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Acute Stress Does Not Affect Motor Imagery Ability in Young, Healthy Participants: A Randomized Trial

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ABSTRACT

Motor imagery (MI) is the mental representation of a movement without its execution. It activates internal representations of the movement without external stimulus through different memory-related processes. Although acute stress is frequent in the population and affects supraspinal structures essential for memory functionality, it is still unknown how that stress affects MI capacity and temporal congruence (TC) between execution and movement imagination. This study aimed to discover how acute stress may influence MI capacity and TC in the subscales of internal and external visual imagery and kinesthetic imagery. A double-blind, randomized trial was conducted. Sixty-two young, healthy subjects (mean age = 20.65 [2.54]; 39 females and 23 males) unfamiliar with the assessment and uses of MI were recruited. Participants were assigned by stratified randomization to the stress group or the control group. Stress was induced by the Maastricht Acute Stress Test (MAST), while the control group performed the MAST control protocol. MI capacity and TC were assessed before (t1) and after (t2) MAST stress or control using the Movement Imagery Questionnaire-3 (MIQ-3). Electrodermal activity and heart rate variability were further recorded as control variables to assess stress induction. Thirty subjects in the stress group and 26 subjects in the control group were analyzed. No significant group differences were observed when comparing MI capacity or TC in any subscales. These findings suggest that acute stress does not significantly affect MI capacity or TC in young, healthy, non-experienced MI subjects. MI could thus be a relevant helpful technique in stressful situations.

1 | Introduction

Motor imagery (MI) is the mental representation of a movement or action without actual body movement [1, 2]. It is a complex cognitive process without external stimulus involving memory mechanisms, during which internal movement representations are activated [1]. Accordingly, the dorsolateral prefrontal cortex, whose activity is closely related to working memory [3], has been found to be activated during MI [4]. Likewise, the hippocampus, which is critical for memory processes, has also been shown to be involved in imagery processes [5]. Overall, looking at the neurophysiological architecture of MI reveals that similar brain regions are activated during MI and actual movement execution [4]. Because of their functional correspondence, MI practice has

thus been recommended as a relevant technique to improve motor learning and performance, both in sports and various rehabilitation contexts [1, 2, 6]. Therefore, there has been a growing interest in the research and clinical field during the last two decades, to generate guidelines for effective interventions with MI [7].

For an MI intervention to be effective and to elaborate appropriate and relevant imagery training programs, the individual's MI ability must be thoroughly assessed. MI is a multidimensional construct [8], and the objectivation of its content is a challenge due to its concealed nature. Among the approaches that can be used to evaluate its accuracy [8], the individual imagery ability can be assessed by self-reported questionnaires, which assess the capacity to generate the mental image of the movement, or by the mental chronometry paradigm, which assesses the capacity to maintain temporal congruence (TC) between MI and corresponding physical practice [9]. MI capacity and TC relevantly complement each other and should be examined for a complete assessment of MI ability [9, 10]. Interestingly, it allows a distinct assessment of internal visual imagery (IVI), external visual imagery (EVI), and kinesthetic imagery (KI) abilities. Such distinction appears a critical issue, as even though all imagery modalities remain related constructs, evidence showed that they are mediated by different neural networks [11, 12]. Because practice can rapidly improve the ability to imagine [1], low scores on self-reported questionnaires and difficulties in maintaining the TC between actual practice and MI should not preclude imagery interventions, as long as the participant can generate the mental image of the movement.

Researchers have extensively found that MI can positively affect certain emotional states, including stress [13]. However, few researches have investigated whether stress affects MI ability. Stress can be considered a state of homeostasis threat that arises when the demands of the environment exceed the organism's capacity to adapt so that physiological and behavioral changes take place to maintain that dynamic balance between autonomic divisions [14]. Following exposure to a stressful stimulus, an immediate response of the sympathetic nervous system (SNS) and a slow reaction of hypothalamus-pituitary–adrenal axis (HPA) activation occurs [15–18]. Consequently, adrenalin and cortisol are released, which contributes to modifying the activity of supraspinal structures such as the hippocampus, amygdala, and prefrontal cortex [16]. Thus, although many studies have supported the adverse effects of acute stress on memory [19–21], other studies have found no such negative effects depending on factors such as the time elapsed between the stressor and the evaluated task [22, 23] or the complexity of the evaluated task [24, 25]. In addition, the stress response relates to the type of stressor. Physical and cognitive stressors elicit robust SNS responses, and psychosocial stressors similarly activate the SNS and the HPA axis [15, 18].

The pilot study by Schlatter et al. [26] specifically explored the influence of acute stress on implicit and explicit MI. Implicit MI involves mentally representing actions without receiving specific MI instructions, and a mental rotation task assessed it. During explicit MI, subjects are requested to perform MI through concrete instructions, so it was evaluated by a sequential pointing task in which subjects were asked to complete the task physically and then imagine it by combining the visual and kinesthetic imagery modalities. Using the socially evaluated cold pressor test, Schlatter et al. [26] reported a negative influence of stress on the implicit MI, but not on the explicit MI task.

Stress is common among people who receive physiotherapeutic treatment and may also be good candidates for the MI approach. Acute stressful situations can occur in different rehabilitation settings since injury or disease situations can be physical and psychological stressors for patients. Similarly, the pain resulting from these conditions can also be a psychological stressor [14]. As some authors point out, the physiotherapist should consider psychological stress because it can affect the effectiveness of treatment [27]. Also, in sports, besides because of injuries [28], acute stress can frequently appear in critical moments for athletes, such as during pre-competition or competition [29]. In those situations, athletes use MI more frequently and freely [30], moments when the frequency of injuries increases [31]. The increasing use of MI in these contexts makes it necessary to deeply explore whether acute stress with physical and psychological components may affect MI ability as well as the capacity to appropriately use distinct MI modalities.

Spurred by these pilot results, the present study sought to determine how acute stress may influence MI capacity on the subscales IVI, EVI, and KI and the TC between executed and imagined movement in participants with no MI experience. We hypothesized that there will be no differences between participants who are induced acute stress and those who are not induced acute stress in IVI, EVI, and KI capacity, and TC between executed and imagined movement.

Knowing these issues would allow establishing a starting point to explore whether MI can be an equally effective technique in different acute stress situations, in which MI can be used to improve motor learning and performance. This study contributes to determine appropriate clinical and experimental guidelines for designing more effective MI interventions.

2 | Methods

2.1 | Design

We conducted a double-blind, randomized trial. The test subject was unaware of what the other subjects were doing. An investigator blinded to the intervention was in charge of analyzing the data.

Stratified allocation using the sex stratum accomplished randomization to ensure that the proportion of males and females was homogeneous in all groups. Thus, we attempted to achieve balanced groups and completed the sample that males did not fill with females to obtain the appropriate sample size within each group. Simple random allocation (1:1) to the intervention groups (stress or control) was performed within each stratum using the Epidat 4.2 program. We placed the randomization results in sealed envelopes that the investigator in charge of the experiments opened during the study.

The study obtained the favorable opinion of the Ethics Committee of Research and Animal Experimentation of the University of

Alcalá (CEID2022/2/036). It was registered in the ClinicalTrials.gov clinical trials database (NCT04912713).

2.2 | Participants

The study sample consisted of 62 young healthy subjects (mean age = 20.65 [2.54]; 39 females and 23 males) with normal or corrected vision and hearing. All were unfamiliar with the assessment and use of MI. Exclusion criteria included traumatic processes in the last 6 months; visual, motor or right/left-handedness disorders; history of any neurological, cardiovascular, or myopathic disease; intake of any medication that interferes with the nervous system; lesions or skin diseases located in the areas of placement of the physiological measurement devices used during the experiment; and the presence of trait or state anxiety scores as assessed by the State–Trait Anxiety Inventory (STAI) (percentile ≥75%) [32].

Due to the novel characteristics of the study, the sampling structure was unknown, so we estimated the sample size based on a confidence level of 95% ($Z_\alpha = 1.96$), an estimated variance of 10%, and an accuracy of 5%. Afterward, a loss proportion of 20% was estimated, setting the minimum sample size per intervention group at 20 subjects, later set at 30 subjects per intervention group to increase the power size of the study. Participants were recruited from the University of Alcalá and the Complutense University of Madrid by consecutive nonprobability sampling from June 2021 until the end of the sample in September 2022. All participants voluntarily participated in the experiment after reading the Information Sheet and signing the Informed Consent in accordance with the Declaration of Helsinki.

2.3 | Materials and Variables

2.3.1 | Movement Imagery Questionnaire-3

MI capacity and TC were assessed using the Spanish version of the Movement Imagery Questionnaire-3 (MIQ-3), validated in the young population [12, 33]. Williams et al. [10] suggested that the MIQ-3 is a good candidate for MI and TC assessments.

The MIQ-3 consists of 12 items distributed in three subscales, which, respectively, measure the capacity of IVI, EVI, and KI. Thus, in each subscale, the same four movements are repeated: flexion and extension of the knee and hip of the right lower limb from standing position, jumping, horizontal adduction of the non-dominant upper limb and going to touch the feet with the hands through hip flexion from standing position. After physically executing each item, participants must imagine the same movement in the required subscale and then score the ease of imagining on a 7-point Likert scale, where higher scores represent greater ease [12]. The dependent variable for measuring MI capacity was the score obtained on the MIQ-3 in each subscale and over the total scale.

On the other hand, TC refers to the temporal course of action [15] and is considered a semi-objective measure. To evaluate the TC, the researcher conducting the experiment used a stopwatch to record the duration of the execution and imagination of each movement. Subsequently, the dependent variable discrepancy time was calculated by finding the absolute value of the difference between execution and imagination times. Discrepancy times were calculated for each subscale and the total scale.

2.3.2 | Stress Induction—Maastricht Acute Stress Test

The Maastricht acute stress test (MAST) is a noninvasive protocol that induces acute stress by combining psychological (psychosocial evaluative threat, uncontrollability, and unpredictability) and physical (sensation of pain through intense cold) stress components. It has a preparatory phase of 5 min and an experimental phase of 10 min. The MAST reliably generates solid subjective, autonomic, and neuroendocrine stress responses, lasting up to 20–30 min after protocol termination. Additionally, there is a validated non-stressful counterpart protocol to MAST (MAST control) [18].

2.3.3 | Dependent Variables to Control Stress Induction

Physiological data were recorded to confirm that a significant stressor effect occurred in the stress group and that no such effect occurred in the control group. Electrodermal activity (EDA) and heart rate variability (HRV) were measured using the Empatica E4 portable wrist device (Empatica, Milan, Italy). The E4 has demonstrated the capacity to detect changes in these parameters under stress [34].

The EDA, measured as skin conductance in microsiemens, was recorded with a sampling frequency of 4 Hz. Subsequently, a continuous decomposition analysis of the signal [35] was performed with the free software Ledalab version 3.4.9., run in Matlab version 2022b (Mathworks, Natick, Massachusetts, USA). The tonic component of the EDA was used as the dependent variable. Higher values represented greater autonomic nervous system activation (ANS) [14].

Blood volume pulse data, necessary for HRV calculation, was collected by photoplethysmography with a sampling rate of 64 Hz. Subsequently, the data were analyzed in the frequency domain using Kubios HRV Premium software version 3.5.0., as recommended by Empatica. To obtain a comparable measure across participants [36], the estimated relative power was calculated in normalized units (n.u.) for the low frequency (LF) (0.04–0.15 Hz) and high frequency (HF) (0.15–0.4 Hz) bands, as well as the LF/HF ratio. LF has been associated primarily with the sympathetic system, and HF with the parasympathetic system, as well as high values of the LF/HF ratio reflect sympathetic dominance and low values parasympathetic dominance [36]. The normalized LF, HF, and LF/HF ratio values were used as dependent variables.

2.4 | Procedure

2.4.1 | Preliminary Assessments and Participant Flow

A total of 68 subjects were recruited for the study. After signing the Informed Consent, the subjects completed an initial questionnaire and the STAI to verify that they met the inclusion

criteria and to collect the sociodemographic characteristics of the sample. The final study sample consisted of 62 participants, who were randomized to the stress group ($n = 32$) and the control group ($n = 30$). Finally, data from 30 subjects in the stress group and 26 subjects in the control group were analyzed. Figure 1 contains the Flow diagram.

2.4.2 | Experimental Session

All participants were required to avoid ingesting caffeine, theine, alcohol, opiates, tranquilizers, hypnotics, and other substances that could affect the nervous system during the 8 h before the experimental session.

During the experimental session, after recording the time the experiment started, the E4 was placed in the subjects' non-dominant hands following the placement protocols indicated by the manufacturer. First, the experimenter gave basic and homogenized instructions to all subjects about the types of MI. Then, the experimenter showed an example of performing the task for them to understand the task but not practice it. Subsequently, subjects performed the MIQ-3 for the first time (moment t1) while the experimenter recorded with a stopwatch the execution and imagination times to the subjects' "start" and "stop" commands in each of them. Subjects then performed the MAST (stress or control) protocol with their dominant hand. After 20 min from the stressor's onset, participants performed the MIQ-3 for the second time (moment t2) while the experimenter recorded the execution and imagination times with a stopwatch. Finally, the E4 device was removed.

2.5 | Statistical Analysis

We used the free software RStudio version 2022.02.3 to perform all statistical analyses.

We checked the normality of the variables. After calculating the lambda parameter by maximum likelihood estimation, we performed logarithmic Box-Cox transformations on the dependent

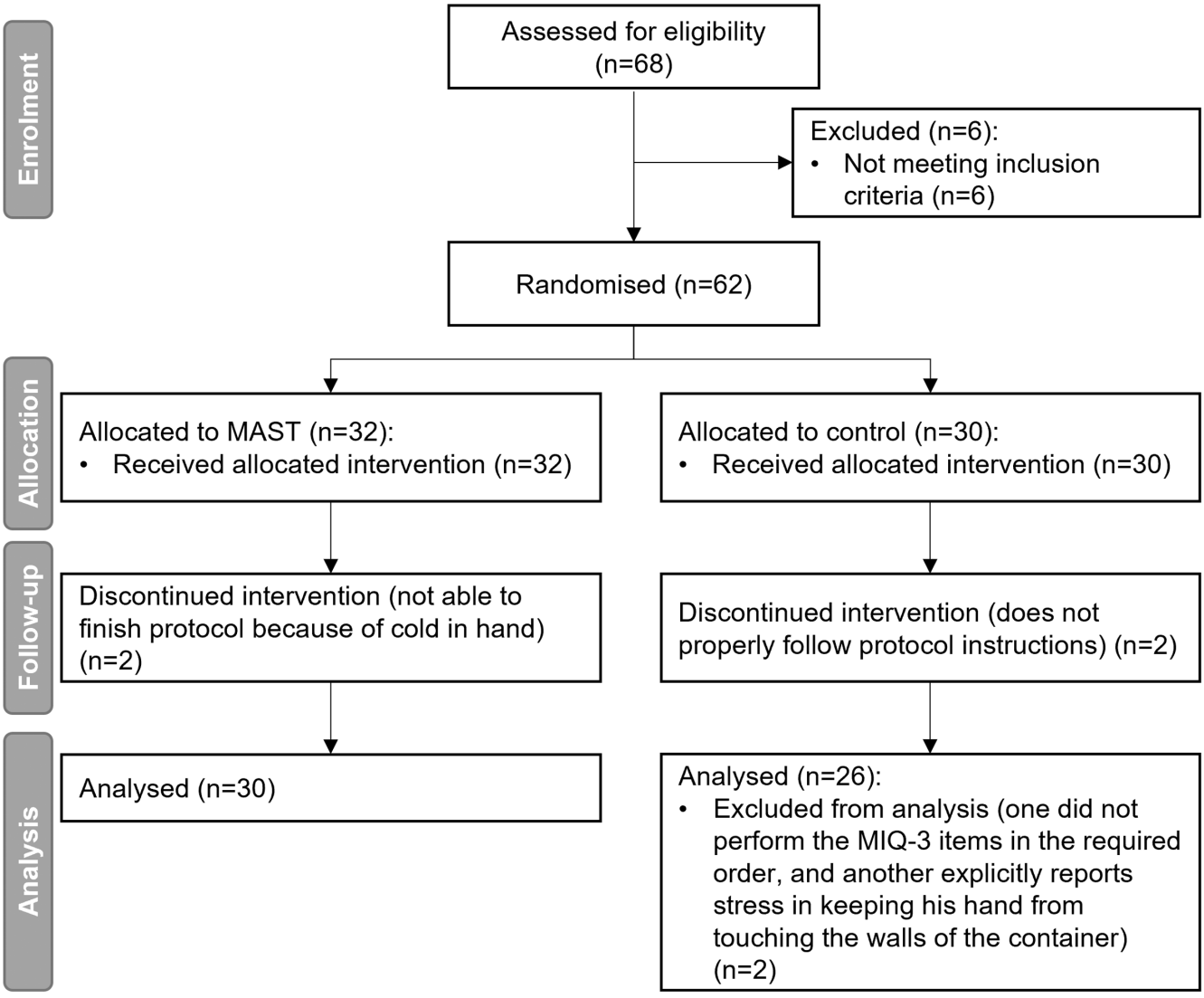

FIGURE 1 | Flow diagram of study participants according to CONSORT criteria. MAST, Maastricht Acute Stress Test; MIQ-3, Movement Imagery Questionnaire-3; *n*, sample.

variables that did not meet the normality assumption. These steps allowed us to apply parametric tests.

We studied the homogeneity of the groups by calculating the χ^2 for qualitative variables, using the Mann–Whitney *U*-test for non-normal quantitative variables and *t*-tests for independent samples for normal, homoscedastic quantitative variables. We found the stress and control groups to be homogeneous in MIQ-3 scores and discrepancy times in all subscales and at the global level before the MAST protocol (t1), ensuring the equality of the groups before the intervention.

We analyzed the effects of stress induction using a mixed factorial ANOVA on the dependent variables of EDA, LF, HF, and LF/HF ratio. For this purpose, we analyzed the intrasubject factor PERIOD (MAST start, MAST end) and the intersubject factor GROUP (control, stress).

Using mixed factorial ANOVA, we analyzed the dependent variables related to MIQ-3 scores and discrepancy times. In both cases, for the analyses in the subscales, we analyzed the intrasubject factors SUBSCALE (IVI, EVI, KI) and MOMENT (t1, t2) and the intersubject factor GROUP (control, stress). For the overall MIQ-3 analyses, we analyzed the intrasubject factor MOMENT (t1, t2) and the intersubject factor GROUP (control, stress). In all ANOVAs, we set the type I error at an $\alpha = 5\%$ level and calculated eta-squared effect sizes (η^2). We interpreted these as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$) effect sizes. We performed post hoc multiple comparisons *t*-tests with Bonferroni correction for significant outcomes and calculated effect sizes through Cohen's (*d*). We interpreted these values as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$).

3 | Results

3.1 | Sample Characteristics and Homogeneity Between Groups

The groups were homogeneous. Baseline comparisons indicated no significant differences between the groups, equivalent at t1 in their MIQ-3 scores and discrepancy times (Table 1).

3.2 | Stress Induction

The analysis of physiological variables was possible in 25 subjects of the control group and 20 subjects of the stress group in the case of EDA (80% of the analysis subjects) and of 23 subjects of the control group and 20 subjects of the stress group in the case of HRV (77% of the analysis subjects).

The mixed factorial ANOVA for EDA showed a significant main effect of group ($F(1, 43) = 7.58, p = 0.009, \eta^2 = 0.144$), period ($F(1, 43) = 5.75, p = 0.02, \eta^2 = 0.006$), and group × period interaction ($F(1, 43) = 20.57, p < 0.001, \eta^2 = 0.02$). Post hoc multiple comparisons revealed no significant differences between groups at the MAST start period and did show significant differences ($p < 0.001, d = -1.16$) of EDA at the MAST end period between the control group ($M = 2.03$; SD = 2.75) and the stress group ($M = 6.17$; SD = 4.53). Significant differences ($p < 0.001, d = -0.9$) were also found within the stress group between the MAST start ($M = 4.21$; SD = 4.12) and MAST end ($M = 6.17$; SD = 4.53) periods (Figure 2A).

The mixed factorial ANOVA for LF showed a significant main effect of period ($F(1, 41) = 6.175, p = 0.017, \eta^2 = 0.037$), and group × period interaction ($F(1, 41) = 4.743, p = 0.035, \eta^2 = 0.028$). The analysis showed no significant main effect of group. Post hoc multiple comparisons revealed significant differences ($p = 0.015, d = -0.61$) of LF within the stress group between MAST start ($M = 50.4$; SD = 20.7) and MAST end ($M = 64.1$; SD = 14.8) periods.

Mixed factorial ANOVA for HF showed a significant main effect of period ($F(1, 41) = 6.182, p = 0.017, \eta^2 = 0.037$), and group × period interaction ($F(1, 41) = 4.751, p = 0.035, \eta^2 = 0.029$). The analysis showed no main effect of group. Post hoc multiple comparisons revealed significant differences ($p = 0.014, d = 0.61$) of HF within the stress group between MAST start ($M = 49.5$; SD = 20.7) and MAST end ($M = 35.9$; SD = 14.8) periods.

Mixed factorial ANOVA for the LF/HF ratio showed a significant main effect of period ($F(1, 41) = 5.697, p = 0.022, \eta^2 = 0.033$), and group × period interaction ($F(1, 41) = 4.557, p = 0.039, \eta^2 = 0.026$). The analysis showed no main effect of group. Post hoc multiple comparisons revealed significant differences ($p = 0.016, d = -0.59$) of the LF/HF ratio within the stress group between MAST start ($M = 1.48$; SD = 1.25) and MAST end ($M = 2.36$; SD = 1.60) periods. In addition, post hoc multiple comparisons showed no significant differences between groups at the MAST start period in any of the HRV variables (Figure 2B–D).

3.3 | MI Capacity

Mixed factorial ANOVA for the analysis of MIQ-3 scores by subscales showed a significant main effect of subscale ($F(2,108) = 7.75$, $p < 0.001$, $\eta^2 = 0.06$) and moment ($F(1, 54) = 23.2, p < 0.001$, $\eta^2 = 0.01$), but no significant main effects of group or the various interactions between factors. Post hoc multiple comparisons (Figure 3) revealed a significant difference ($p = 0.001, d = 0.47$) between IVI ($M = 5.38$; SD = 1.02) and KI ($M = 4.87$; SD = 1.16) and a significant difference ($p < 0.001, d = 0.56$) between EVI ($M = 5.49$; SD = 1.03) and KI, as well as showing a significant difference ($p < 0.001, d = -0.41$) between t1 ($M = 5.14$; SD = 1.09) and t2 ($M = 5.36$; SD = 1.11).

Mixed factorial ANOVA for MIQ-3 total score showed a significant main effect of moment ($F(1, 54) = 23.2, p < 0.001, \eta^2 = 0.02$), but showed no significant main effects of group or group × moment interaction. Post hoc multiple comparisons revealed a significant difference ($p < 0.001, d = -0.66$) between t1 and t2.

3.4 | Temporal Congruence

Mixed factorial ANOVA for the analysis of MIQ-3 subscale discrepancy times showed a significant main effect of moment ($F(1, 53) = 30.46, p < 0.001, \eta^2 = 0.06$), but no significant

TABLE 1 | Sample characteristics and homogeneity of the groups (control vs. stress).

	Control ($n = 26$)	Stress ($n = 30$)	Statistical	p
Sex			X^2	0.95
Female	18 (69%)	21 (70%)		
Male	8 (31%)	9 (30%)		
Age	19.5 (18; 21.8)	19 (18; 20)	Mann–Whitney U	0.65
STAI (percentile)				
State	35.3 (17.7)	32.7 (17.3)	t-test	0.58
Trait	37.5 (26.2; 55)	45 (24.5; 58.8)	Mann–Whitney U	0.84
Time of day (h)	13:00 (2:53)	12:18 (2:13)	t-test	0.29
MIQ-3 score—t1				
IVI	5.36 (0.81)	5.22 (1.10)	t-test	0.62
EVI	5.33 (1.01)	5.43 (1.10)	t-test	0.71
KI	4.97 (1.01)	4.56 (1.25)	t-test	0.18
Global	5.22 (0.74)	5.07 (0.76)	t-test	0.47
Discrepancy time (s)—t1				
IVI	1.63 (0.85)	2.01 (1.07)	t-test	0.16
EVI	1.68 (0.84)	1.78 (0.73)	t-test	0.52
KI	1.70 (0.72)	1.68 (0.8)	t-test	0.92
Global	1.67 (0.69)	1.82 (0.72)	t-test	0.36

Note: Values expressed as n (%), median (Q_1; Q_2), or mean (SD).
Abbreviations: EVI, external visual imagery; IVI, internal visual imagery; KI, kinesthetic imagery; MIQ-3, Movement Imagery Questionnaire-3; n, sample; Q_1, first quartile; Q_3, third quartile; SD, standard deviation; STAI, State–Trait Anxiety Inventory; t1, moment t1.

main effects of group, subscale, or the various interactions between factors. Post hoc multiple comparisons (Figure 4) revealed a significant difference ($p < 0.001, d = 0.63$) between t1 ($M = 1.75$; SD = 0.842) and t2 ($M = 1.39$; SD = 0.81).

Mixed factorial ANOVA for the discrepancy times of the overall MIQ-3 items showed a main effect of moment ($F(1, 53) = 31.41, p < 0.001, \eta^2 = 0.084$), but no main effects of group or group × moment interaction. Post hoc multiple comparisons revealed a significant difference ($p < 0.001, d = 0.77$) between t1 and t2.

4 | Discussion

The present study sought to find out how acute stress might influence the capacity for motor imagery (MI) on the internal visual imagery (IVI), external visual imagery (EVI), and kinesthetic imagery (KI) subscales, as well as the temporal congruence (TC) between executed and imagined movement in participants with no MI experience. Data revealed no significant differences in MI capacity or TC when comparing acutely and non-acutely stressed participants on any IVI, EVI, and KI subscales of the Movement Imagery Questionnaire-3 (MIQ-3).

The present results confirmed our initial hypothesis and are congruent with the pilot study of Schlatter et al. [26], where acute stress exposure did not degrade explicit MI. Our data are also consistent with studies reporting that the memory processes involved in MI are not negatively affected by acute stress when there is a time interval between the stressor and task evaluation [22] or when the cognitive load of the task is low [24, 25].

Thus, the absence of significant differences in MI ability between stressed and non-stressed participants in the present study could be explained by the time interval between the onset of the stressor and the evaluation of the MI task (20 min). Following stress exposure, sympathetic activation of the autonomic nervous system (ANS) and hypothalamus–pituitary–adrenal axis (HPA) takes place, with a progressive increase in cortisol levels in the bloodstream [15–18]. However, cortisol does not peak in the blood until 20–30 min after the stressor's onset [18], when the stress response corresponds primarily to the HPA axis. Thus, as pointed out by Xin et al. [21], the adverse effects of acute stress in studies exploring its influence on memory could be related to the concurrent activation of the ANS and HPA axes immediately after the stressor. Likewise, the study by Elzinga et al. [22] showed that memory was impaired when increased cortisol levels and adrenergic activity occurred but not when adrenergic activity had stabilized, suggesting that sympathetic nervous system (SNS) activation is crucial for acute stress to have adverse effects on memory. Thus, most previous studies that have shown adverse effects of acute stress on memory assessed the task immediately after acute stress induction [19, 20] or shortly after acute stress

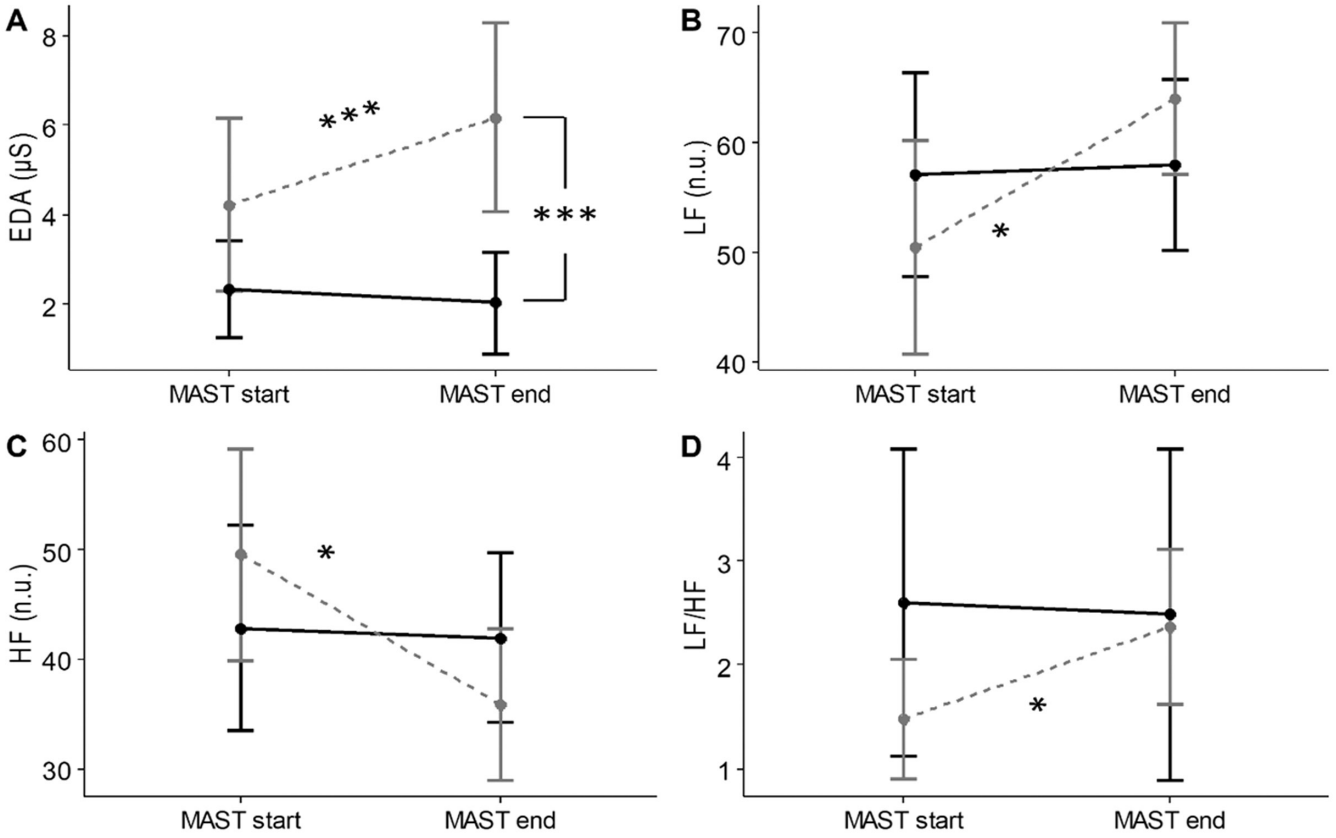

FIGURE 2 | Interaction between GROUP (solid black line: Control group; dashed gray line: Stress group) and PERIOD (MAST start; MAST end). Error bars represent 95% confidence intervals. Significant differences with $p < 0.05$ represented by one asterisk (*) and significant differences with $p < 0.001$ represented by three asterisks (***). (A) Tonic electrodermal activity (EDA). (B) Low frequency (LF). (C) High frequency (HF). (D) Low frequency/high frequency ratio (LF/HF). MAST, Maastricht acute stress test; μS, microsiemens; n.u., normalized units.

exposure [21]. However, our results are in line with the studies of Oei et al. [24] and Lai et al. [25], where the memory task was assessed at 20 min after the stressor's onset, and no adverse effects of stress on the task were found either. Similarly, in the study by Schlatter et al. [26], the explicit MI task was assessed between 15 and 22 min after the onset of the stressor, and no adverse effects of acute stress on the imagery task assessed were seen either, again coinciding with the results obtained in our study. Likewise, our results regarding the physiological variables of electrodermal activity (EDA) and heart rate variability (HRV) demonstrated a successful induction of stress with consistent activation of the ANS following the Maastricht Acute Stress Test (MAST) protocol [18] in the stress group compared to the control group. Previous studies have shown that MAST produces consistent ANS and neuroendocrine activation up to 30 min after the stressor's onset [17, 18]. Therefore, the absence of stress effect in our study could be since, at the time of MI ability assessment, the activity of the SNS might have stabilized, and the predominant stress response would be of the HPA axis. Future studies should examine the role of cortisol in the influence of acute stress on MI ability. Also, future studies should certainly explore the immediate effects of acute stress on MI ability since athletes frequently use MI not only in the early pre-competition period, but also during competition, where the effects of stress are immediate.

Another possible explanation for the absence of significant differences in MI ability between the stress and control groups might be related to the cognitive load or the complexity of the imagery task. Although the MIQ-3 involved MI from different imagery modalities and perspectives (IVI, EVI, and KI), and the movements that subjects had to imagine included different body parts, these remained quite simple, and each participant performed them at their own pace and without time pressure. The workload might thus not have been sufficient to observe detrimental effects of stress. This explanation would be congruent with previous studies by Lai et al. [25], who found no effect of stress on working memory tasks at low loads, and that of Oie et al. [24], who observed that working memory was only affected by stress at high task loads (tasks with higher complexity). Likewise, our results are in line with the study of Schlatter et al. [26], who did not report a detrimental effect of stress in an explicit MI task combining the visual imagery and kinesthetic modalities of movement on a simple sequential pointing task without time pressure. As these authors pointed out, the low complexity of the task may have preserved task performance under stress. Future studies should thus explore the effects of acute stress in more complex MI tasks on the three subscales IVI, EVI, and KI, before drawing firm conclusions about the impermeability of MI to acute stress. The results of the present study suggest that IM is a robust process that is not easily influenced by stress.

In addition to the absence of significant differences between stress and control groups, present results showed that all

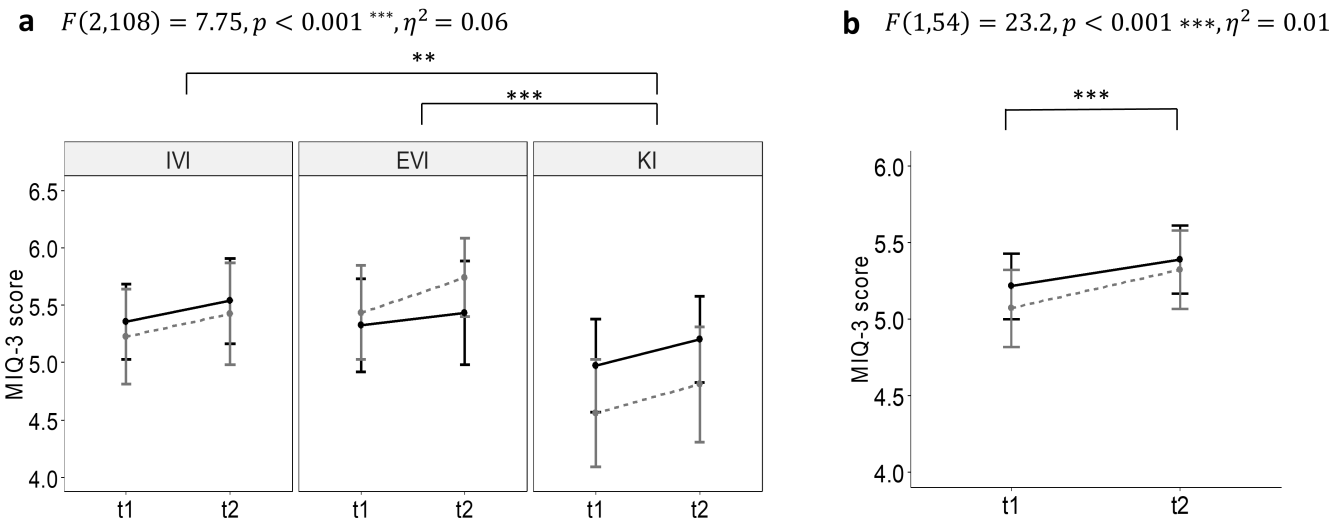

FIGURE 3 | Results graph for MIQ-3 scores by GROUP (solid black line: Control group; dashed gray line: Stress group). Error bars represent 95% confidence intervals. Significant differences with $p < 0.01$ represented by two asterisks (**) and significant differences with $p < 0.001$ represented by three asterisks (***). (a) Significant main effect of the SUBSCALE factor and post hoc comparisons. (b) Significant main effect of the MOMENT factor and post hoc comparison. EVI, external visual imagery; IVI, internal visual imagery; KI, kinesthetic imagery; MIQ-3, Movement Imagery Questionnaire-3; t1, moment t1; t2, moment t2.

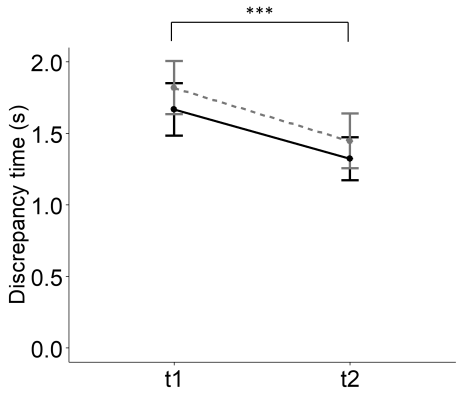

FIGURE 4 | Results for discrepancy time and MOMENT factor (t1; t2) by GROUP (solid black line: Control group; dashed gray line: Stress group). Error bars represent 95% confidence intervals. Significant differences with $p < 0.001$ represented by three asterisks (***). t1, moment t1; t2, moment t2.

participants improved MI ability and TC at t2. Previous studies have pointed out that MI ability may be modulated by certain personality traits, most especially extraversion [37], neuroticism [38], as well as openness to experience and body esteem [39]. Such variables might thus be considered when tailoring individualized MI programs to match athletes' personality profiles, thereby enhancing their performance through optimized MI techniques. Even though MI ability may be treated as a trait, which is a stable feature and does not change quickly, it may thus be influenced by personality traits and can be improved with practice [1]. In this vein, we postulate that the improvement in MI ability observed in this study could be explained by the combination of physical and mental practice involved in performing the MIQ-3, which might also have attenuated stress's effects on MI. Previous studies have observed that the visual and kinesthetic information stored during physical practice helps maintain kinesthetic sensations and assists in the vividness and accuracy of MI [40]. Hence, as suggested in previous studies [41], it seems reasonable to perform protocols combining physical and mental practice whenever possible. Future studies should explore whether acute stress could affect MI ability in MI tasks that do not alternate mental and physical practice to apply MI in clinical settings where physical practice is not possible, such as during periods of immobilization. On the other hand, our results of improved MI ability at t2 in both groups align with previous studies, which observed that MI practice combined with physical practice contributed to improve imagery ability as early as the first MI practice session [42]. Our results thus support the idea that MI improves with training from the first practice session, so that no participant with low MI capacity should be excluded from an MI program.

Additionally, the present data revealed differences in MI capacity when comparing IVI and KI, as well as EVI and KI. The fact that subjects had no experience in the explicit use of MI could explain these differences. Thus, the present data support previous studies that have shown that subjects with little experience prefer exteroceptive data, such as visual information, for the first phases of learning, as it is the information available to build the memory of the action, and that, subsequently, kinesthetic information of the movement serves to build such memory [43]. On the other hand, we did not observe these differences between subscales in the TC, reinforcing the idea that MI is a multidimensional construct. For a complete assessment of MI, we should thus ideally explore different imagery characteristics, such as MI capacity and TC, in imagery subscales [10].

As with all experimental research, the present study has limitations that should be considered. Physiological variables were collected using the Empatica E4 wristband. While recent research has shown this device to be reliable for discriminating

stress [34], and we followed all the manufacturer's guidelines for placement and use protocols, technical problems in recording the signals prevented full analysis in few participants. We analyzed EDA in 80% and HRV in 77% of the participants, confirming the induction of acute stress generated by the MAST protocol in the stress group, as reported in previous studies [18]. On the other hand, future studies should incorporate correlates of attentional focus and concentration during MI tasks. In this study, such measures were not taken, so it cannot be excluded that the improvement in MI ability at t2 could also be due to a greater concentration of the subjects during the task.

5 | Perspective and Conclusions

As far as we know, this study is the first randomized clinical trial exploring MI ability under the influence of acute stress in the different IVI, EVI, and KI subscales. MI and TC between execution and movement imagination were not unaffected by acute stress in young, healthy, non-expert MI participants.

This pattern of results allows us to establish a starting point to explore this topic under different stress situations. The results notably suggest that MI, performed in any of the three forms of IVI, EVI, and KI, could be an equally helpful technique in acute stress situations. This fact matters because acute stress can occur in various clinical and experimental settings where professionals use MI as an intervention technique for learning or improving movement, such as in sports and physiotherapy. The high likelihood of encountering participants in these contexts with acute stress states requires further research to establish clinical practice guidelines and clear instructions for effective MI use.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Research data are not shared.

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