and falsifies the functional-equivalence model.

Limitations and Future Research

First, a point of reflection in similar future studies should be the number of trials presented to the participants during the experiment. In the current study the participants executed twelve pointing tasks, six of which with a small target and six of which with a large target. Of these twelve pointing tasks, half of the trials also had a memory task. The choice of a relatively small amount of trials was made to avoid potential confounding learning effects that could occur if the participants executed the task excessively during the experiment. However, it can also be argued that it can be beneficial to add more trials than in the current study to enhance the clarity and the power of the resulting data. This then might result in a more realistic view on the actual differences between overt actions and mental movements. In the future, researchers should be aware of this trade-off in the design of motor imagery studies.

Another point of improvement would be in the design of the experiment as well. In the current experiment, the targets were presented at random distance from the start button and were standardized at the point of data analysis. However, with this standardization the natural flow of movement (including acceleration and deceleration) was not considered. In a future research it should be recommended to make standardized differences from the start point to the target point, considering the natural flow of movements. This would most likely also result in a more realistic view between overt action and mental movements.

Additionally, the participants were not tested for individual differences in advance of the experiment. As such, there were no elaborate corrections done for differences between individuals in their mental imagery abilities. In future studies this could be considered by doing the VIMQ-2 questionnaire (as mentioned in the methods section), in advance of the experiment. This way, the data and the results can be tailored to the motor imagery skills of the individual and can give a clearer picture of the differences between motor imagery and overt action.

Another point of possible improvement is in the design of the stimuli. In the current study participants were presented with four digits for the memory task. One can argue that the memory task could have potentially been more taxing, for example by adding more digits or adding a combination of digits and letters. Even though the results suggest that the memory task had the expected delaying effect in the experiment, adding a more difficult memory task might also help make potential differences or similarities clear between overt action and mental movements. An additional suggestion for the design of the memory task would be to add memory tasks of varying difficulties, again to highlight any possible distinctions between overt action and mental movements.

Additionally, it would seem beneficial to use different types of interference tasks to test the motor-cognitive model of motor imagery. Glover, Bibby and Tuomi (2020), also suggest that it should not matter what the interference task is, as long as it taxes executive resources. Additionally, motor imagery should be tested over varying situations and types of tasks. In this way, the conditions in which motor imagery and overt action are functionally different or similar might be further explored, mapped, and narrowed down.

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Appendix A

Instructions given to the participants in the motor imagery group

We will now continue to the trials, but don't worry. You can practice first. Make sure to carefully read through the instructions. The instructor will also take you through them. After the instructions, there will be practice trials.

1. When 4 digits appear on screen, memorize them. When you have memorized these digits you can click to continue. Otherwise, if 60 seconds have passed you will continue automatically.
2. When a start button appears on the screen, click on it. Keep the cursor here, as this is the starting position.
3. When you click the start button, a target will appear on the screen. IMAGINE that you are moving the cursor to the target in order to click on it. The cursor will remain in the start button. Instead of clicking on the target, you can click your mouse in the start button when you have completed you imagined movement.
4. When you see a recall screen, fill in the 4 digits that you have most recently memorized.

The researcher will leave the room now. You can wave your hands at the camera to your right, and the researcher will come back. You can do this at any point in time during the experiment.

Appendix B

Instructions given to the participants in the overt action group

We will now continue to the trials, but don't worry. You can practice first. Make sure to carefully read through the instructions. The instructor will also take you through them. After the instructions, there will be practice trials.

1. When 4 digits appear on screen, memorize them. When you have memorized these digits you can click to continue. Otherwise, if 60 seconds have passed you will continue automatically.
2. When a start button appears on the screen, click on it. Keep the cursor here, as this is the starting position.
3. When you click the start button, a target will appear on the screen. With your mouse move the cursor to the target to click on it.
4. When you see a recall screen, fill in the 4 digits that you have most recently memorized.

The researcher will leave the room now. You can wave your hands at the camera to your right, and the researcher will come back. You can do this at any point in time during the experiment.