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Acute stress does not influence the learning of a precise manual task: A randomized clinical trial

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ABSTRACT

Acute stress is frequent in sports and rehabilitation contexts and can impact cognitive processes essential for motor learning. This study aimed to investigate the influence of induced acute stress on the learning of a precise manual task, examining its effect on five key parameters of fine motor control: trajectory error, trajectory error direction, time error, tracing accuracy, and task accuracy. A double-masked, randomized clinical trial with 62 participants (average age 20.65 ± 2.54 years; 39 females; 23 males) was conducted. To examine the effects of stress, participants were assigned to either a stress or a control group through stratified randomization by sex. Initially, all participants underwent the Maastricht Acute Stress Test (in its acute stress and control versions, respectively). Subsequently, they performed the precise manual task on a graphic tablet at three stages of the learning process: acquisition, short-term retrieval, and long-term retrieval. Electrodermal activity and heart rate variability were recorded to assess stress induction. Data analysis from 30 stress group participants and 25 control group participants revealed no statistically significant differences between groups in any of the variables studied at the three learning stages. Both groups exhibited statistically significant improvements in time error, trajectory error direction, and tracing accuracy during both short-term and long-term retrieval compared to acquisition. Our findings suggest that acute physical and psychological stress does not markedly impair learning a precise manual task of adhering to a specific trajectory and pace among young adults.

1. Introduction

Motor learning has been defined as a set of processes related to experience or practice that lead to relatively permanent improvements in the capability for skilled performance (Schmidt & Lee, 2019). Individuals may be subjected to different physical and psychological stressors in contexts such as sports or rehabilitation, where the goal may be to learn or relearn movement (Bali & Jaggi, 2015; Evans et al., 2012).

Stress is a state of threatened homeostasis during which adaptive physiological and behavioral changes occur (Bali & Jaggi, 2015). During the stress response, adrenaline and cortisol are released into the bloodstream (Thomas & Wulff, 2023). The release of these substances can influence cognitive processes such as attention and memory (Schwabe et al., 2022; Thomas & Wulff, 2023). Following exposure to a stressor, there appears to be increased difficulty in maintaining attention (Olver et al., 2015) and storing information unrelated to the stressor (Schwabe et al., 2022).

Attention and memory are fundamental in motor learning. Sufficient

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Abbreviations: EDA, electrodermal activity; EHI, Edinburgh Handedness Inventory; HF, high frequency; HRV, heart rate variability; LF, low frequency; MAST, Maastricht Acute Stress Test; n.u., normalized units; STAI, State-Trait Anxiety Inventory.

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attentional resources are necessary for learning to take place (Song, 2019). Likewise, the learning process involves the formation of motor memory (Kantak & Winstein, 2012). During the initial learning stage of a task, results from neuroimaging studies support the idea that there is increased cognitive demand (Lohse et al., 2014). As motor learning takes place, the attentional demands decrease (Schmidt & Lee, 2019). Thus, it has been suggested that stress less influences motor performance when the learning task no longer requires the investment of so many cognitive resources (SánchezCabeza & MáximoBocanegra, 2017; Schmidt & Lee, 2019). Among all the tasks humans can learn, manipulating objects with the hands is one of the most demanding and complex motor functions (Blank et al., 2000). It involves the movement of different parts of the upper limb with different synergies to produce precise grips (e.g., to write with a pen) (Blank et al., 2000; Schmidt & Lee, 2019; Shim et al., 2010).

The study by Aiken (2015) explored the effects of different stressors on learning a manual task. This task was performed with a non-inking electronic pen and required precision. During the task, participants were asked to draw a path between two targets while avoiding two rectangular barriers. The path had to be completed in 2 s. Participants were randomly assigned to three groups where they either only performed the manual task or performed it simultaneously with an arithmetic task or while listening to continuous noise. The results showed that simultaneous performance of the manual task with the arithmetic task or while listening to noise led to an increased workload due to increased attentional demands (Aiken, 2015). During the concurrent performance of the arithmetic task with the manual task, the motor performance of the manual task was impaired. Nevertheless, participants were able to learn the manual task (Aiken, 2015). However, it has not been explored how the physical and psychological stress elicited before a manual task requiring precision influences its learning.

This study aimed to determine the effects of provoked acute stress on learning a manual task requiring accuracy, as assessed by five parameters of fine motor control: trajectory error, trajectory error direction, time error, tracing accuracy, and task accuracy. Participants induced with acute physical and psychological stress are expected to show a negative effect of stress on learning, such that they exhibit worse motor performance during acquisition, short-term retrieval, and long-term retrieval in all five parameters of fine motor control than participants not subjected to acute stress.

2. Methods

Participants were recruited through consecutive non-probabilistic sampling. Following the Helsinki Declaration, 68 participants voluntarily agreed to participate in the study after signing informed consent. Inclusion criteria were having normal or corrected vision and hearing. Exclusion criteria included presenting visual or motor problems that affect the normal execution of the task or the distinction between right and left; history of neurological, cardiovascular, or myopathic disease; skin injury in the area where physiological measurement devices were placed during the experiment; intake of medications or substances such as theine, caffeine, or alcohol that could interfere with the nervous system in the 8 h before the experimental session; and the presence of trait or state anxiety assessed through the State-Trait Anxiety Inventory (STAI) (percentile ≥75 %) (Spielberger et al., 2010). Six participants were excluded from the study for not meeting the selection criteria. The minimum sample size for the study was estimated based on the guidelines of Argimón Pallás and Jiménez Villa (2019). The following parameters were chosen for the estimate: a confidence level of 95 % ($\alpha = 0.05$), a variability of the parameters of 10 %, a confidence interval width of 5 %, and a dropout rate of 20 %. Based on these assumptions, the calculated minimum sample size per group was 20 participants. In addition, an a priori study power analysis was performed with the free program G*Power version 3.1.9.7., with an alpha level of 0.05 and an effect size of 0.25. Finally, a total sample of 62 participants was established, which corresponded to a study power (1-β) of 0.975. The final sample had an average age of 20.65 (SD = 2.54; 39 women and 23 men). Participants were randomized to the stress group (n = 32) or the control group (n = 30).

An experimental, randomized, and double-blind trial was conducted. Randomization was carried out through stratified assignment by sex (male or female). Simple random assignment [1:1] to the stress or control group was performed within each stratum using the Epidat 4.2 program. The study received a favorable opinion from the Ethics Committee for Research and Animal Experimentation of the University of Alcalá (CEID2022/2/036) and was registered in ClinicalTrials.gov (NCT04912713).

A single individual session was conducted for each participant in a well-lit, quiet room where only the participant and the researcher were present. All instructions were displayed on a computer in the presence of the researcher, who ensured the proper conduct of the procedure. At the beginning of the session, all participants completed the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971) to determine their dominant hand.

Subsequently, all participants underwent the non-invasive Maastricht Acute Stress Test (MAST) protocol (Smeets et al., 2012). Those in the stress group underwent the MAST protocol to induce acute stress, which combines psychological stressors (evaluative social threat, uncontrollability, and unpredictability) and physical stressors (intense cold pain applied to the non-dominant hand). The protocol lasts 15 min and reliably generates strong subjective, autonomic, and neuroendocrine stress responses (Smeets et al., 2012). Participants in the control group underwent a non-stressful protocol analogous to MAST (MAST control) (Smeets et al., 2012).

After completing the MAST or MAST control protocol, all participants performed the same precise manual learning task: tracing over a reference circle of 127 mm in diameter with an inkless pen using their non-dominant hand in a continuous motion at a pace of 2 s per turn for a total of 40 s. The sound of a metronome guided the pace. They were instructed to perform the task as accurately as possible and at the specified pace. The starting point of the trajectory was marked by a cross located at the top-center of the reference circle. Each metronome beat had to coincide with passing the cross without stopping at it. Participants were seated stably, without resting any part of the upper limb and always keeping the pen perpendicular to the surface (Figure 1). The task was performed on a Trust Panora graphic tablet model with 2048 pressure sensitivity levels and an ergonomic wireless optical pen (Trust International B.V., Dordrecht, The Netherlands). These materials are sensitive to the characteristics of the evaluated task (Nunez-Nagy, 2012). The traces on the graphic tablet were stored using Matlab version 2022b (Mathworks®, Natick, Massachusetts, USA). The graphic tablet was calibrated before conducting all experiments (Nunez-Nagy, 2012).

All participants read the instructions to familiarize themselves with the materials and the task without time pressure and before data collection. Subsequently, the participants performed the task at three different moments: acquisition (immediately after the MAST or MAST control protocol), short-term retrieval (2 min after completing the acquisition phase), and long-term retrieval (20 min after the short-term retrieval phase).

Two participants from the stress group and five from the control group were removed from the study for not correctly performing the requested tasks during the experimental session. Thus, data from 30 participants in the stress group and 25 in the control group were analyzed.

The manual task traces were stored and processed using Matlab to calculate the parameters of fine motor control on each turn: trajectory error, trajectory error direction, time error, tracing accuracy, and task accuracy.

Trajectory error represented the magnitude of the tracing error when following the model circle, regardless of the time spent. It was expressed as an area in pixel^2 and calculated as the absolute value of the difference

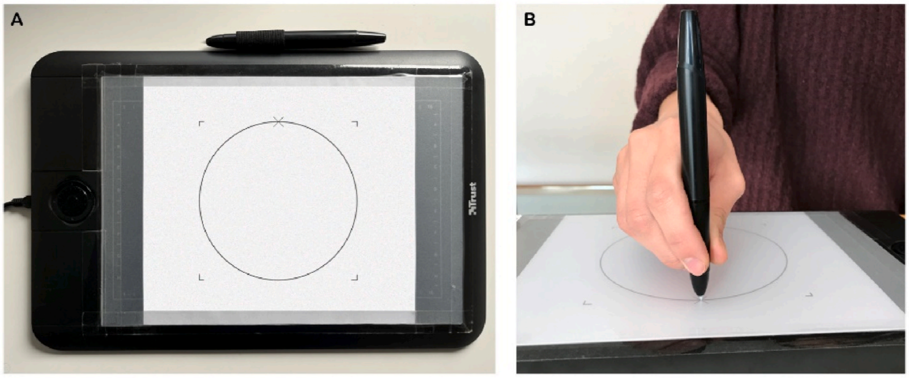

Figure 1. A) Trust Panora graphic tablet, ergonomic wireless optical pen, and model circle. B) Manual task starting position.

between a) the area defined by the triangle formed by each pair of consecutive points of the traced trajectory and the center of the model circle and b) the corresponding sector of the model circle. A more detailed explanation of the error calculation can be found in Appendix A.

Trajectory error direction was characterized by its sign, indicating whether the trajectory error occurred mostly inward or outward relative to the model circle. Like the trajectory error, it was expressed as an area in pixel^2. A negative sign indicated that the trajectory error was mostly inward towards the center of the model circle, while a positive sign indicated that it was mostly outward away from the center of the model circle.

Time error represented the time the participant deviated from the requested time (2 s) without considering the correctness of the tracing adjustment to the model circle. It was expressed in seconds (s) and calculated as the absolute difference between the time used by the participant and the requested time.

Tracing accuracy represented the participant's ability to make the slightest trajectory error, even at a pace different from the requested pace (2 s per turn). It was expressed in pixel*second and calculated as the quotient of trajectory error divided by speed. Thus, lower values of this parameter reflected greater tracing accuracy within a specific time.

Task accuracy represented the participant's ability to make the smallest trajectory error while adjusting to the requested pace (2 s per turn). It was expressed in pixel^2*seconds and calculated as the product of the quotient of the trajectory error for the turn divided by the average of all turns and the time error of the turn divided by the average of all turns. In this manner, lower values of this parameter reflected a better adjustment to the model circle at the requested pace.

The average of all turns for each fine motor control parameter, and each learning process stage was calculated: acquisition, short-term retrieval, and long-term retrieval. The findings of the study by Shim et al. (2010) suggest that the synergistic forces of the hand-pen contact increase in the initial phase and decrease in the final phase during circle tracing. Thus, to standardize the variability of modulation of such forces among participants, data from the first and last turn of each learning process stage were removed from the average of all turns.

Additionally, electrodermal activity (EDA) and heart rate variability (HRV) were assessed in all participants during the initial (MAST start) and final (MAST end) periods of both versions of the MAST protocol to confirm the correct induction of stress. The physiological data were recorded using the portable Empatica E4 device (Empatica, Milan, Italy), which was placed on the wrist of the non-dominant hand. The EDA, measured as a skin conductance signal, was recorded with the E4 device in microSiemens with a sampling frequency of 4 Hz. Subsequently, a continuous decomposition analysis of the signal into its tonic and phasic components was performed (Posada-Quintero & Chon, 2020), using the free software Ledalab version 3.4.9 (Benedek & Kaernbach, 2010). The tonic component represents changes during a specific period, and the phasic component represents transient and rapid events (Posada-Quintero & Chon, 2020). The tonic component of the skin conductance signal was used as the dependent variable to evaluate the EDA during the MAST start and end periods. Higher values indicated greater activation of the sympathetic system (Bali & Jaggi, 2015). On the other hand, blood volume pulse data were collected with the E4 device using photoplethysmography with a sampling frequency of 64 Hz. Later, the data were analyzed in the frequency domain using the Kubios HRV Premium software version 3.5.0 (Tarvainen et al., 2014), as recommended by Empatica. To obtain a comparable measure among participants, the relative estimated power in normalized units (n.u.) of the low frequency (LF) (0.04–0.15 Hz) and high frequency (HF) (0.15–0.4 Hz) bands was calculated. The LF/HF ratio was also calculated (Shaffer & Ginsberg, 2017). LF is primarily associated with the sympathetic system and HF with the parasympathetic system. High LF/HF ratio values reflect sympathetic dominance and low values reflect parasympathetic dominance (Shaffer & Ginsberg, 2017). The relative estimated power of LF and HF and the LF/HF ratio were used as dependent variables.

Statistical analyses were conducted using the free software RStudio version 2022.02.3. The lambda parameter was calculated using maximum likelihood estimation for dependent variables that did not meet the normality assumption. Box-Cox logarithmic transformations were performed to allow the application of parametric tests.

The study of group homogeneity for qualitative variables was performed using the χ^2 test or the exact Fisher test, depending on whether the expected frequency was greater or less than 5, respectively. The Mann-Whitney *U* test was conducted for quantitative variables that did not conform to the normal curve. For those that conformed to the normal curve and met the principle of homoscedasticity, t-tests for independent samples were performed.

The stress induction was explored through a mixed factorial ANOVA on the dependent variables of EDA, LF, HF, and LF/HF ratio. The within-subject factor PERIOD (MAST start, MAST end) and the between-subject factor GROUP (control, stress) were analyzed. Differences between groups during the learning of the manual task were analyzed using a mixed factorial ANOVA on the dependent variables trajectory error, trajectory error direction, time error, tracing accuracy, and task accuracy. The within-subject factor MOMENT (acquisition, short-term retrieval, long-term retrieval) and the between-subject factor GROUP (control, stress) were examined. In all ANOVA analyses, Type I error was set at a level of $\alpha = 5\%$. The effect size eta squared (η^2) was calculated and interpreted as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), and large ($\eta^2 = 0.14$). For significant results, post-hoc t-tests with Bonferroni correction were conducted. The effect size was calculated using Cohen's (d) and interpreted as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$).

3. Results

The two groups were homogeneous regarding sex, age, handedness, anxiety level (STAI scores), and time of day the experiment was conducted (see Table 1).

Although technical problems with signal recording prevented the analysis of physiological variables in some participants, EDA was analyzed in 20 participants from the stress group and 25 from the control group (81.82 % of participants), and HRV in 20 participants from the stress group and 23 from the control group (78.18 % of participants).

The mixed factorial ANOVA for EDA showed a significant main effect of group, $F(1,43) = 7.575$, $p = 0.009$, $\eta^2 = 0.144$, and period, $F(1,43) = 5.747$, $p = 0.021$, $\eta^2 = 0.006$, as well as a significant interaction of group × period, $F(1,43) = 20.568$, $p < 0.001$, $\eta^2 = 0.020$. Post-hoc multiple comparisons did not reveal significant differences in EDA between groups in the MAST start period, $t(42.1) = -1.693$, $p = 0.098$, $d = -0.506$, but did show significant differences in the MAST end period between the control group ($M = 2.03$; $SD = 2.75$) and the stress group ($M = 6.17$; $SD = 4.53$), $t(42.9) = -3.929$, $p < 0.001$, $d = -1.162$. Significant differences were also found within the stress group between the MAST start period ($M = 4.21$; $SD = 4.12$) and MAST end period ($M = 6.17$; $SD = 4.53$), $t(19) = -4.006$, $p < 0.001$, $d = -0.896$ (Figure 2A).

The mixed factorial ANOVA for the low frequency (LF) band of the heart rate variability did not show a significant main effect of group, $F(1,41) = 0.003$, $p = 0.955$, $\eta^2 < 0.001$, but did for period, $F(1,41) = 6.175$, $p = 0.017$, $\eta^2 = 0.037$, and a significant interaction of group × period, $F(1,41) = 4.743$, $p = 0.035$, $\eta^2 = 0.028$. Post-hoc multiple comparisons revealed significant differences in LF within the stress group between the MAST start period ($M = 50.4$; $SD = 20.7$) and MAST end period ($M = 64.1$; $SD = 14.8$), $t(19) = -2.691$, $p = 0.015$, $d = -0.602$. No significant differences were found between groups during the MAST start period for LF, $t(40.6) = 1.031$, $p = 0.309$, $d = 0.315$.

The mixed factorial ANOVA for the high frequency (HF) band of the heart rate variability did not show a significant main effect of group, $F(1,41) = 0.003$, $p = 0.955$, $\eta^2 < 0.001$, but did for period, $F(1,41) = 6.182$, $p = 0.017$, $\eta^2 = 0.037$, and a significant interaction of group × period, $F(1,41) = 4.751$, $p = 0.035$, $\eta^2 = 0.029$. Post-hoc multiple comparisons revealed significant differences in HF within the stress group between the MAST start period ($M = 49.5$; $SD = 20.7$) and MAST end period ($M = 35.9$; $SD = 14.8$), $t(19) = 2.693$, $p = 0.014$, $d = 0.602$. No significant differences were found between groups during the MAST start period for HF, $t(40.6) = -1.032$, $p = 0.308$, $d = -0.315$.

Table 1
Socio-demographic characteristics of the participants.

	Control (n = 25)	Stress (n = 30)	Statistical	p-value
Sex [n (%)]			X^2	0.87
Female	17 (68 %)	21 (70 %)		
Male	8 (32 %)	9 (30 %)		
Age	20 (18; 22)	19 (18; 20)	Mann-Whitney U	0.61
Laterality [n (%)]			Fisher's exact test	0.39
Right	21 (84 %)	28 (93.33 %)		
Left	4 (16 %)	2 (6.67 %)		
EHI	22 (20; 24)	21 (20; 22)	Mann-Whitney U	0.27
STAI (%)				
State	35.9 ± 17.8	32.7 ± 17.3	*t*-test	0.5
Trait	40 (25; 55)	45 (24.5; 58.8)	Mann-Whitney U	0.9
Time of day	12:54h ± 2:49h	12:18h ± 2:13h	*t*-test	0.41

Values expressed as M ± SD or Md (Q1; Q3). n = sample; M = Mean; SD=Standard Deviation; Md = Median; Q_1 = first quartile; Q_3 = third quartile; EHI = Edinburgh Handedness Inventory; STAI=State-Trait Anxiety Inventory.

The mixed factorial ANOVA for the LF/HF ratio did not show a significant main effect of group, $F(1,41) = 0.065$, $p = 0.800$, $\eta^2 = 0.001$, but did for period, $F(1,41) = 5.697$, $p = 0.022$, $\eta^2 = 0.033$ and a significant interaction of group × period, $F(1,41) = 4.557$, $p = 0.039$, $\eta^2 = 0.026$. Post-hoc multiple comparisons revealed significant differences in the LF/HF ratio within the stress group between the MAST start period ($M = 1.48$; $SD = 1.25$) and MAST end period ($M = 2.36$; $SD = 1.60$), $t(19) = -2.635$, $p = 0.016$, $d = -0.589$. No significant differences were found between groups during the MAST start period for LF/HF ratio, $t(41) = 1.169$, $p = 0.249$, $d = 0.356$ (Figure 2B-D).

The data obtained from EDA and HRV (LF, HF, and LF/HF) show a significant increase in sympathetic dominance in the stress group during the MAST end period, which was not detected in the control group.

The mixed factorial ANOVA for trajectory error showed no significant main effect for group, $F(1,53) = 0.486$, $p = 0.489$, $\eta^2 = 0.006$, or moment, $F(2,106) = 0.927$, $p = 0.399$, $\eta^2 = 0.005$, and no significant interaction effect of group × moment $F(2,106) = 1.469$, $p = 0.235$, $\eta^2 = 0.008$.

The mixed factorial ANOVA for trajectory error direction showed a significant main effect for moment, $F(1.62, 85.99) = 10.068$, $p < 0.001$, $\eta^2 = 0.07$), but not for group, $F(1,53) = 1.411$, $p = 0.240$, $\eta^2 = 0.016$, or the interaction of group × moment, $F(1.62, 85.99) = 0.792$, $p = 0.433$, $\eta^2 = 0.006$. Post-hoc multiple comparisons revealed significant differences between acquisition ($M = -12887$; $SD = 9392$) and short-term retrieval ($M = -8099$; $SD = 8130$), $t(54) = -4.565$, $p < 0.001$, $d = -0.616$, as well as between acquisition and long-term retrieval ($M = -6730$; $SD = 12091$), $t(54) = -3.695$, $p = 0.002$, $d = -0.498$.

The mixed factorial ANOVA for time error showed a significant main effect for moment, $F(1.43,75.62) = 15.985$, $p < 0.001$, $\eta^2 = 0.128$), but not for group, $F(1,53) = 0.107$, $p = 0.745$, $\eta^2 = 0.001$, or the interaction of group × moment, $F(1.43,75.62) = 0.100$, $p = 0.838$, $\eta^2 < 0.001$. Post-hoc multiple comparisons revealed significant differences between acquisition ($M = 0.32$; $SD = 0.45$) and short-term retrieval ($M = 0.17$; $SD = 0.08$), $t(54) = 4.537$, $p < 0.001$, $d = 0.612$, as well as between acquisition and long-term retrieval ($M = 0.17$; $SD = 0.1$), $t(54) = 4.185$, $p < 0.001$, $d = 0.564$.

The mixed factorial ANOVA for tracing accuracy showed a significant main effect for moment, $F(1.68, 89.11) = 8.845$, $p < 0.001$, $\eta^2 = 0.06$, but not for group, $F(1,53) = 2.013$, $p = 0.162$, $\eta^2 = 0.023$, or the interaction of group × moment, $F(1.68,89.11) = 0.845$, $p = 0.415$, $\eta^2 = 0.006$. Post-hoc multiple comparisons revealed significant differences between acquisition ($M = 54.4$; $SD = 11.5$) and short-term retrieval ($M = 49.6$; $SD = 6.54$), $t(54) = 3.599$, $p = 0.002$, $d = 0.485$, as well as between acquisition and long-term retrieval ($M = 49.7$; $SD = 7.08$), $t(54) = 3.005$, $p = 0.012$, $d = 0.405$.

The mixed factorial ANOVA for task accuracy showed no significant main effect for group, $F(1,53) = 0.129$, $p = 0.720$, $\eta^2 = 0.001$, or moment, $F(1.38,73.12) = 0.389$, $p = 0.602$, $\eta^2 = 0.003$, and no significant interaction effect of group × moment $F(1.38,73.12) = 0.153$, $p = 0.777$, $\eta^2 = 0.001$ (Figure 3).

4. Discussion

This study aimed to explore the effects that induced acute stress could have on learning a manual task requiring precision, evaluated through five parameters of fine motor control: trajectory error, trajectory error direction, time error, tracing accuracy, and task accuracy. It was hypothesized that participants subjected to acute stress would exhibit a negative effect of stress on learning, hence showing poorer motor performance than participants not subjected to stress across all evaluated parameters. The analysis of the physiological variables of the participants confirmed the induction of acute stress generated by the

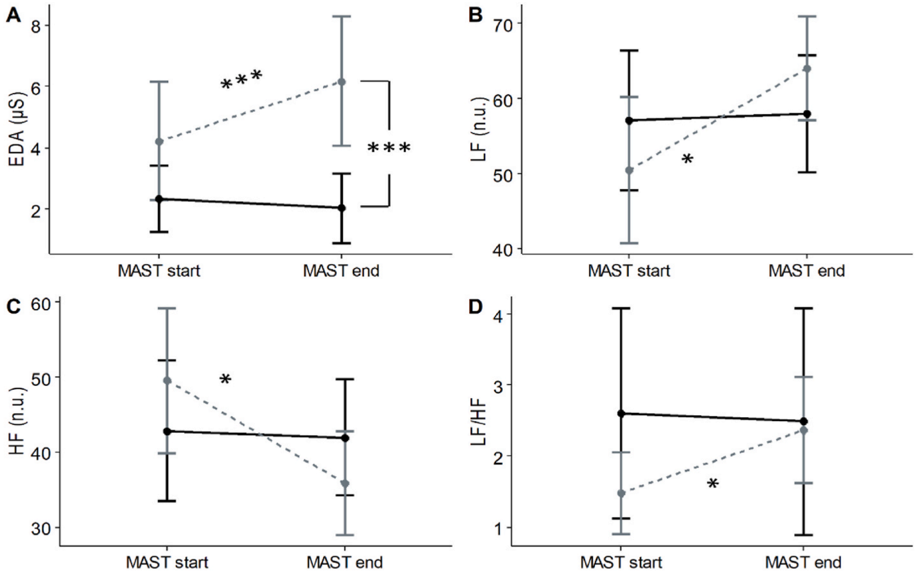

Figure 2. Interaction between GROUP (solid black line: control group; dashed gray line: stress group) and PERIOD (MAST start; MAST end) for: A) Tonic Electrodermal Activity (EDA); B) Low frequency (LF) band of the heart rate variability; C) High frequency (HF) band of the heart rate variability; D) Low frequency/High frequency ratio (LF/HF). 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 (***). MAST, Maastricht Acute Stress Test; μS, microSiemens; n.u., normalized units.

Maastricht Acute Stress Test protocol in the stress group, as referred to in previous studies (Smeets et al., 2012). When comparing the performance of participants subjected to acute stress with that of controls, it was observed that both groups showed statistically significant learning regarding time error, trajectory error direction, and tracing accuracy, from the acquisition moment to the moments of short-term and long-term retrieval, with no statistically significant differences between the two groups. Furthermore, no significant differences were found in trajectory error and task accuracy between the two groups of participants, nor at different moments of the learning process.

The statistically significant decrease in time error observed in this study in both groups, from the acquisition moment to the moments of short-term and long-term retrieval, respectively, evidences a learning process of time adjustment. All participants improved their ability to adjust to the 2 s per turn pace guided by the metronome. This rhythm adjustment learning process could be attributed to the benefit of auditory guidance. Previous studies indicate that the auditory system is most suitable for guiding temporal coordination between a movement and a rhythm, as it activates motor pathways more than the visual system (Comstock et al., 2018). The results of the present study are consistent with this idea, suggesting that auditory guidance could assist in the temporal coordination between a precision manual task and a rhythm, regardless of the presence or absence of acute stress. Auditory guidance could help dissipate the effects of acute stress on the learning of precision manual tasks that require synchronization with a rhythm. However, since auditory guidance was present in all conditions of the current study, our findings can neither clearly support nor refute this idea. Therefore, future studies should explore whether stress can differentially affect the learning of precision manual tasks when these require or do not require auditory temporal synchronization. On the other hand, although all participants in this study improved their ability to adjust to the 2-s-per-turn pace guided by the metronome, they did not perform the task precisely at that pace. It is essential to consider that the coordination of movement with the rhythm set by the metronome had to be carried out through a continuous movement, and tasks that require synchronizing a movement with a rhythm are more complex for continuous movements than discrete ones (Studenka & Zelaznik, 2011). The sensorimotor coupling seems to be weakened in continuous movements (Repp & Su, 2013). In this vein, our study's results suggest that the continuity of movement complicates the synchronization of movement with an exact rhythm, both in participants subjected to stress and those not subjected to it.

The results also seem to indicate that neither of the two groups showed learning regarding trajectory error or task accuracy. Participants did not significantly reduce the error in tracing over the model circle at the imposed pace of 2 s per turn. These findings align with the study by Gatouillat et al. (2017), who investigated the drawing of continuous circles at various free or metronome-imposed speeds. They observed that when the metronome imposed the speed of circle tracing, trajectory error increased, and execution precision decreased. The outcomes of our research underscore that spatial precision learning is affected when attempting to adjust the learning of a manual task to a specific time. This effect is observed regardless of whether participants are subjected to acute stress.

In this study, both groups obtained negative values in the trajectory error direction throughout the learning process. This indicates that all participants committed the trajectory error mostly inward towards the center of the model circle, regardless of the presence or absence of stress. These results are consistent with those of Gatouillat et al. (2017), who also observed negative radial errors when exploring the tracing of circles at different speeds set by the sound of a metronome. In the present study, negative values in the trajectory error direction decreased significantly at short-term and long-term retrieval moments compared to the acquisition moment in both groups. These results suggest that all participants learned to bring their traces closer to the trajectory of the model circle.

Finally, regarding the variable of tracing accuracy, this study found statistically significant improvements throughout the learning process in both groups. All participants reduced the amount of tracing error committed when following the model circle at any pace, regardless of whether they adjusted precisely to the imposed rhythm of 2 s per turn. These results could be explained by the effect of visual guidance for tracing that the circle model could provide. Cohen et al. (2018) analyzed the differences in precision of circle tracing when visual guidance was available or not. Their study showed that circle tracing with visual guidance achieved better precision values. These precision differences seem to be because the task of circle tracing is guided by external visual stimuli, and drawing without visual guidance is guided by internal stimuli. As has been reported, internal stimuli are based on memory

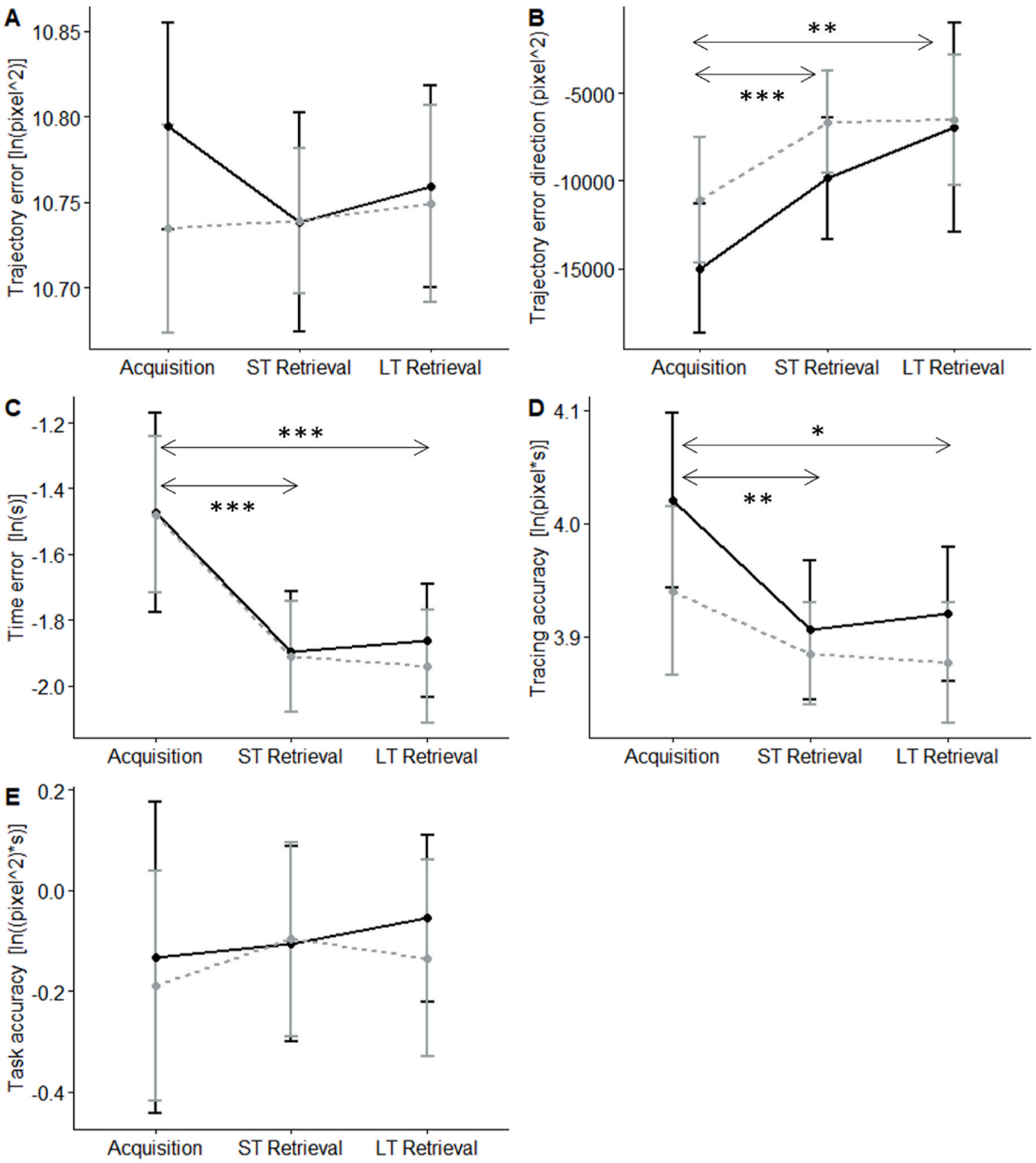

Figure 3. Interaction between GROUP (solid black line: control group; dashed gray line: stress group) and MOMENT (acquisition; ST retrieval; LT retrieval) for: A) Trajectory error; B) Trajectory error direction; C) Time error; D) Tracing accuracy; E) Task accuracy. Error bars represent 95 % confidence intervals. Significant differences with $p < 0.05$ are represented by one asterisk (*), with $p < 0.01$ by two asterisks (**), with $p < 0.001$ by three asterisks (***). s = second; ST = Short-Term; LT = Long-Term.[11]

processes and require a more significant amount of cognitive resources than external stimuli (Gowen & Miall, 2007). Therefore, external visual guidance in our study could have facilitated the statistically significant improvement in tracing accuracy for all participants without the induced acute stress affecting learning. Thus, visual guidance could help dissipate the effects of stress on the learning of manual tasks requiring precise execution. Future studies could explore the differential effects of stress on precision manual tasks with and without visual guidance.

In the task used in the present study, participants were asked to learn to adjust to a model trajectory as accurately as possible while following the rhythm set by the sound of a metronome. The recent review by Martins et al. (2024) points out that fine motor skills need to integrate sensory inputs with motor outputs. The review also indicates that stress disrupts this sensorimotor integration (Martins et al., 2024). Therefore, it was expected that the assessed task would be affected by the presence of stress. However, visual and auditory guidance might have facilitated the integration of sensory inputs and motor outputs. This could have contributed to the absence of between-group differences observed in the study.

Another aspect to consider in interpreting the results of this study is the potential effect of how acute stress was induced. Aiken (2015) conducted a study where participants were asked to learn a manual task requiring precision. The performance of three groups of participants was compared: those who only performed the manual task, those who performed it simultaneously with an arithmetic mental task, and those who performed it while listening to continuous noise. Thus, acute stress was induced either by the simultaneous performance of the arithmetic mental task or by listening to constant noise, which increased the workload (Aiken, 2015). The results showed that the arithmetic mental task simultaneous to the manual task impaired motor performance, though all participants learned the task (Aiken, 2015). In our research, stress was induced before the acquisition of the task. It could then be thought that not finding significant differences between the two groups in our study in motor performance during the learning process could be due to the stressor being induced before learning, not producing an increase in cognitive load (Aiken, 2015). The results of our study suggest that physical and psychological stress induced prior to the task does not affect the performance or learning of a precision manual task. This is especially important in sports and rehabilitation settings, where individuals may face physical and psychological stressors.

5. Conclusion

To our knowledge, this is the first study to explore whether physical and psychological stressors can influence the learning of a precision manual task. Acute stress induced before the task does not seem to affect the learning of a precision manual task audibly and visually guided in young participants. These results expand the knowledge to continue exploring the effects of acute stress on the learning of various precision manual tasks in different contexts. Advancement in this line of research will allow the design of effective motor learning interventions tailored to the needs and circumstances of individuals at each moment of the learning process that contribute to minimizing the potential adverse effects of acute stress in both the sports and rehabilitation fields.

CRediT authorship contribution statement

Sara Trapero-Asenjo: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Conceptualization. **Sara Fernández-Guinea:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization. **M.A. Rubio:** Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation. **Daniel Pecos-Martin:** Validation, Formal analysis. **Susana Nunez-Nagy:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2024.102726.

Appendices

A. Calculation of trajectory error

The error in the execution of a trajectory is calculated from the sum of the errors between each of the points defining the trajectory. The error between two consecutive points is the difference between the area of the sector of the reference circle and the sector formed by the points with center in this circle (Figure A1.).

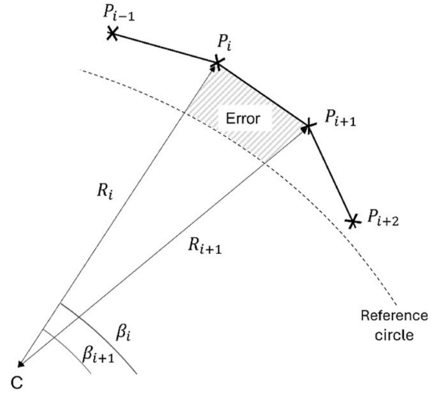

Figure A.1. Calculation of the sum of the error on each trajectory

For the calculation of the error, the angle $|\beta_i - \beta_{i+1}|$ is considered to be small, and the following approximations can be made. The area described by the sector of the trajectory executed between two points S_i^u is defined as the area of the triangle formed by two consecutive points P_i, P_{i+1} and the center of the reference circle C, which is calculated using Heron's formula. Using the small angle approximation, the area of the sector of the

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[1] Box-cox transformed variables are depicted where a transformation was required (all except trajectory error direction).

reference circle S_i^r, defined by the points of the trajectory P_i, P_{i+1}, is calculated by Equation A.1.

$$S_i^r = \frac{\overline{R_i}|\beta_i - \beta_{i+1}|}{2} \qquad \text{Equation A.1}$$

where:

$$\overline{R_i} = \frac{(R_i + R_{i+1})}{2} \qquad \text{Equation A.2}$$

The error of the trajectory between points i and $i + 1$, $E(i)$, is the absolute value between the values S_i^r and S_i^u (Equation A.3.).

$$E(i) = \left|S_i^r - S_i^u\right| \qquad \text{Equation A.3}$$

The total error of a trajectory is defined as the sum of the error of each of the points forming the trajectory (Equation A.4.).

$$E_j = \sum_{i=1}^{n} E_j(i) \qquad \text{Equation A.4}$$

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