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Differential effects of hypnotizability on visuomotor adaptation and sequential motor learning

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Abstract

Background

Sensorimotor adaptation depends on cerebellar mechanisms that integrate sensory feedback and motor commands, whereas sequential motor learning primarily relies on cortico-striatal circuits. Hypnotizability is a psychophysiological trait associated with cerebellar morphofunctional characteristics and peculiar sensorimotor control. This study investigated whether hypnotizability differentially influences visuomotor adaptation and sequential motor learning.

Methods

After hypnotic assessment through the Stanford Hypnotic Susceptibility Scale: form A (SHSS: A, score: 0–12), participants were assigned to medium-to-high (MH, n = 15; SHSS: 7–12) or low-to-medium (LM, n = 18; SHSS score: 0–5) hypnotizability groups. Participants performed a visuomotor adaptation task (VAT) using joystick-controlled reaching movements of the arm under no-perturbation (0°), rightward (+ 20°), and leftward (− 20°) perturbation conditions, followed by a sequential finger-tapping task (FFT). Heart rate (HR) and skin conductance level (SCL) were recorded throughout both tasks.

Results

Perturbation reduced the number of hits and increased the trajectory errors in both groups, with larger trajectory errors in MH than in LM under rightward perturbation, despite comparable improvements in the number of hits. Autonomic variables indicated an increasing sympathetic tone across VAT in both groups. In the FTT, MH executed movement more slowly than LM, although both groups exhibited comparable accuracy. HR and SCL remained stable and did not differ between groups.

Conclusions

Higher hypnotizability was associated with reduced visuomotor precision but preserved adaptation and sequential motor learning. These task-specific effects may reflect hypnotizability-related differences in cerebellar morpho-functional characteristics during sensorimotor adaptation, while the hemispheric functional asymmetry could account for the sequential motor performance.

Introduction

Motor learning relies on the continuous updating of motor behavior in response to practice and environmental changes. Sensorimotor adaptation is a fundamental component of this process, allowing movements to remain accurate by recalibrating motor commands in response to altered sensory feedback via cerebellar mechanisms driven by sensory prediction errors (Krakauer et al., 2019). In parallel, sequential motor learning enables the acquisition and optimization of skilled action sequences through repeated practice and relies on partially distinct cortico-striatal and cortical networks (Doyon et al., 2009; Krakauer et al., 2019). Although these forms of motor learning engage partly overlapping neural

circuits, they depend on different computational mechanisms, making them useful paradigms for determining whether individual characteristics selectively influence specific aspects of motor learning.

Hypnotizability is a stable psychophysiological trait that remains largely unchanged throughout adulthood (Piccione et al., 1989). Standardized scales classify individuals as highly (highs), moderately (mediums), or low (lows) hypnotizable based on their responsiveness to suggestions that affect perception, memory, and behavior, including analgesia, amnesia, and paralysis (Elkins et al., 2015). Beyond hypnotic responsiveness, hypnotizability is associated with distinct cerebral (Landry et al., 2017; Picerni et al., 2025) and cerebellar morphometry features (Picerni et al., 2019; 2025), as well as different physiological and behavioral characteristics (Santarcangelo, 2024). Compared with lows, highs exhibit reduced gray matter volume (GMV) in the left cerebellar lobules IV–VI (Picerni et al., 2019), a finding that may contribute to their less precise postural control under altered visual and proprioceptive conditions (Santarcangelo et al., 2008; Solari et al., 2016). Likewise, highs exhibit lower visuomotor accuracy when throwing a ball toward a central target (Menzocchi et al., 2015). Although both groups show the expected adaptation of launch direction following prism exposure (Alexander et al., 2011), highs consistently exhibit larger movement errors than lows and, unlike lows, do not show evidence of learning across consecutive trials in either postural or visuomotor tasks (Santarcangelo et al., 2008; Menzocchi et al., 2015). Furthermore, under altered visual feedback, lows perform similarly when localizing hand position after active and passive reaching movements, whereas highs demonstrate fewer localization errors following active than passive movements, suggesting a greater resilience on motor commands than sensory feedback during sensorimotor integration (Padilla-Castaneda et al., 2015). The differences observed in sensorimotor integration between highs and lows are unlikely to be explained by GMV differences in the basal ganglia; indeed, the basal ganglia cooperate with the cerebellum in motor control but do not exhibit GMV differences related to hypnotizability (Picerni et al., 2025). Together, these findings suggest that hypnotizability may selectively influence sensorimotor integration and error-based motor adaptation. Whether this influence extends to other forms of motor learning remains unknown. Previous work has examined sequential motor execution rather than learning, reporting comparable sensorimotor activation in highs and lows during finger tapping (Gemignani et al., 2004).

The present study investigated whether visuomotor adaptation and sequential motor learning differ between highs and lows. We hypothesized highs would exhibit reduced visuomotor adaptation accuracy under perturbed sensory feedback compared with lows (Santarcangelo et al., 2008; Menzocchi et al., 2015), whereas sequential motor learning would be comparable between groups as it primarily relies on cortico-striatal networks rather than cerebellar mechanisms (Doyon et al., 2009). In addition, given the involvement of the autonomic nervous system in motor control and motor learning (Janig et al., 2014; Benarroch 2020; Yokoi et al., 2022; Yokoi, 2025), HR and SCL were recorded during both tasks.

Methods

The study was approved by the Bioethics Committee of the University of Pisa (n. 29/2022) and was conducted in accordance with the Declaration of Helsinki.

Participants

Thirty-three healthy volunteers (15 females; mean age ± SD: 27.2 ± 8.5 years) with normal or corrected-to-normal vision participated in the study. They were right-handed, as assessed with the Edinburgh Handedness Inventory (Oldfield, 1971). After obtaining written informed consent, a semi-structured interview confirmed the absence of neurological, psychiatric, or major medical disorders, sleep and attention disturbances, current medication, and regular video game practice (> 1h/week). Hypnotizability was assessed using the Italian version of the Stanford Hypnotic Susceptibility Scale, Form A (SHSS: A; Weitzenhoffer & Hilgard, 1959). Participants were initially classified as high (n = 13; SHSS: A ≥ 8), medium (n = 7; SHSS: A = 5–7), or low (n = 13; SHSS: A ≤ 4) hypnotizable. Because only seven participants were medium hypnotizable, they were pooled with the adjacent groups, resulting in a medium-to-high (MH) group (n = 14, 8 females; SHSS: A = 8.88 ± 1.32) and a low-to-medium (LM) group (n = 19, 7 females; SHSS: A = 2.88 ± 1.82). *A priori* power analyses performed with G*power (with f = .025, 1 - ß = .95, α = .05) indicated that a minimum of 18 and 20 participants were required for VAT and FTT analyses.

Experimental procedure

The experimental session took place between 9:00 and 12:00 a.m. (to exclude cognitive load and fatigue due to preceding activities) in a quiet, dim, temperature-controlled room to prevent bias in the recorded autonomic variables.

Visuomotor adaptation task (VAT)

The VAT was programmed in Python using the Pygame library within a custom experimental framework. Participants sat approximately 60 cm from the laptop display and controlled an on-screen cursor with a joystick using their left (non-dominant) hand. At the beginning of each trial, the cursor was positioned within a home circle located below the center of the screen. Participants were required to maintain the cursor within the home position for 500 ms while fixating it before each trial (Fig. 1). Following this fixation period, a green target appeared in the upper part of the screen, serving as the imperative go cue. Participants were instructed to initiate the movement only after target onset and to perform a single reaching movement toward the center of the target as accurately and quickly as possible. They had 800 ms to complete the movement. If they had not reached the target within this time, the trial was considered a miss. Movements initiated before target appearance triggered a warning signal (yellow circle surrounding the cursor), requiring participants to return to the home position before the trial resumed. Following movement completion, visual feedback indicating whether the target had been successfully reached was displayed for 800 ms. The VAT was performed under three visuomotor conditions presented in a randomized order: no perturbation (0°), leftward (− 20°), and rightward (+ 20°), corresponding to rotations of the visual cursor. Each condition consisted of 200 reaching trials. Performance was quantified using two complementary measures: the number of successful target hits (HITS) and the mean-square error (MSE), calculated as the deviation of the executed trajectory from the

ideal straight-line trajectory between the home position and the target. Heart rate (HR, bpm) and skin conductance level (SCL, µS) were measured during the task.

Finger tapping task (FTT)

The FTT was performed with the left (non-dominant) hand. Participants placed their little, ring, middle, and index fingers on four adjacent keyboard keys, corresponding to positions 1 to 4 of the sequence. The task consisted of repeatedly performing an eight-item sequence (i.e., 4-2-3-1-3-2-4-1), with each number corresponding to one finger. Before practice, participants viewed the sequence displayed on the screen and were instructed to reproduce it on the keyboard until achieving three consecutive correct repetitions to familiarize themselves with the task. Then, they completed 10 blocks of finger tapping lasting 30s each, separated by a 20-s rest interval. During each block, they repeatedly reproduced the displayed sequence as quickly and accurately as possible. Motor performance was assessed using the number of correctly completed sequences during each 30-s trial and the mean time (s) employed to correctly execute as many sequences as they can. HR and SCL were recorded throughout the task.

Each participant completed one VAT and one FTT, with the order randomized across participants. Therefore, participants performed both tasks once.

Electrocardiogram and skin conductance level acquisition and analysis

Electrocardiogram (ECG) and SCL signal were continuously monitored using a Psylab device (Contact Precision Instrument, Chur, Switzerland) and stored for offline analysis. ECG was acquired using disposable electrodes (https://www.fiab.it/it/index.php) placed according to the standard DI configuration, whereas SCL was recorded using two electrodes attached to the middle phalanges of the index and middle fingers of the dominant hand. A common reference electrode was used for both recording, and all signals were sampled at 250 Hz. ECG recordings were visually inspected for noise, movement artifacts, and ectopic beats. Artifactual R-peaks were corrected using cubic spline interpolation, and recordings containing more than 5% artifacts were excluded. The ECG signal was band-pass filtered (0.5–20 Hz) and heart rate (HR) was computed as 60/mean RR interval for each experimental condition (for VAT: no perturbation, left and rightward perturbation. For FTT: each block). For SCL, abrupt signal variations exceeding 3 standard deviations from the local mean, computed over a 2-s sliding window, were identified as artifacts. The signal was then detrended, baseline-corrected by subtracting its value, low-pass butter filtered using a fourth-order Butterworth filter (0.5 Hz cutoff) and smoothed with a Savitzky-Golay filter (Savitzky & Golay, 1964).

Statistical analysis

Statistical analyses were performed using SPSS 15 (IBM Corp., Armonk, NY, USA). Normality was assessed using the Shapiro-Wilk test. For the VAT, the 200 trials were divided *a posteriori* into four consecutive Blocks of 50 trials (B1–B4). The HITS and MSE were averaged within each Block and analyzed using repeated-measures analyses of variance (RM-ANOVAs) with Group (MH, LM) as the

between-subjects factor, and Condition (0°, -20°, + 20°) and Block (B1–B4) as within-subjects factors. Motor performance during FTT was analyzed using RM-ANOVAs with Group (MH, LM) as the between-subject factor and block (b1-b10) as the within-subject factor. Separate analyses were performed for the number of correctly completed sequences and mean movement time. HR and SCL were analyzed using the same repeated-measures ANOVA design. When the assumption of sphericity was violated, Greenhouse–Geisser corrections were applied. Contrast analysis was used for post hoc within-group comparisons. Statistical significance was set at $p < 0.05$.

Results

VAT

HITSexhibited significant main effects of Condition ($F(2,62) = 90.35$, $p < .001$, $\eta^2 = .80$) and Block ($F(3, 93) = 11.28$, $p < .001$, $\eta^2 = .34$) and a significant Condition x Block interaction ($F(6,186) = 4.94$, $p < .001$, $\eta^2 = .18$). Post hoc analysis revealed significantly more target hits in the no perturbation condition than in both perturbation conditions across all Blocks (Figure 2; Table S1). In addition, the rightward perturbation (+20°) resulted in fewer hits than the leftward perturbation (-20°) during B1, B2, and B4, whereas no difference was observed during B3 (Table S1). The Group effect ($p = .32$) and the Block x Group ($p = .47$), Condition x Group ($p = .80$) and Block x Condition x Group ($p = .097$) interactions were not significant.

MSE showed significant main effects of Condition ($F(2,62) = 618.62$, $p < .001$, $\eta^2 = .96$) and Block ($F(3,93) = 10.65$, $p < .001$, $\eta^2 = .33$). Significant Group x Condition ($F(2,62) = 40.82$, $p < .001$, $\eta^2 = .65$), and Group x Block x Condition ($F(6,186) = 8.88$, $p < .001$, $\eta^2 = .29$) interactions were observed. Post hoc analyses of the three-way interaction (Figure 3) revealed that the difference between hypnotizability groups was observed only for the rightward perturbation (+20°). In this condition, MH group exhibited a greater MSE than LM group during B2 ($p < .002$), B3 ($p < .001$), and B4 ($p < .001$). Furthermore, MSE progressively increased across Blocks in the MH group, with higher values in B2, B3, and B4 than in B1, whereas no significant Block effect was observed in the LM group. No between-group differences were found in either the no-perturbation or left perturbation (-20°) conditions. Within both groups, MSE was greater in the perturbation conditions than in the no-perturbation conditions (Table S2).

HR (Figure 4a) revealed only a significant Block effect ($F(3,93) = 4.19$, $p=.016$, $\eta^2 =.119$, $\alpha = .750$) with B1 < B4 ($F(1,31) =7.26$, $p=.011$) and B3 < B4 ($F(1,31) = 11.18$, $p =.002$), and no significant difference between B1 and B2, and between B2 and B3. No significant Condition ($p = .39$) and Group ($p = .67$) effects were disclosed.

SCL (Figure 4b) showed significant Condition ($F(2,62) = 3.83$, $p = .027$, $\eta^2 = .110$, $\alpha = .675$) and Block effects ($F(3,93) = 12.63$, $p = .0001$, $\eta^2 =.290$, $\alpha = .982$). The Condition effect consisted of higher SCL in the leftward deviated condition than in the no perturbation condition ($F1,31) = 6.24$, $p=.018$), and no other significant difference. The Block effect consisted of B1 > B2 (df:1,31; $F = 26.07$, $p = .0001$), B1 > B3

(F = 11.52, p = .002); B2 < B4 (F = 33.04, p = .0001), B3 = B4. Group effect did not reach significance (p = .31).

FTT

The number of correctly performed sequences exhibited a significant block effect (F(9,279) = 2.58, p < .05, η^2 = .077, α = .664), indicating an increase across blocks compared to b1 (df:1,31; b2, F = 17.78, p < .001; b3, F = 11.83, p < .01; b4, F= 1.81, p < .002; b5, F= 21.17, p < .001; b6, F = 4.75, p <.05). No significant **Group** effect (p = .60) and **Group × block (p = .76)** interaction were found.

The mean movement time employed for correctly executed sequences (Figure 5) exhibited significant main effects of Group (F(1,31) = 5.03, p < .05, η^2 = .140) and block effects (F(9,279) = 10.61, p < .001, η^2 = .25). Overall, MH group required more time to complete the correct sequences than LM group. However, both groups exhibited a progressive reduction in execution time across trials (Table S3). No significant **Group × block** interaction was observed (p = .87).

HR and SCL did not differ significantly between groups (HR: p = .45; SCL: p = .29) and remained stable across blocks (HR: p = .98; SCL: p = .70). No significant Group × block interactions were observed (all p > .05).

Discussion

The study investigated whether hypnotizability differentially influences visuomotor adaptation and sequential motor learning. Overall, the results indicate that hypnotizability does not impair motor learning generally but rather exerts a task-specific effect. Indeed, individuals with higher hypnotizability exhibited reduced accuracy during visuomotor adaptation, sequential motor learning showed comparable accuracy across groups, although finger-tapping performance was slower in highly than in low hypnotizable participants.

Kinesthetic perturbation significantly affected visuomotor adaptation in both hypnotizability groups, with fewer hits and greater trajectory error under perturbation than under no-perturbation conditions. This finding is consistent with seminal studies reporting that external perturbations initially increase movement errors before compensatory mechanisms progressively recalibrate motor output (Shadmehr & Mussa-Ivaldi, 1994; Krakauer et al., 2000). Importantly, although the number of successful hits improved across Blocks in both groups and under both perturbation directions, the high hypnotizable participants exhibited a progressive increase in trajectory error under the rightward perturbation. In contrast, trajectory errors remained stable across Blocks in the low-hypnotizable group, regardless of the perturbation condition. The highs' dissociation between hits and the trajectory error suggests that medium-to-high hypnotizability did not impair the ability to compensate for the perturbation but rather reduced the precision with which the movement trajectories were corrected during adaptation. The poorer performance of the highly hypnotizable participants under rightward rather than leftward perturbation (which occurs despite the former movement approaching the target, whereas the latter

does not) may reflect the preferential extensor-over-flexor strategy observed in the general population (Sainburg and Kalakanis, 2000). This asymmetry could be further enhanced in highs because of the lower excitability of the right motor cortex relative to the left one in the ordinary state of consciousness (Santarcangelo and De Pascalis, 2020). While this interpretation remains speculative, the highs' progressive increase in trajectory error across Blocks may reflect less effective sensorimotor integration with central commands, as previously suggested by postural and visuomotor tasks (Santarcangelo et al., 2008; Menzocchi et al., 2015). Since highly hypnotizable participants exhibited larger trajectory errors than lows, despite a similar number of successful hits, we argue that cerebellar-dependent adaptation remained functional but operated at a lower level of precision, consistent with the stabilogram diffusion analysis of body sway (Santarcangelo et al., 2008) and with the preserved directional adaptation, but reduced accuracy observed during prisms adaptation (Menzocchi et al., 2015). Since brain morphometry can account for behavioral variability even in the absence of functional assessment (Llera et al., 2019), the observed hypnotizability-related differences in visuomotor adaptation may critically depend on the cerebellar mechanisms involved in detecting sensory prediction errors and updating motor commands (Tseng et al., 2007; Synofzik et al., 2008; Krakauer et al., 2019), which differ according to hypnotizability

The changes in heart rate and tonic skin conductance across Blocks indicate an initial shift toward sympathetic predominance, followed by a progressive return to baseline. We hypothesize that this pattern accompanied the progressive acquisition of motor skills, as indicated by an increase in successful hits. Interestingly, the sympathetic responses have recently been shown to scale with movement error, suggesting a potential contribution of autonomic activity to implicit motor learning (Nogami et al., 2025). However, earlier studies of autonomic responses during sensorimotor adaptation have mainly relied on pupil dilation as an index of sympathetic arousal and have reported inconsistent findings (Yokoi and Weiler, 2022). Thus, direct comparison with the present findings should be approached with caution.

Since brain morphometry can account for behavioral variability even in the absence of functional assessment (Llera et al., 2019), the observed hypnotizability-related differences in visuomotor adaptation may reflect differences in the cerebellar mechanisms involved in detecting sensory prediction errors and updating motor commands (Tseng et al., 2007; Synofzik et al., 2008, Krakauer et al., 2019), which have been previously shown to differ according to hypnotizability.

In contrast to visuomotor adaptation, sequential finger tapping was only slightly impaired in participants with higher hypnotizability. Indeed, the two groups exhibited the same number of correctly performed sequences, likely due to the repetitive nature of the task, which relies more heavily on cortico-striatal than cerebellar circuits (Doyon et al., 2009), in the absence of hypnotizability-related differences in basal ganglia GMV (Picerni et al., 2025). The slower performance observed in highly hypnotizable participants may reflect lower excitability of left motoneurons associated with hypnotizability-related hemispheric cortical asymmetry (Santarcangelo & De Pascalis, 2020). Importantly, both groups progressively reduced the time required to correctly execute the sequences across blocks, indicating preserved sequential motor learning in the absence of sensorimotor perturbation. Thus, unlike postural and visuomotor tasks,

in which highs fail to improve their performance across repeated trials (Santarcangelo et al., 2008; Menzocchi et al., 2015), in the present study highly hypnotizable participants were able to acquire and optimize repetitive motor sequences similarly to low hypnotizables. This interpretation is consistent with evidence that two weeks of motor imagery training improves the functional equivalence between repetitive actual and imagined left arm-and-hand movements in both highs and lows (Malloggi & Santarcangelo, 2026). Owing to the repetitive nature of finger tapping, neither heart rate nor tonic skin conductance changed across blocks and differed between groups (Boettger et al., 2010). Heart rate increased slightly from the first to the last block, whereas skin conductance showed modest block-related fluctuations, suggesting limited autonomic modulation during task performance.

We must acknowledge a few limitations of the study. First, the inclusion of a small number of medium-hypnotizable participants (scores of 7 in the high group and 5 in the low group) may have attenuated the observed group differences. Second, the available sample size did not allow us to examine possible sex differences. Nonetheless, the sex-related differences reported in force production, endurance, and sensorimotor adaptation appear to reflect different motor strategies while resulting in comparable overall performance (Moreno-Briseño et al., 2010).

Summary

The present findings indicate that hypnotizability differentially influences visuomotor adaptation and sequential motor performance. Participants with higher hypnotizability exhibit reduced precision during sensorimotor adaptation. likely due to less efficient cerebellar-dependent error-correction mechanisms, while preserving the ability to compensate for visuomotor perturbations (Santarcangelo et al., 2008; Menzocchi et al., 2015). Also, highly hypnotizables perform the sequential motor task more slowly than low hypnotizables, although both groups exhibit comparable motor accuracy and learning, which can be accounted for by the well-established functional asymmetry between the anterior regions of the brain hemispheres observed in highs in the ordinary state of consciousness (Santarcangelo and De Pascalis, 2020). The autonomic balance shifts toward a sympathetic prevalence only during visuomotor adaptation in both groups.

Future research should combine behavioral tasks with neurophysiological assessments to directly link cerebral and cerebellar mechanisms to the observed behavioral differences and to clarify the contribution of autonomic activity to action (Nogami et al., 2025). Overall, our findings further support the view that hypnotizability modulates sensorimotor functions independently of hypnotic induction and specific suggestions (Santarcangelo, 2024), thereby accounting for differences in daily behavior.

Declarations

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Author Contribution

EM, ELS, and UD : conceptualization; EM: investigation and data curation; DT and GD:software , EM visualization; EM, ELS write the paper; ELS: supervision; EM, ELS, and UD wrote the paper

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Data availability statement.

Data available on request from the authors.

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Figures

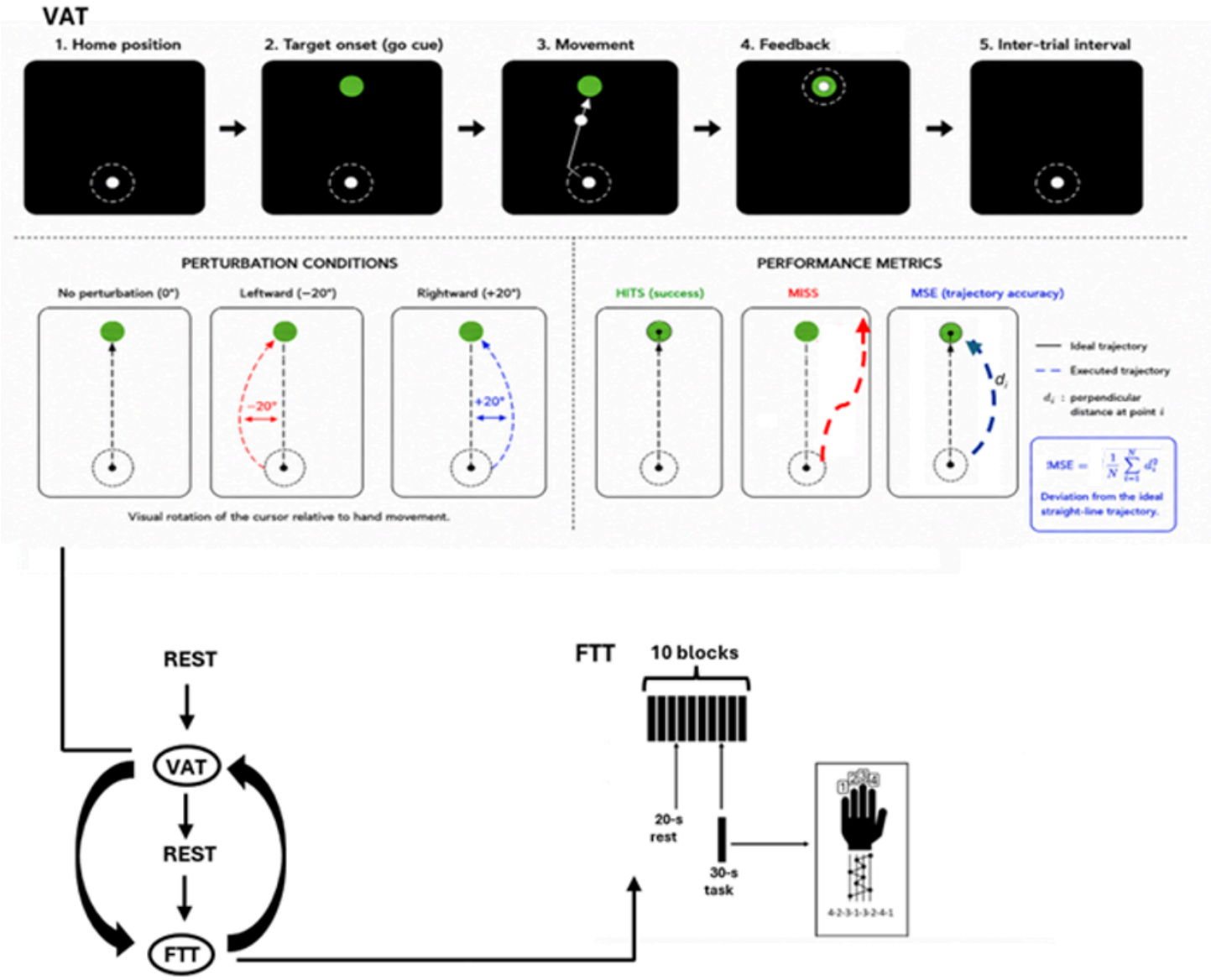


Figure 1

Experimental design of the Visuomotor adaptation (VAT) and sequential finger-tapping (FTT) tasks. VAT consisted of joystick-controlled reaching movements performed under no-perturbation (0°), leftward (−20°), and rightward (+20°) cursor rotation conditions presented in a randomized order. Each trial included a 500 ms home-position period, target onset (go cue), movement execution, visual feedback (800 ms), and an inter-trial interval. Performance was quantified by the number of successful target hits (HITS) and the mean-square error (MSE), computed as the deviation of the executed trajectory from the ideal straight-line path between the home position and the target. The sequential FTT consisted of repeatedly performing an 8-item finger sequence during ten 30-s practice blocks separated by 20-s rest intervals. The order of VAT and FTT was randomized across participants. Each participant completed one VAT and one FTT, with the order randomized across participants. Therefore, participants performed both tasks once.

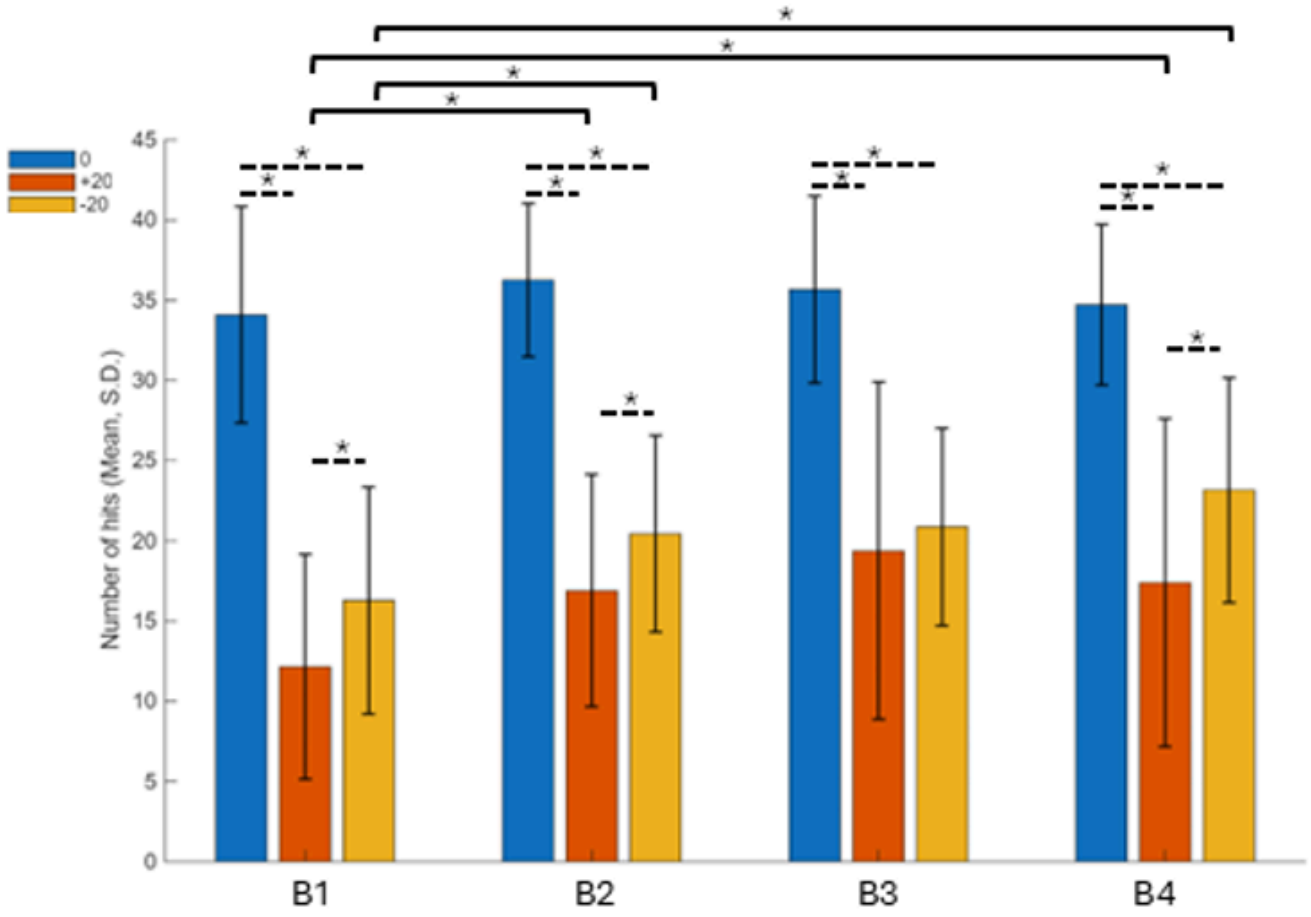


Figure 2

Number of successful hits across Blocks (B1,… for the no-perturbation (0°), rightward (+20°), and leftward (-20°) perturbation conditions. Both groups increased their HITS across Blocks in both perturbation conditions. Continuous and dotted lines (*) indicate significant Block and condition differences, respectively.

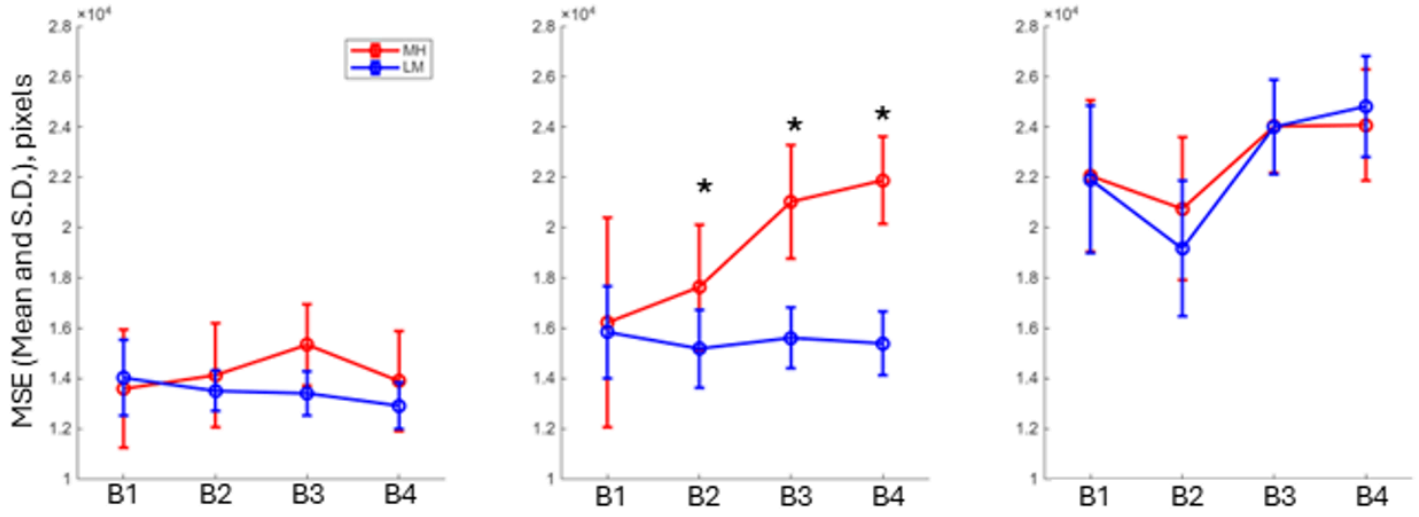


Figure 3

Mean MSE across Blocks under the no-perturbation (0°), rightward (+20°), and leftward (-20°) perturbation conditions in MH and LM hypnotizability. * Significant between-groups ($p < .05$). Under the +20° perturbation, MSE was significantly greater in MH than in LM participants in Blocks B2–B4. For statistics, see text.

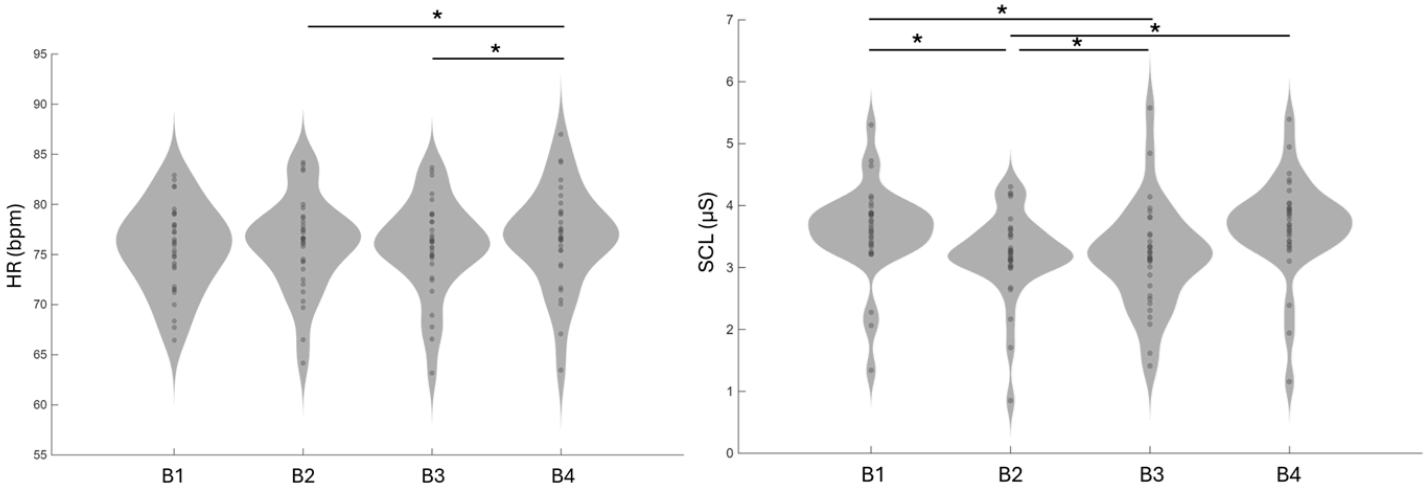


Figure 4

Autonomic responses across VAT Blocks. (a) Heart rate (HR, bpm). (b) Skin conductance level (SCL). Violin plots show the distribution of individual values across the four experimental Blocks (B1–B4). Dots represent individual participants. Horizontal bars denote significant differences between Blocks ($p < 0.05$).

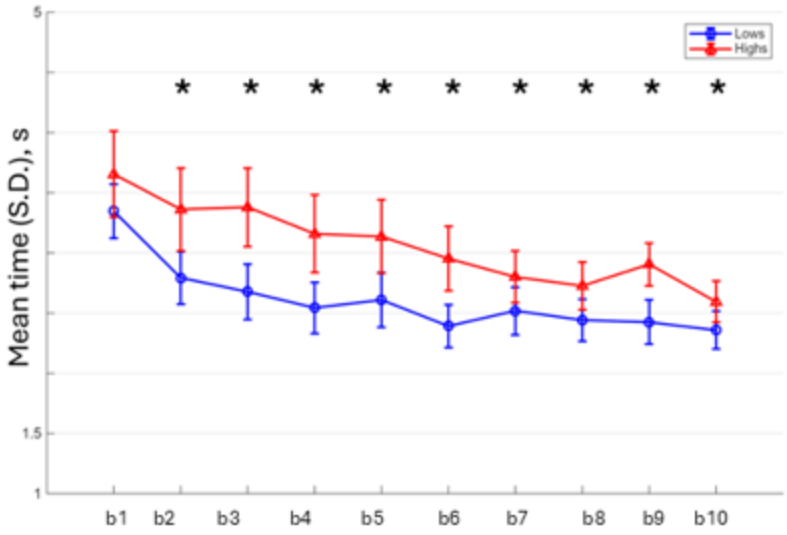


Figure 5

Time employed to complete correct FTT sequences in each block (1-10). Abscissae, order of blocks; ordinate, employed time (Mean, SD). *, significant differences between the first (T1) and subsequent blocks in both groups. It decreased in both groups, although more in highly hypnotizables (MH) than in low hypnotizables (LM). For statistics, see text.

Supplementary Files

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