International Journal of Psychophysiology 174 (2022) 57–65

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Registered Reports

Motor imagery and the muscle system

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ARTICLE INFO

Keywords:
Electromyography
Tensiomyography
Mental imagery
Biceps brachii
Muscle contractile properties

ABSTRACT

Many studies have investigated the activation of cortical areas and corticospinal excitability during motor imagery (MI) in relation to motor execution. Similar activation of cortical areas during imagined and executed bodily movements and increased corticospinal excitability while imagining movements has been demonstrated. Despite these similarities on the central nervous system level, there is no overt movement during MI. This suggests that centrally generated signals must be inhibited at some level. Second, even in the absence of movement, some studies find behavioral effects of MI interventions. Most of the studies have investigated the role of MI on the cortical or spinal level, but less is known about the peripheral level, such as the muscle system. Testing muscular excitability during MI will give further hints whether and how low-threshold motor commands during MI reach the muscular system. Furthermore, the extent of the shown effects during imagery depends considerably on type of imagery, available proprioceptive information, and imagery ability. Therefore, this study investigates muscular excitability of the biceps brachii muscle manipulating imagery mode (MI vs. visual imagery) and proprioceptive information (with or without muscle effort). 40 participants were included in the analysis. The mechanical response of the muscle after a single electrical stimulus was assessed via tensiomyography. The corresponding variables maximal displacement, delay time, and contraction velocity were used to calculate 2 × 2 ANOVAs with repeated measurements. The absence of interaction effects shows that possible imagery effects on the muscle system are not increased by effort. MI altered time to contraction with lower delay time compared to control condition. Velocity and maximal displacement of the muscle belly during contraction did not differ between imagery conditions. This indicates that MI might impact on the initiation of muscle contraction but does not change the contraction itself. Thus, neuronal factors are moving further into focus in the context of MI research.

1. Introduction

Motor imagery (MI) is a first-person mental simulation of a movement without corresponding motor output (Jeannerod, 1994). Although MI is a multi-sensory procedure, most of the mentioned following studies acknowledge that in first-person MI, a kinesthetic representation of one's own movements is activated. Despite this lack of observable movements, studies have shown improvements in movement output, e.g., muscle strength increases after movement simulation training, especially using MI, not visual imagery, in a first-person perspective with kinesthetic impressions of one's own movements (Yue and Cole, 1992; Reiser et al., 2011; Grosprêtre et al., 2018). A number of hypotheses and theories have been suggested to explain these motor changes. These include among others the theories of Carpenter (1894) and Jacobsen (1931), which are based on the ideo-motor principle, stating that human actions are causally initiated by the simple idea of the sensory consequences that result from them. When humans have learned these action-effect relationships, a bidirectional connection between the two is established, allowing bodily movements to inversely follow from the mind's idea of the movements "unhesitatingly and immediately", according to James's (1890) definition of ideo-motor action. This suggests that an action is initiated by the pure anticipation of its effects and that some fragmentary signals activate the muscles during motor planning or MI. However, MI effects have so far mostly been investigated on the cortical (Munzert et al., 2009), spinal (Grosprêtre et al., 2016), and behavioral level (Di Rienzo et al., 2016), but in-depth studies of muscular activation during MI are lacking.

Regarding cortical areas, there is evidence that MI and actual

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https://doi.org/10.1016/j.ijpsycho.2022.02.004
Received 26 October 2021; Received in revised form 7 February 2022; Accepted 9 February 2022
Available online 12 February 2022

movement show overlapping activation patterns (Lotze et al., 1999; Jeannerod, 2001; Munzert et al., 2009), although not identical (Zabicki et al., 2017). For example, the primary motor cortex is involved during the imagination of motor movements (Lotze and Zentgraf, 2010). Corticospinal excitability during first-person MI compared to rest (Facchini et al., 2002; Tremblay et al., 2001) and compared to third-person imagery of the same movement was raised (Bakker et al., 2008; Stinear et al., 2006). Whereas there is consistent evidence concerning activation and excitability during MI at a cortical and corticospinal level, the results at the spinal level are not clear yet (Grosprêtre et al., 2016). The online effects of MI on the activation of subcortical structures via subliminal cortical output during MI are more variable compared to the effects on brain areas (Grosprêtre et al., 2019). As an index of spinal excitability, many authors used the Hoffmann (H)-reflex amplitude during MI. The H-reflex is analogous to the mechanically induced spinal stretch reflex and measures the reflectory reaction of muscles after electrical stimulation of sensory fibers in their innervating nerves. A change in the reflex response during MI is attributed to small motor commands that reach the spinal network. While some studies showed no influence or even a reduction of the H-reflex (Hashimoto and Rothwell, 1999; Li et al., 2004; Oishi et al., 1994), other studies found an increase of the H-reflex during MI (Bonnet et al., 1997; Cowley et al., 2008). Despite the different results on H-reflex, Grosprêtre et al. (2019) assumed that spinal structures are activated during MI even in the absence of H-reflex modulation. They showed the impact of MI on the spinal level to more sensitive structures, i.e., the spinal presynaptic network. They argue that the activation threshold of parts of the spinal presynaptic network, i.e., the spinal interneurons is lower than that of the motoneurons, allowing them to be more sensitive to subliminal cortical output generated by MI. These results support the idea that low-threshold signals are sent from the cortex via the spinal cord to the muscles and can be found at least on the spinal level during MI.

The influence of MI on peripheral structures, especially on muscles, still has to be clarified. In MI research, summed and background EMG measurements have mostly been used to control for overt movements due to muscle activation in the target muscle. Here, in some studies, the background EMG during MI was increased (Guillot et al., 2007; Jacobsen, 1931); in other studies, this increase could be reversed via feedback to make sure to measure the participants in a fully relaxed state (e.g., Aoyama and Kaneko, 2011; Yue and Cole, 1992). Subjects were told to maximally activate the brain but not to activate the muscle, to be sure that the effects are related to MI only and not to muscle activation. Guillot and Collet (2005) postulated that recording EMG activity during MI should not be considered a sensitive and reliable method to evaluate MI ability, similarly, it also may not be the best method to detect subliminal muscle activation and increased muscle excitability during MI. The measurement of muscle activity with surface EMG may not be sensitive enough to detect the assumed subliminal increased activation, similar to the H-reflex on the spinal level, and more importantly, it might not detect any temporarily altered excitability of the muscle.

A more detailed method to study the role of the muscle system could be tensiomyography measurements (TMG). TMG is a non-invasive method that detects the mechanical response of the muscle after a single electrical stimulus. This technique can be used to assess muscular excitability independently from spinal effects at one discrete measuring point. In contrast to EMG, TMG records the mechanical reaction after a single electrical stimulus and does not accumulate action potentials over a period of time. Therefore, TMG could be more sensitive to low-threshold motor commands and might help to further elucidate the influence of MI on the muscles.

Several studies investigated the influence of type and condition of MI on behavioral effects. Beside the first-person MI discussed so far, a common type of imagery is an imagination usually associated with an external, third-person visual image perspective (VI). Studies have shown more pronounced strength increases after MI than VI training, especially using MI in first-person perspective with kinesthetic impressions (Yue and Cole, 1992; Reiser et al., 2011; Grosprêtre et al., 2018). Not only the type of imagery such as MI or VI seems to be a determining factor for peripheral physiological effects, but also task-specific instructions such as that bending the right arm only elicits muscular responses at the right arm (Munzert and Krüger, 2018). Furthermore, according to the PETTLEP model, it seems to be helpful for MI to make it as 'physical' as possible (Wakefield and Smith, 2012). Suitable to this, Lorey et al. (2009) also pointed out the influence of proprioceptive information during first-person imagery. Proprioceptive information of the actual body posture (i.e., hand position) during MI feeds into a hand motor representation. The blood-oxygen-level dependent (BOLD) signal in parietal structures was also influenced by subjects' own arm postures (de Lange et al., 2006). The influence of proprioception on MI is also shown for corticospinal excitability. Compatibility between real hand position and imagined movement show greater motor-evoked potentials (MEP) compared to incompatible hand positions (Vargas et al., 2004). Guillot et al. (2013) demonstrated that coupling MI with movement leads to enhanced MI quality and temporal congruence between MI and motor performance. Jiang et al. (2017) suggest that small voluntary muscle contractions combined with MI showed greater strength improvements after a six-week training session than small voluntary muscle contractions without MI. The authors compared muscle strength improvements of their own study with the quite similar study of Yao et al. (2013) and observed an almost 10% difference (20.47% vs. 10.8%). Since the only difference between the two studies was the small voluntary contraction during MI, the authors hypothesized that combining MI with low-level muscle activation can yield greater strength increases than a similar imagery training program without added muscle activation.

This suggests that posture or small movements have an influence on MI and might even improve MI quality. Furthermore, results of MI studies also depend on the ability to imagine movements. Considering that MI is a multidimensional construct, there are various methods to measure imagery ability, e.g., questionnaires, neurophysiological correlates, or mental rotation tasks. Lebon et al. (2012) showed that MI ability, assessed by multidimensional tests, is related to the modulation of corticomotor excitability during MI. Imagery ability estimated by autonomic response is correlated to sporting performance enhancement (Roure et al., 1999). Ruffino et al. (2017) showed that motor performance may be positively influenced, but not predicted, by the ability to form vivid movement images during MI.

According to the literature, three questions arise: (1) Does MI influence muscle excitability? (2) Does a muscle effort condition with low-level muscle activation increase the effects of MI on muscle excitability? (3) Is the extent of altered excitability during MI influenced by the ability to generate MI? The following numbered hypotheses correspond to specific, numbered analysis plans, which will be discussed in the Methods section.

1). As a main effect concerning imagery condition, we hypothesized that MI will lead to an increased excitability of the biceps brachii muscle compared to VI.

We hypothesized that during MI conditions low-threshold motor commands are sent to the muscle system. This will change contractile parameters during a muscle twitch of the biceps brachii muscle. Using TMG in this research context for the first time, we make the following predictions: The maximal radial displacement of the muscle belly (D_m) is used as an indicator for muscle stiffness and contractile force (García-Manso et al., 2012; Macgregor et al., 2018). Incomplete inhibition of the motor command should lead to a higher muscle stiffness due to low-threshold signals during MI. This should be seen by a lower D_m, as shown in motor-execution studies (Alvarez-Diaz et al., 2015; Rey et al., 2012). Furthermore, we expected a higher contraction velocity (V_c) indicating a faster stimulus transmission and an unchanged or even decreased delay time (T_d) (García-Manso et al., 2012). T_d represents the time between delivery of the

electrical stimulus and 10% of D_m, providing a measure of muscle responsiveness.

We also hypothesized that imagery and muscle effort condition will interact, with a more pronounced effect during the MI task with muscle effort (50 N). According to the results of Jiang et al. (2017), we expected that a certain level of motor output to the target muscle would lead to a release of inhibition of the descending pathway via the control system. Therefore, motor commands during MI will be sent to the target muscle without inhibition, which may result in a stronger muscle activation command. Regarding the TMG output, this would result in a lower D_m, a higher V_c and a decreased T_d during MI-50 N compared to VI conditions and MI with no muscle effort (0 N).

2). Additionally, a relation between imagery ability measured with three different tasks (German test of the controllability of motor imagery - TKBV, Vividness of Movement Imagery Questionnaire - VMIQ-2 and the change of heart rate variability during MI compared to VI - Δ-HRV), and the change of the muscle excitability during the MI task was expected. Therefore, higher scores on imagery assessments will be accompanied by greater change of TMG parameters. The better the imagery ability (higher score TKBV, lower score VMIQ-2, and lower, meaning a higher negative value of Δ-HRV), the greater the change of the TMG parameters. Furthermore, it is expected that the selected variables will co-vary with the scores in TKBV, VMIQ-2 and Δ-HRV.

3). Differences in EMG activation between imagery conditions were not anticipated (Aoyama and Kaneko, 2011; Mercier et al., 2008; Yue and Cole, 1992).

2. Material and methods

2.1. Subjects

Data were collected from women and men who are aged between 18 and 35 years. The experimental protocol has been approved by the local Ethics Committee and participation was voluntary. Injuries of the musculoskeletal system of the upper body which occurred in the last six months before the investigation were defined as exclusion criteria. Also, subjects with cardiopulmonary or neurological disorders were excluded. The measurements toke place at the Institute of Sports Sciences, Goethe University Frankfurt. Data was collected from volunteers that did not violate any of the exclusion criteria and was carried out by employees of the Goethe University Frankfurt. For sample size calculation, the R package 'Superpower' (Lakens and Caldwell, 2021) was used. As no studies exist to date that measured the effect of MI on muscular excitability with TMG, the effect strengths of MI studies in the area of cortical excitability as well as the change of the H-reflex during MI were considered. A weighted average of the reported effect size partial η^2 according to the number of participants in the studies was computed. For further calculation, the weighted average effect size was halved according to recommendations by the Open Science Collaboration (2015), since there is a tendency to overestimate effect strengths. Further calculations were based on the halved effect size and alpha error was set at 0.05. The number of participants was calculated for the planned test and the expected interaction between the two considered factors, a two-way repeated-measures analysis of variance with the conditions imagery (MI and VI) and muscle effort (0 N and 50 N). The package calculates the power as output for a given sample size. A power of 0.95 was reached with a sample size of 45. The detailed analysis can be found at https://osf.io/yzga8/.

2.2. Study design

The measurements were carried out on three days (see Fig. 1). Between measurements 2 and 3, the time period had to be at least two days and maximum seven days. Participants were requested to avoid any intense exercise prior to measurements 2 and 3. On the first day of measurements, participants were tested for their ability to imagine movements with three different methodological approaches. One captures the ability of imagination through a self-report, another one by behavior, and the third one via neurophysiological correlates. The participants were requested to complete the "Vividness of Movement Imagery Questionnaire" (VMIQ-2; Roberts et al., 2008) or the German translation of this questionnaire (Dahm et al., 2019), depending on the native language. The questionnaire assesses individuals' ability to imagine themselves performing twelve simple motor tasks from three perspectives: internal visual imagery, external visual imagery, and kinesthetic imagery. Participants rate their internal representation of the motor task on a Likert scale from 1 (perfectly clear and vivid) to 5 (no image at all, you only know that you are "thinking" of the skill). As a second test, the "Test zur Kontrollierbarkeit von Bewegungsvorstellungen" [German test of the controllability of motor imagery] (TKBV; Schott, 2013) was used, which measures the ability to manipulate one's motor representation based on various instructions. The test contains a total of 10 tasks, each with six consecutive instructions. The participants are requested to close their eyes, the instructions are given with an interval of 3 s. After the six instructions, the respondents must actively assume the final body position as soon as possible. The participants get points for every correct position of the body segments and the correct final position. As it is known that MI influences the autonomic nervous system (Guillot and Collet, 2010; Collet et al., 2013), the heart rate variability (HRV) was collected as a third covariate. The change of HRV during imagery of a landscape and motor imagery of a squat were compared. To get into a state of relaxation, participants are given a five-minute rest, remaining in a sitting position. Electrodes were placed on the following landmarks: V1 - fourth intercostal space on the right sternum, V2 - fourth intercostal space at the left sternum, V3 - midway between placement of V2 and V4, V4 - fifth intercostal space at the midclavicular line, V5 - anterior axillary line on the same horizontal level as V4, V6 - mid-axillary line on the same horizontal level as V4 and V5, RA (right arm) – above the right wrist, RL (right leg) - above the right ankle, LA (left arm) – above the left wrist, and LL (left leg) - above the

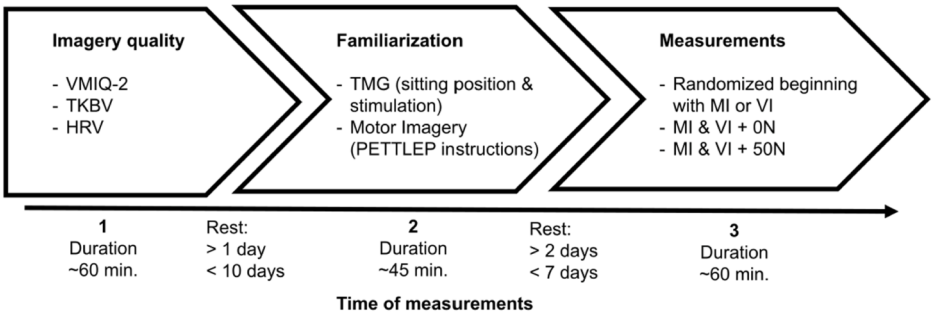

Fig. 1. Timeline of measurements.

left ankle. Measurements start with 30 s of instructed imagery of a landscape. After a break of 1 min, participants start with another 30 s of instructed motor imagery of squats. While the conventional minimum of recording for HRV evaluation is 5 min, the reliability of ultra-short-term periods of 30 s could be shown (Baek et al., 2015). The recording time of 30 s was chosen to avoid a loss of concentration during the imagery conditions. The participants were tested according to the recommendations from Laborde et al. (2017) in a sitting position, knees with a 90° angle, hands on the thighs and eyes closed. Data was collected with a 12 channel ECG device (Custo med, Germany).

On the second day, the participants were familiarized with the tensiomyographic measurement (TMG-BMC, Ljubljana, Slovenia). The specific body position, including seat height and arm length adjustment, were set and documented and test measurements were carried out to get the participants familiar with electric muscle stimulation. During the TMG tests, the participants' upper arm lay completely on a sloped upholstery (see Fig. 2). The wrist was fixed to the bar of a biceps curling machine so that the participants could hold the muscles relaxed in a reliable position. Additionally, subjects were asked to practice MI of maximal isometric contraction of the biceps brachii during first-person observation with PETTLEP-based instructions (Physical, Environment, Task, Timing, Learning, Emotion, Perspective; Holmes and Collins, 2001). To avoid muscle contractions on the active arm (i.e., the subject's right arm) during MI, participants received feedback with the help of EMG. The test runs were practiced until there was no visible change in the EMG signal compared to rest. To control muscle activity during imagery, EMG electrodes (Covidien, Kendall electrodes H93SG, 2 cm inter-electrode distance) were placed parallel to the muscle fibers proximal and distal to the TMG sensor on the biceps brachii. According to the recommendations of the SENIAM initiative (Surface Electromyography for the Non-Invasive Assessment of Muscles), the skin was shaved and dry-cleaned with alcohol to keep low impedance. Electrode placement was marked on the skin to ensure the same positions between every condition. The signals were be acquired with a frequency of 5000 Hz by the Biopac System (MP160 BIOPAC EMG-2R wireless sensor) and filtered with a bandpass filter (bandwidth 12 to 500 Hz).

On the third day, the participants' muscular excitability was assessed according to the two-level independent imagery conditions (MI, imagery of a maximal isometric contraction of the biceps brachii & VI, mental imagery of a landscape) and muscle effort (0 N, relaxed position, hands are fixed on the biceps curling machine & 50 N, contraction against the biceps curling machine to produce 50 N). All participants performed each condition as repeated measures in a within-design. The order of imagination conditions was randomly assigned for each participant. To avoid fatigue effects, the 0 N condition was always before the 50 N condition with a 3-min break between each condition. So two possible sequences existed: 1) MI-0 N, VI-0 N, MI-50 N, VI-50 N and 2) VI-0 N, MI-0 N, VI-50 N, MI-50 N. The instructions of the imagery tasks were repeated at the beginning of each condition; keywords ("get ready", "go" and "stop") were used during each measurement. To check if participants performed the correct type of imagery, they were regularly asked to describe the nature of the images after MI and VI. After each stimulation, participants were requested to rate the vividness of the last MI or VI trial, using a 5 point Likert scale based on the VMIQ-2 (Zabicki et al., 2017). Trials with a drop by 2 points of the vividness scale were repeated. For the measurements of the excitability of the muscle, participants were seated and their wrist was fixed as determined at the second appointment. The contractile properties of the biceps brachii muscle of the right arm were assessed by tensiomyography (TMG-BMC, Ljubljana, Slovenia). The displacement-measuring sensor was placed on the point of maximal muscle belly displacement during contraction, detected by manual palpation during voluntary muscle contraction. The self-adhesive electrodes (5 × 5 cm, axion GmbH, Leonberg, Germany) were placed symmetrically at a distance of 5 cm lateral and medial from the displacement-measuring sensor on the biceps brachii. Both, the position of the electrodes and the measuring point were marked with permanent ink to assure identical measuring locations in consecutive measurements. During the measurements, the sensor was placed perpendicular to the muscle. A single monophasic square wave with 1 ms pulses was delivered from the TMG stimulator to trigger the mechanical response of the muscle. The stimulation protocol started with 20 mA and was increased by 10 mA every 30 s to minimize the effects of fatigue and potentiation (Wilson et al., 2018). The intensity of stimulation was increased until no further displacement of the muscle belly was observed or the maximum of 100 mA is reached. The reliability of TMG for the biceps brachii muscle has been shown (Krizaj et al., 2008).

To ensure a static force of 0 N or 50 N during the four conditions, participants received live feedback in both conditions via a force-time curve on a screen (Diagnos 2000, Germany), which was connected to the biceps curl machine (Schnell, Germany).

Data collection was terminated after the previously calculated sample size was reached.

2.3. Data analysis

During the VMIQ-2, participants rate the vividness of each image

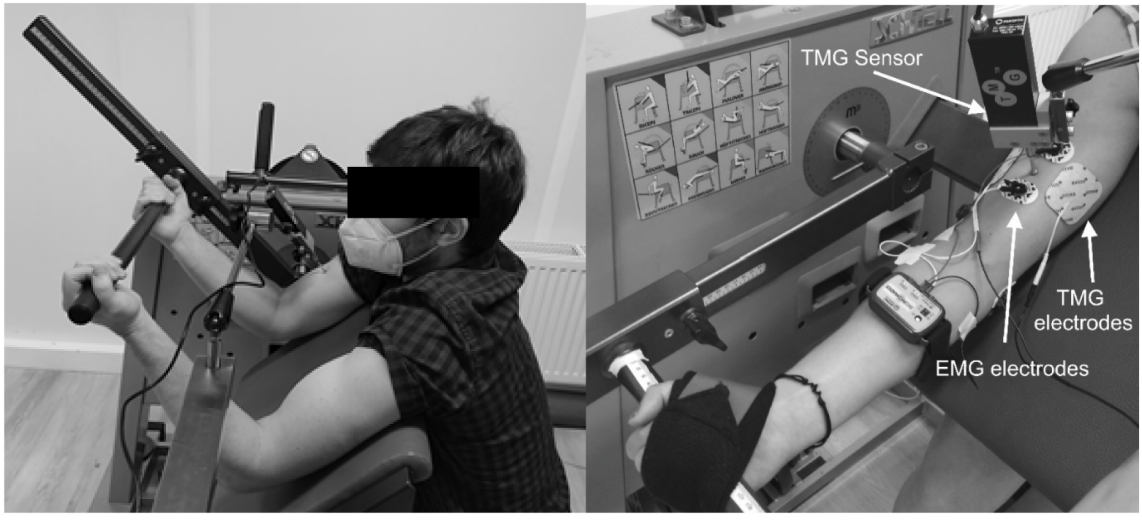

Fig. 2. Experimental set-up. Participants are seated in a biceps curling machine (left). The TMG sensor is placed on the m. biceps brachii and measures muscle belly displacement after an electrical stimulus. EMG records muscle activation during imagery conditions (right).

using a 5-point Likert scale, with scores from each item summed to provide a vividness score for each component (internal visual imagery, external visual imagery, and kinesthetic imagery) of between 12 and 60, with lower scores indicating more vivid images. Exclusion criteria for the VMIQ-2 were an incomplete questionnaire and marks between two values.

In the TKBV, the correct assumption of the body position is evaluated for every ten tasks, each with six consecutive instructions. For every correct body position, the participant receives one point. In total, 0 to 50 points can be reached, with higher scores indicating a more detailed motor representation. Trials were not counted if instructions were presented in a wrong way or were not audible for the participants. Wrong instructions were evaluated if the indication of the movement was announced incorrectly or if the pause between consecutive instructions was too long (more than 5 s) or too short (less than 2 s).

Heart rate and heart rate variability were recorded as beat-to-beat intervals using a 12 channel ECG device (custo med, Germany) during the 30 s of each imagery condition. The full ECG recording (custo diagnostic Version 4.5.1, Germany) was inspected visually, and artifacts (e.g. missed or spurious beats) were corrected manually (Shaffer and Combatalade, 2013; Laborde et al., 2017). Each successive time difference between heartbeats in ms (RR) was exported and further processed with the software Kubios (Kubios HRV Version 3.3.1, Finland). Root-mean square of successive differences (RMSSD) was calculated for each imagery condition. If participants showed overt movements, measurements were repeated or, if not possible, data excluded. Overt movements are defined as an observable lifting of one or both arms from the legs, or one or two legs from the ground. The third exclusion criterion for movements during data collection was head movements of more than 45° in each direction. The data of the HRV were excluded if there were less than 20 s valid data points. Data points were excluded for three or more consecutive artifacts.

All dependent variables were calculated on the maximal radial displacement curve over time. The maximal radial displacement (D_m) is expressed in millimeters (mm) and reflects the highest point of the curve. The delay time (T_d) represents the time in milliseconds (ms) between the electrical impulse and 10% of the maximal displacement. The contraction velocity is the calculated slope of the displacement curve over time $V_c = (90\%D_m - 10\%D_m)$ / (contraction time from 10 to 90% D_m). Parameters D_m and T_d were calculated by the TMG software. V_c was computed using the above-mentioned calculation via MATLAB R2019b (MathWorks, USA). The statistical evaluation only included the trial with the highest value of D_m for each condition. If self-reported vividness dropped more than 2 points, the trial was repeated once. If there was visible involuntary contraction (visible control of the target muscle) during the 0 N condition of the participants, the data was excluded. Exclusion criterion for the TMG measurements during both imagery conditions at the 50 N trials was if participants failed to remain the force in the range of 30 to 70 N.

Only those EMG data were analyzed where the corresponding TMG trials were included in the statistics. EMG signals were filtered with a band-pass filter (bandwidth 10 to 500 Hz), the filtered signals were processed to calculate the root-mean square EMG (RMS). The last 500 ms before external stimulation of the TMG stimulator were used for calculation. Data were excluded if technical problems (e.g., removing of electrodes, errors in data transmission) occurred.

2.4. Statistical analysis

Statistical analyses were performed with software SPSS (IBM SPSS Statistics for Windows Version 25). Results are expressed as means (M) and standard deviation (SD). Data were checked for outliers using the Median Absolute Deviation (MAD) method. According to the recommendations of Leys et al. (2013), the threshold was set to 2.5. Outliers were excluded from data analysis.

To test hypothesis 1), TMG data (D_m; T_d; V_c) were tested for normal distribution using Shapiro-Wilks tests prior to the statistical analysis. A repeated-measures analysis of variance (ANOVA) was used to determine effects of imagery conditions (MI, VI) and muscle effort condition (0 N, 50 N) on the TMG parameters. Effect size is reported as partial eta-squared. In case of violations of normal-distribution assumption, the Friedman test was used instead of repeated-measures ANOVA.

In hypothesis 2), the influence of MI ability on the dependent variables was tested. Therefore, the relationship between the ability to imagine movements (Score TKBV; VMIQ; Δ-HRV) and the percentage change of the TMG variables (D_m; T_d; V_c) using the Spearman correlation coefficient was analyzed. Additionally, if the conditions of normal distribution tested in 1) are given, a repeated-measures analysis of covariance (ANCOVA) with the parameters described in 1) and the covariates (Score TKBV; VMIQ; Δ-HRV) was calculated separately for each of the three covariates.

To control for differences in muscle activation over imagery conditions, hypothesis 3), the pre-stimulus background EMG activity was compared between imagery conditions. Data was checked for normal distribution using a Shapiro-Wilk test. The RMS of EMG signals 500 ms before the TMG stimulus was checked separately for 0 N and 50 N for differences in mean values using a paired *t*-test over imagery conditions. For violation of normal distribution of the data, a Wilcoxon-test was used. Alpha level for all tests was set at 0.05.

2.5. Deviations from preregistration

Compared to preregistration, the tense in introduction and especially methodology were adjusted (from future to past tense). Furthermore, a few parts of text have been reworded to increase readability, however, the content has never been changed. For example in Section 2.1. *Subjects* we changed "A weighted average of the reported effect size partial η^2 and participants of the study was computed." into "A weighted average of the reported effect size partial η^2 according to the number of participants in the studies was computed."

As calculated previously, 45 persons were measured. After filtering outliers (using the sample size calculation described in Section 2.1. *Subjects*), there were 40 remaining participants for the main analyses.

In addition to methodology, the values of the covariates for the ANCOVAs were centered (subtracting the mean covariate score from each covariate score) first (Schneider et al., 2015).

3. Results

Results are presented in line with the hypotheses formulated in Section 2.4. *Statistical analysis.* Following the power analysis (see Section 2.1. *Subjects*), 45 volunteers (21 female, 24 male, M_{age} 24.9 ± 3.7 years) participated in this study. After removing outliers with the MAD method (for more details, see Section 2.4. Statistical analysis), calculations were carried out with $n = 40$ participants for D_m and V_c and $n = 37$ participants for T_d. EMG data of two participants were excluded from the analysis due to technical problems. Table 1 reports the means and standard deviations of TMG parameters and Table 2 displays the results of the tasks measuring imagery ability.

Hypothesis 1): Shapiro–Wilk tests showed no violation of the normal distribution for D_m and T_d ($p \geq .05$) over all conditions. However, there was a violation of the normal distribution for V_c in the VI 0 N condition ($p = .018$).

A repeated-measures ANOVA showed a significant main effect of effort on D_m, $F(1, 39) = 1142.73$, $p < .001$, $\eta^2 = 0.967$, with higher values for 0 N than for 50 N (see Fig. 3a). There was no significant interaction between effort and imagery, $F(1, 39) = 0.002$, $p = .962$, $\eta^2 < 0.000$, and no main effect of imagery, $F(1,39) = 0.19$, $p = .660$, $\eta^2 = 0.005$. There was a significant main effect of effort on T_d, $F(1, 36) = 17.32$, $p < .001$, $\eta^2 = 0.325$, and a main effect of imagery, $F(1, 36) = 4.99$, $p = .032$, $\eta^2 = 0.122$, with shorter delay times for 50 N and MI (see Fig. 3b). There was no significant effort and imagery interaction, $F(1,$

Table 1
Means (*M*) and standard deviations (*SD*) for the tensiomyographic parameters radial displacement (D_m), contraction velocity (V_c), and delay time (T_d) for the imagery and effort conditions.

TMG-variable	Imagery	Effort	*M*	*SD*
D_m [mm] $n = 40$	VI	0 N	14.47	2.67
		50 N	1.96	0.85
	MI	0 N	14.39	2.65
		50 N	1.89	0.86
V_c [mm/ms] $n = 40$	VI	0 N	0.435	0.08
		50 N	0.035	0.01
	MI	0 N	0.424	0.11
		50 N	0.034	0.01
T_d [mm] $n = 37$	VI	0 N	28.10	3.40
		50 N	25.62	2.12
	MI	0 N	27.46	2.47
		50 N	25.04	2.54

Table 2
Means (*M*) and standard deviations (*SD*) of the German test of the Controllability of Motor Imagery (TKBV), Vividness of Movement Imagery Questionnaire (VMIQ-2), heart rate variability (RMSSD), heart rate (HR), and root-mean square EMG (RMS) during motor and visual imagery for all participants ($n = 45$).

Imagery tasks	Variable	*M*	*SD*
TKBV	Score	43.80	3.29
	Time [s]	2.54	1.39
VMIQ-2 Score	Internal	22.64	7.77
	External	20.60	6.35
	Kinesthetic	22.67	7.49
	Overall	21.97	6.29
HRV	VI RMSSD [ms]	43.68	21.74
	VI HR [beats/min]	75.68	12.16
	MI RMSSD [ms]	32.55	17.30
	MI HR [beats/min]	80.58	13.73
EMG	MI RMS [mV]	0.0064	0.0033
	VI RMS [mV]	0.0058	0.0029

36) = 0.01, $p = .907$, $\eta^2 < 0.000$. Analysis of V_c also revealed no significant interaction between effort and imagery, $F(1, 39) = 3.08$, $p = .087$, $\eta^2 = 0.073$, but significant main effects of imagery, $F(1, 39) = 4.25$, $p = .046$, $\eta^2 = 0.098$, and effort, $F(1, 39) = 1006.32$, $p < .001$, $\eta^2 = 0.963$, with higher values for VI and 0 N (see Fig. 3c). Due to the violation of the normal distribution, a Friedmann test for V_c was calculated. This analysis indicated different velocities between conditions, $\chi^2(3) = 96.87$, $p < .001$. Post-hoc analysis was conducted with the Wilcoxon signed-rank test (Bonferroni-corrected). It appears that imagery did not significantly change V_c for both 0 N, $Z = 0.10$, $p = 1.0$, and 50 N, $Z = 0.25$, $p = 1.0$. However, there were statistically significant reductions of velocity in the 50 N condition in MI, $Z = 2.08$, $p < .001$, and VI, $Z = 1.93$, $p < .001$.

Hypothesis 2): Table 3 reports Spearman correlations between any of the TMG (D_m, T_d, V_c) variables with each of the three tests for imagery ability (Score TKBV, VMIQ-2, Δ-HRV).

Table 4 presents the results of the repeated-measures analysis of covariance with imagery and effort conditions and the respective covariates (TKBV or VMIQ or Δ-HRV) for D_m or T_d. No analysis with the parameter V_c was conducted due to the violation of the normal distribution.

Hypothesis 3): Due to the violation of the normal distribution in the EMG data for MI ($p = .037$) and VI ($p = .005$), we used a Wilcoxon test. There was no significant difference in EMG between VI and MI, $z = -0.652$, $p = .514$.

4. Discussion

The objective of this study was to investigate whether muscle contractility is influenced by imagery (visual imagery of a landscape, VI; imagery of maximal isometric contraction of the bicepcs brachii, MI), and whether imagery and effort conditions interact. Analyses showed no interaction between imagery and effort conditions for all analyzed parameters. Neither D_m, T_d, nor V_c suggest that imagery is affected by the change in physical effort. We hypothesized that low muscle activation would cancel the inhibition of the MI signal and that this would lead to stronger signals reaching the muscle. However, this could not be confirmed for acute effects. Nonetheless, in another intervention study, Jiang et al. (2017) showed that low-effort strength training combined with a simultaneous imagination of maximal contraction did lead to higher strength gains. Hence, there is either no acute interaction effect between imagery and effort on muscle properties or effort dominates the imagery effect. Our study corroborates the strong effect of effort on muscular contractility. All three TMG parameters revealed a main effect of effort with high values for partial eta squared (D_m: $\eta^2 = 0.967$, T_d: $\eta^2 = 0.325$, and V_c: $\eta^2 = 0.963$). The 50 N condition did not actually appear to be a low activation, but rather quite a high percentage of maximum strength for some participants ($M = 44.3\%$, SD: ± 15.7). This circumstance explains why the effort condition shows such a large effect and could also be the reason why the imagery effect was dominated by the effort effect. In future studies, an individual percentage of maximum strength could be chosen to provide better comparability of muscle activation. Another aspect to be considered in the 50 N condition is that the second task (effort task) may distract the participants from the imagination, since they have to watch a screen and pull the biceps curler. This speculation, however, is not confirmed by the subjective rating of the participants: Comparing their ratings of vividness between the MI 0 N ($M = 1.9$, $SD = 0.67$) and MI 50 N ($M = 1.9$, $SD = 0.76$) condition, no significant difference is shown $t(39) = -0.24$, $p = .81$.

The TMG parameters T_d and V_c differed between imagery conditions. Because V_c did not follow a normal distribution, we calculated a Friedman test. A robust change of V_c cannot be assumed due to the lack of any main effect of imagery combined with a low effect size ($\eta^2 = 0.098$) in the ANOVA. Our participants showed no effect of imagery for D_m and V_c, – both parameters describing characteristics of muscle contraction – whereas T_d represents the initiation of contraction. Therefore, our results could indicate that the signal generated during MI is not high enough to trigger or even influence muscle contraction, which, in addition to the parameters D_m and V_c, is also shown by the unchanged EMG activity during MI (see also Yue and Cole, 1992; Mercier et al., 2008; Aoyama and Kaneko, 2011).

As hypothesized, there is a reduction in delay time due to MI. This indicates a faster transmission of the electrical impulse via the TMG stimulator across the muscle. T_d is influenced by the predominant fiber type in the respective skeletal muscle structure, its degree of fatigue, and its activation level (García-Manso et al., 2011). Considering our within-subject design, the impact of fiber type could not be a major focus. To keep fatigue comparable across conditions, one half of the participants started with VI and the other half with MI. Thus, fatigue should not have had a major discriminative impact. Hence, the reduction of T_d due to MI could be related to a change in muscle-activation level.

There seems to be an incomplete inhibition on the spinal level indicated by the decreased delay time in MI. Grosprêtre et al. (2019) postulated that it is not the α-motoneuron itself, but more sensitive structures, i.e., the spinal presynaptic network, that are involved during MI. They also hypothesized that there might be a small neurotransmitter release of the synapse during mental practice that is not sufficient to modulate spinal excitability. The reduced delay time would seem to support this hypothesis that the neurotransmitter release is too small to cause changes in muscle contraction, but is large enough to accelerate the initiation of the contraction. This indicates that the ideo-motor principle can be at least partially supported by our results. It seems that fragmentary signals are sent out during MI, but the signals seem to be too weak to influence the muscle contraction itself but the gating of the muscle contraction.

Adjunct tests showed that participants were able to generate vivid

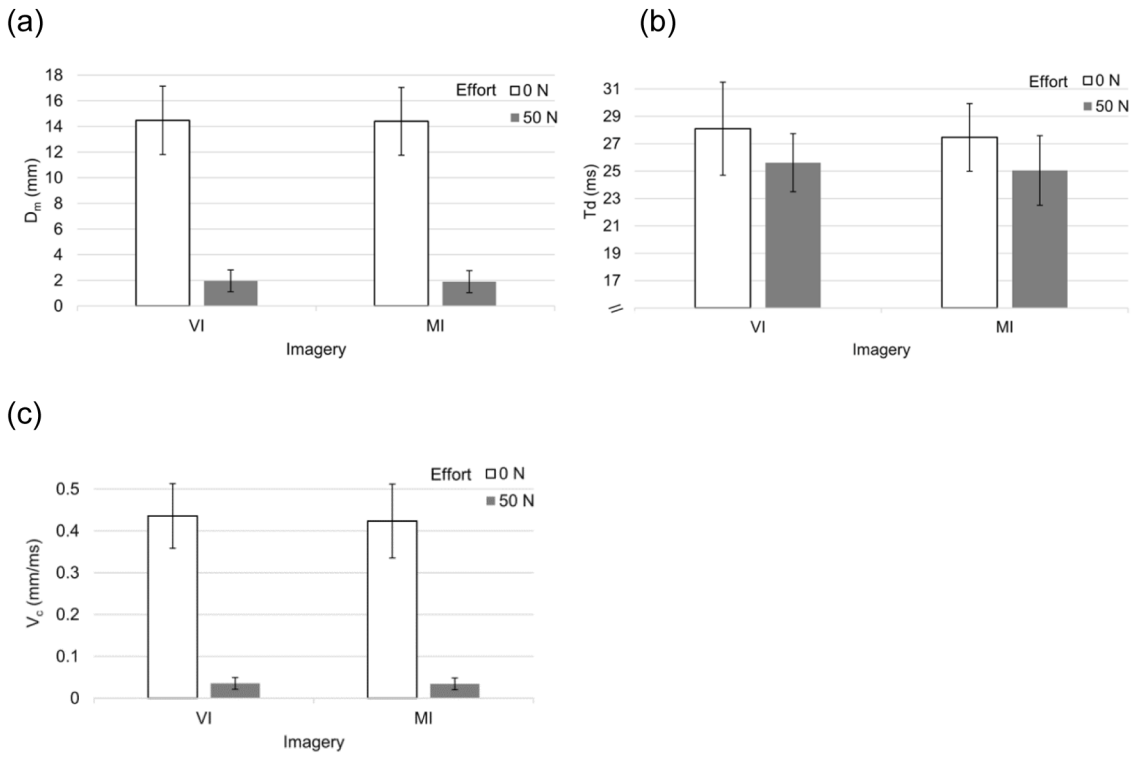

Fig. 3. Results of TMG parameters for all imagery and effort conditions. Bars and error bars show means ±1 standard error of the mean. Graphs show results for (a) maximal radial displacement (D_m), (b) delay time between electrical impulse and 10% of the maximal displacement (T_d), and (c) contraction velocity as the calculated slope of the displacement curve over time (V_c).

Table 3
Spearman correlations between scores in imagery ability and percent change (VI to MI) of TMG parameters.

	% Change 0 N D_m	% Change 0 N T_d	% Change 0 N V_c	% Change 50 N D_m	% Change 50 N T_d	% Change 50 N V_c
	$n = 40$	$n = 37$	$n = 40$	$n = 40$	$n = 37$	$n = 40$
Score TKBV	0.153	0.117	−0.137	0.159	0.213	0.177
VMIQ	−0.239	0.040	−0.160	0.020	−0.067	0.075
Δ-HRV	0.131	0.129	0.214	0.315*	0.208	0.350*

* $p < .05$.

Table 4
Results of repeated-measures analysis of covariance (ANCOVA) with the parameters maximal radial displacement (D_m) and delay time (T_d) and the covariates (TKBV, VMIQ-2, Δ-HRV).

Imagery tasks	Within-subject effect	D_m			T_d		
		F (1, 38)	*p*	η^2	*F (1, 35)*	*p*	η^2
TKBV	Imagery	0.30	0.586	0.008	**4.72**	**0.037**	**0.119**
	Imagery × TKBV	1.54	0.222	0.039	1.97	0.169	0.053
	Effort	**1167.32**	**<0.001**	**0.968**	**16.69**	**<0.001**	**0.323**
	Effort × TKBV	1.86	0.181	0.047	0.77	0.386	0.022
	Imagery × Effort	0.02	0.899	0.000	0.03	0.871	0.001
	Imagery × Effort × TKBV	0.89	0.350	0.023	0.58	0.451	0.016
VMIQ-2	Imagery	0.19	0.663	0.005	**4.33**	**0.045**	**0.110**
	Imagery × VMIQ-2	0.07	0.794	0.002	0.58	0.450	0.016
	Effort	**1127.34**	**<0.001**	**0.967**	**16.22**	**<0.001**	**0.317**
	Effort × VMIQ-2	0.49	0.489	0.013	0.05	0.833	0.001
	Imagery × Effort	0.01	0.960	0.000	0.01	0.936	0.000
	Imagery × Effort × VMIQ-2	0.17	0.684	0.004	0.05	0.824	0.001
Δ-HRV	Imagery	0.11	0.748	0.003	**5.63**	**0.023**	**0.139**
	Imagery × Δ-HRV	0.35	0.566	0.009	2.12	0.155	0.057
	Effort	**1153.83**	**<0.001**	**0.968**	**16.93**	**<0.001**	**0.326**
	Effort × Δ-HRV	2.09	0.156	0.052	0.063	0.803	0.002
	Imagery × Effort	0.003	0.960	0.000	0.016	0.899	0.000
	Imagery × Effort × Δ-HRV	0.000	0.982	0.000	0.028	0.869	0.001

Bold values indicates statistically significant at $p < .05$.

images. The mean score on TKBV was 43.8, which is comparable to the data from Schott (2013) with highest values at around 45 in the 18- to 33-year-old age group. The VMIQ-2 results were comparable over all three conditions. Results indicate participants' vividness of imagery was clear and reasonably vivid. Mean change of HRV from VI to MI was −25 percentage points, indicating good and vivid motor imagery. Correlation analyses between values in imagery tests and changes of TMG parameters from VI to MI show only two significant relationships: that between Δ-HRV and D_m as well as that between Δ-HRV and V_c in the effort 50 N condition. The better the imagery, i.e., the greater change in HRV, the higher the increase of D_m and V_c from VI to MI in the 50 N condition. This indicates a relation between vivid imagery and changed contractility during imagery, but only in the 50 N effort condition. No significant correlations could be shown for TKBV and VMIQ-2 plus the 0 N effort condition for all TMG parameters. Comparing the results of the ANCOVA with those of the respective 2 × 2 ANOVA, it can be seen that the co-variable leads to small changes in explained variance. The largest change in imagery is shown for the variable T_d with the co-variable Δ-HRV, producing an increase in partial eta squared from 0.122 to 0.139. This small change as well as the results of the correlation analyses show that there are only minor associations between imagery ability and the effects of MI on contractility. Collet et al. (2011) combined the indices of different tests to generate an MI index supposed to reflect MI ability more adequately. Maybe such an index could be used to identify relations between imagery ability and its effectiveness, because a single test may not adequately cover the spectrum of imagery abilities.

Up to now, brain scans or reflex responses have been used to determine which influence MI has on cortical and spinal structure. Using H-reflex during MI did not produce manifest evidence on the spinal level (Grosprêtre et al., 2016). One possible reason for the conflicting results on the H-reflex could be that MI affects only sensitive structures but not the α-motoneuron (Grosprêtre et al., 2019). The results of this study, measuring acute effects of MI on the muscular system, support this idea. There are no changes in V_c and D_m. Those parameters describe the increase and maximal point of the displacement curve during muscle contraction. Both of these parameters are determined by the activation of the α-motoneuron. However, delay time (Td) describes the duration between stimuli and muscle contraction. Therefore, it can be used as indicator for muscle responsiveness and may be influenced by increased cortical output during MI, which decrease the initiation time of muscle contraction. Thus, with this parameter, a neural influence of MI on the muscle can be observed. But this measuring method cannot determine exactly which neuronal structures are influenced by MI. For this, the results have to be associated to other studies e.g. Grosprêtre et al. (2019). Furthermore, it cannot be precluded that long-term strength gains may also be due to an improved movement planning.

It will be interesting to see whether the reduced delay time is only an acute effect of MI, or whether there is also a long-term adaptation due to MI training.

5. Conclusion

In summary, the present study shows that MI does not change the contraction itself, but its neuronal initiation. There is no interaction effect between imagery and effort, but an imagery effect on delay time. This indicates that signals generated during MI do not activate the α-motoneuron itself, but other structures such as interneurons that might impact on the initiation of the contraction. In addition, it seems that quality of imagery has no influence on MI effects.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

Annotation

See https://osf.io/hjuv6/ for the approved Stage 1 protocol.

Data availability

All data are publicly available:https://osf.io/nz5f8/; DOI 10.17605/OSF.IO/NZ5F8

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