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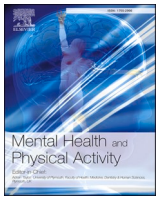

Testing a cognitive-motor dual-task training for autistic children on anticipatory and reactive brain processing, and behavior: A pilot study

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ABSTRACT

Background and aims: This study investigated motor, cognitive, and brain function in children with autism spectrum disorder (ASD) to evaluate the feasibility of a 12-week cognitive-motor dual-task (CMDT) training program aimed at exploring task-related behavioral and neural changes in comparison with typically developing (TD) peers.

Methods: Twenty-one participants (10 ASD, 11 TD; ages 10–14) were recruited. The ASD group underwent a twice-weekly CMDT session, while the TD group was assessed twice to monitor for learning and developmental effects. Pre- and post-training evaluations included motor tests, cognitive and behavioral measures, and event-related potential (ERP) measures during a visuomotor task.

Results: The ASD group showed improvements in motor skills and response speed ($p < 0.05$), getting closer to TD children. ERP indicated significant post-training increases ($p < 0.01$) in the Bereitschaftspotential (BP) and visual negativity (vN), suggesting changes in motor and sensory readiness. The N1 component, commonly linked to attentional processing, was consistently larger in the ASD group ($p < 0.01$), suggesting heightened sensitivity to visual stimuli. The P3 amplitudes, initially minimal in the ASD group, increased ($p < 0.05$) following training, which may reflect changes in task-related neural processing.

Conclusion: These findings suggest that CMDT was associated with changes in motor performance and task-related measures in children with ASD, possibly reflecting changes in brain processes related to anticipation, attention, and cognitive integration.

1. Introduction

Autism spectrum disorder (ASD) is a cluster of neurobiological diseases involving behavior, social relations and communication disruptions, and cognitive problems (e.g., Vismara & Rogers, 2010). The deficit in cognitive-motor functions might cause poorer language skills, movement speed and strength, and emotion regulation, lasting throughout childhood (e.g., Gandotra et al., 2020). The literature on the neurobiological bases of ASD showed atypical cerebellar overgrowth in the first year of life (e.g., Weigelt et al., 2012; Courchesne et al., 2011). Motor control and cognitive functions are disturbed because of this excessive growth, as well as cerebral and limbic functions. These anomalies have been associated with altered cerebral activation that may affect higher-order cognitive functions such as emotion, language, social cognition, and attention (e.g., Wolff et al., 2012). For instance, abnormality in communication between cortical, striatal, and thalamic

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circuits has been proposed as one of several mechanisms contributing to repetitive behaviors observed in ASD (Minshew & Williams, 2007).

At the electrophysiological level, many event-related potential (ERP) studies compared ASD and typically developing (TD) people, showing differences in several post-stimulus components, especially for auditory stimuli, finding reduced mismatch negativity and P1 associated with early sensorial processing and increased attentional orienting for novel sounds indexed by the P3a component. No effects were found for the later P3 component commonly linked with stimulus categorization and memory updating. Studies using language-related stimuli showed diminished responses, suggesting impairments in speech processing. This data suggests that auditory processing is altered in individuals with ASD, while evidence on attentional functions remains mixed. However, sensory processing may interfere with information recognition and integration, and speech comprehension (for a recent review Goncalves & Monteiro, 2023). ERP studied on visual modality also showed deficits in sensory processing, mainly indicating effects on the anterior N1 amplitude for non-face stimuli, and reduced N170 amplitude and increased latency for face stimuli. The P2 and P3 components, often associated with post-perceptual attentional and cognitive processing, are also diminished in some studies. Effects on P1 and N1 components yielded inconsistent results (for recent reviews Farashi et al., 2023; Mazer et al., 2024).

Nevertheless, since sensorimotor dysfunctions are the core issues in ASD, surprisingly, only a few studies investigated anticipatory brain activity as the motor and cognitive preparation for sensorimotor tasks. Sokhadze et al. (2016) found deficits in response selection, measuring the lateralized readiness potential (LRP) during a Posner cueing task. Wakim et al. (2023) found a reduction of motor preparation indexed by the Bereitschaftspotential (BP) preceding self-paced movements. No information is available on motor preparation in sensory-motor tasks. However, a recent study (Häger et al., 2024) proposed that ASD symptoms have been hypothesized to involve alterations in Bayesian inference, potentially reflecting reduced engagement of top-down predictive mechanisms, since they found a reduction of an anticipatory ERP component index of visual readiness and named visual negativity (vN). The vN was first described by Di Russo et al. (2019) as a modality-specific negative ramp rising over occipital areas and preceding any predictable visual stimulus. This shortage of studies on task preparation should spur research toward anticipatory processing for a better understanding of the neural underpinnings of social interaction challenges in ASD.

The ASD deficits affect daily functions, causing challenges in team activities, participation, and social development. Therefore, interventions targeting cognitive and motor functions is the focus of ASD treatments to improve the quality of life of children with ASD. Studies demonstrate that after physical activity treatments, children with ASD showed overall improvements in fundamental movement skills (e.g., Bo et al., 2019) but also improvements in adaptive behaviors and social skills (e.g., Bremer et al., 2015). Therefore, motor-based interventions have been proposed as non-pharmacological approaches supporting functional domains commonly affected in ASD. A modern form of training named cognitive-motor dual-task (CMDT) training has also been used in these patients. The CMDT training is characterized by the simultaneous execution of both cognitive and motor tasks within the same exercise (e.g., Lucia et al., 2023). CMDT training has been tested in children with ASD a few times only. de Souza et al. (2017) and Yaghoubi et al. (2024) tested the effect of a CMDT on the gait and balance of ASD children but found little or no effect. This lack of effect may be related to the limited cognitive–motor challenge of the proposed tasks. Nekar et al. (2022a,b) tested CMDT training based on a multiplayer game using augmented reality and found improvements in social skills and cognitive function; however, no motor tests were used. A randomized control trial study (Asghar et al., 2022) showed that CMDT training using exercises with heavy cognitive loads is more effective than those with a light cognitive load on balance, mobility, and cognitive performance of children with ASD. None of these CMDT protocols included progressions of task difficulty, which is a key feature for successful CMDT training. Progression is essential to avoiding user frustrations at the beginning of the training for tasks that are too difficult; it promotes learning and motivation, positively affecting self-efficacy (e.g., Lucia et al., 2024), especially in children (e.g., Wigfield & Eccles, 2000).

Given that CMDT training for ASD children with the mentioned features is still lacking in this pilot study, we aimed to explore the feasibility and task-related impact of a novel CMDT training, including complex motor and cognitive exercises, but allowing for difficulty progression. In addition, for the first time, the training effect is evaluated not only behaviorally, but also by measuring anticipatory and reactive brain processing during a simple visuomotor task using ERP analysis. If successful, we will tune the training and expand the study to a larger sample. According to ASD literature, before the CMDT training, we expect poorer motor and cognitive skills in ASD than in TD children; these effects should be paralleled by a reduction in reactive brain processing as shown in some studies (e.g., Farashi et al., 2023; Mazer et al., 2024), but we also expect lower BP and vN amplitudes in the ASD group, consistent with previous reports of altered anticipatory neural activity (Häger et al., 2024). If this CMDT training is feasible and engages the targeted processes in children with ASD, we anticipate post-training changes in behavioral and neural measures that could descriptively approach those observed in TD children.

This pilot tested the feasibility of delivering CMDT and assessing motor, cognitive, and ERP outcomes to inform a future, adequately powered trial. Specifically, we hypothesize that the sensorimotor integration, task anticipation, and attention fostered by CMDT may be associated with changes in neural activity during task execution, potentially reflecting increased processing engagement. At the cortical level, this gain may be associated with amplitudes increasing in both the motor (BP) and sensory-cognitive (vN) aspects of top-down anticipatory processing, as well as augmented cognitive resource allocation and task relevance evaluation (P3), particularly under simpler tasks when cognitive efficiency improves (e.g., Polich et al., 2007). Because even simple visuomotor response tasks depend on visual processing, we also hypothesize that CMDT may enhance stimulus detection and subsequent response processes (e.g., Bo et al., 2022) by reinforcing cortical networks involved in cognitive and motor control (e.g., Lucia et al., 2024).

This study will therefore contribute to understanding ASD-related neural dysfunctions and evaluate the feasibility of a non-pharmacological, cost-effective intervention that may simultaneously support motor and cognitive skills in children with ASD.

2. Material and methods

2.1. Participants

Sample size was chosen for feasibility, not statistical power. Thus, for this study, 10 ASD and 11 TD children were recruited; however, one TD child refused to be submitted to the cognitive test and the EEG recording and therefore was excluded from all analyses that were performed on the two groups of ten.

The inclusion criteria for the ASD group were a) age between 10 and 14 years; b) a clinical diagnosis of ASD at level 1 or 2, based on a medical certification provided by a specialist according to the DSM-5; c) eligibility for participation in physical activity protocols as confirmed by clinical evaluation. The exclusion criteria were a) use of medications or substances that could affect cognitive, executive, or motor abilities; b) presence of contraindications for the proposed activities in the protocols; c) recent injuries or conditions that rendered the participant unsuitable for physical exercise. Intellectual disability and language functioning were assessed during clinical evaluation. According to this prior evaluation performed by qualified specialists, participants did not present comorbid intellectual disability or severe language impairment at the time of enrollment that would prevent task execution.

Standardized cognitive or language scores were obtained, but they were not available for inclusion in the analyses. This group included 2 females and 8 males, and the mean age was 12.3 years.

The inclusion criteria for the typical development (TD) group were the absence of any neurological or psychiatric disorders, the absence of any medication during the experimental sessions, and normal or corrected-to-normal vision. Age from 10 to 14 years. A minimum of 6 h of exercise a week in the last 12 months. This group included 2 females and 9 males, and the mean age was 12.8 years. For the cognitive and electrophysiological tests, the group included 2 females and 8 males, and the mean age was 12.9 years, since one TD participant did not agree to the measures.

A flow chart illustrating the enrollment process, including inclusion/exclusion criteria, and the number of participants at each stage of the study, is shown in Fig. 1. The attendance and session completion rates were high (<90%).

Before taking part in the study, both parents of all participants gave their informed consent in accordance with the Declaration of Helsinki after approval by the local ethical committee of the University of Rome "Foro Italico" (CAR 170/2023).

2.2. Procedure

Both groups were submitted to two screening test sessions 12 weeks apart, including motor, cognitive, and electrophysiological measures. During this period, the ASD group performed the CMDT intervention, described below. The TD group was screened twice to monitor potential learning and developmental effects.

2.2.1. CMDT intervention

A CMDT training protocol was implemented over 12 weeks, with two 50-min sessions per week. Sessions were conducted in the sports facilities where the children usually carried out their activities and were scheduled in the early afternoon. The intervention was delivered and supervised by sports kinesiologists with experience with ASD children. Before the intervention, a preparatory training module was administered by experienced professionals to familiarize participants with task procedures and manage ASD-related behavioral needs. The module focused on behavior management, communication strategies, and safety procedures for ASD populations. The instructor-to-participant ratio was two instructors per three children. Moreover, a third staff member was present during each session to ensure supervision and address any potential emergencies. Training intensity was not instrumentally monitored, as the use of devices such as heart rate monitors caused discomfort for the children.

Each session followed a structured routine of dual-task exercises, as reported in Table 1. Activities were performed with approximately 90 s of rest between them, and each session lasted about 50 min. All children started at level 1. The protocol comprised four levels of progressively increasing difficulty (Table 1). Performance was quantified as the number of completed trials. The progression to the next level occurred when a child completed the task twice consecutively with no more than one to two errors. Before starting a new level, a familiarization session was conducted to help children understand the instructions, reduce anxiety, and adapt to the testing environment. In this session, the tasks were first verbally explained and then modeled by instructors. Instructors adjusted pacing and support according to performance. No time limits to complete the task were adopted.

The activities combined motor and cognitive demands. Motor tasks targeted spatial–temporal orientation, static and dynamic balance, aiming and catching precision, upper- and lower-limb coordination, and jumping proficiency. The cognitive component targeted selective and sustained attention, problem-solving, associative memory, numerical calculation, and alphabet recognition. Schematic representations of

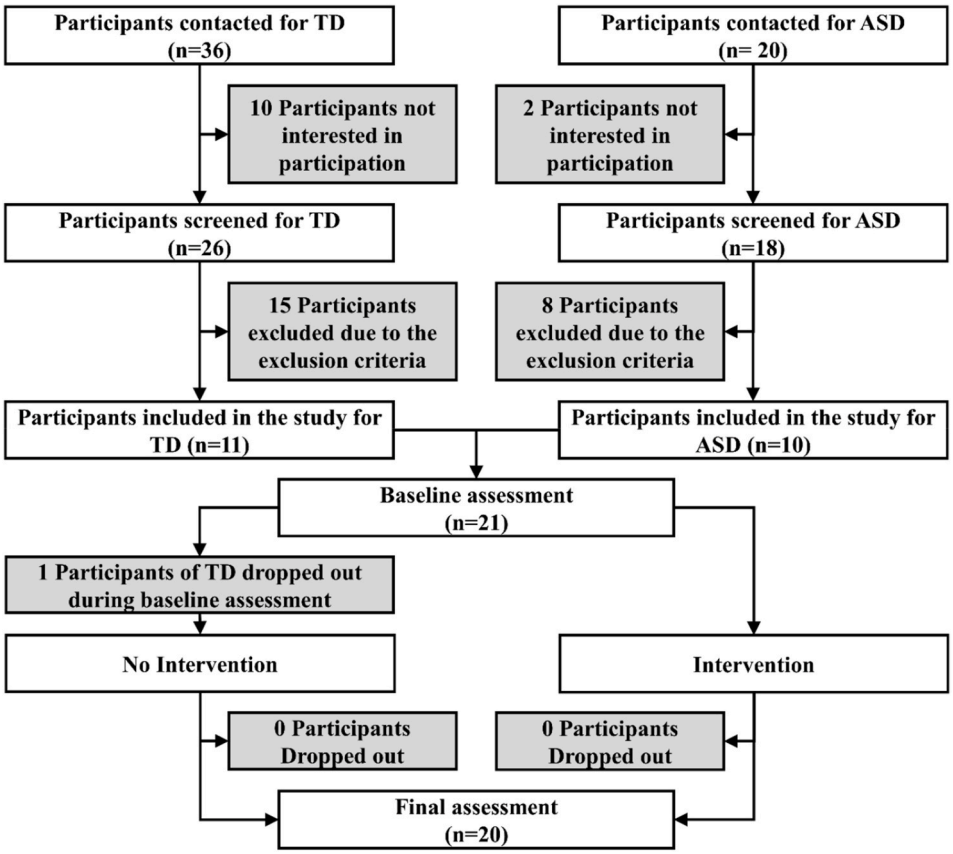

Fig. 1. Flow chart illustrating the enrollment process, including inclusion/exclusion criteria, number of participants at each stage of the study.

Table 1
Description of CMDT training exercises for ASD children across four levels of complexity for each exercise. The threshold to reach the next level was two consecutive task completions with no more than 1-2 errors.

Exercise	Level 1	Level 2	Level 3	Level 4
Flags in order	Following a predefined path, collect the numbered flags sequentially.	Collect flags in ascending numerical order.	Collect the flags in numerical order, placed randomly, bringing them back to the base one at a time and alternating colors (e.g., 1 red, 2 yellow, 3 red, 4 yellow …).	Collect both the numbered flag and the lettered flag (e.g., 1-A, 2-B) and return to the base in sequential order
Shapes and color in motion	Jump inside rings of the same color associated with a geometric shape. The children had to remember the number of executed jumps.	Same task as level 1, but the geometric-shaped equipment and the color are chosen by the operator.	Combined activity with multiple shapes, associating jumps and specific movements. The children had to remember the number of executed jumps.	Same task as Level 3, performed in pairs. One child selects the task modality for the other.
Zoo expedition	Imitate animal movements until reaching the target and completing a task (e.g., wall throw).	Imitate animal movements until the target, adding a more complex task (e.g., catching a ball after it bounces).	Imitate animal movements and perform target shooting at images of animals placed at different heights.	Same task as Level 3, performed in pairs while swapping targets.
Symphony of steps	Run randomly and stop with some ground touches specified by the operator.	Same task as level 1, performed in pairs.	Same task as Level 1, performed in groups of three.	Same task as Level 1, performed in groups.
Jump between letters	Follow the paths of rings arranged to form alphabet letters, jumping with both feet.	Follow more complex letters with varying directions, combining single-leg jumps.	Jump along paths with unstable surfaces and letters requiring advanced movements. Take a numbered flag and add its value to the total number of jumps performed.	Jump along paths with unstable surfaces and letters requiring advanced movements. Provide the name of an animal or object that begins with the same letter as the "letter" flag.

some of these tasks are depicted in Fig. 2. As reported in the introduction section, CMDT activities were selected based on: Sensorimotor deficits commonly documented in ASD literature; prior CMDT research emphasizing simultaneous motor-cognitive integration; and neuro-cognitive theories (e.g., predictive coding, sensorimotor integration deficits) underlying training rationale.

2.2.2. Screening

The measurements described below were conducted in university laboratories, in quiet environments with a controlled temperature of 22 °C, during the early afternoon. Cognitive and motor tests were carried out on separate days, without randomization. Specifically, motor tests (MABC-2) were performed on one day, whereas cognitive tests, including EEG recording, were administered on different, non-consecutive days.

2.2.2.1. Motor test. Motor skills were assessed using the Movement Assessment Battery for Children – Second Edition (M-ABC2), a validated tool (Henderson et al., 2007) designed to identify and classify motor difficulties, targeting children and adolescents aged 3 to 16 years. The M-ABC2 evaluates three main domains: manual dexterity (e.g., hand coordination), aiming and catching (fine and gross motor precision), and static and dynamic balance. This test is widely employed to identify motor impairments, monitor progress in intervention programs, and provide an objective evaluation of a child's motor skills relative to normative standards. The M-ABC2 total standard score was used for statistical analysis. This score is calculated based on the performance of the child across the three main domains of the test. Each domain was

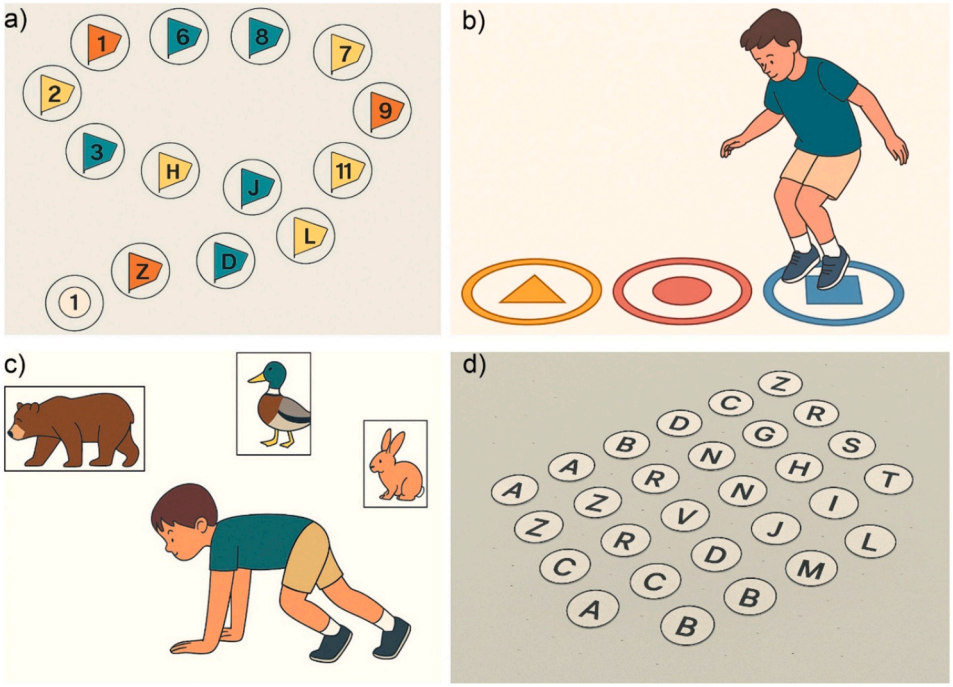

Fig. 2. Schematic representation of the CMDT training exercises: a) Flags in order; b) Shapes and color in motion, c) Zoo expedition; d) Jump between letters. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

assessed independently and then summed into a total score. The total score is age-standardized, with normative values ranging from 1 to 19 for children, where higher scores indicate better motor performance. To avoid bias, one or two practice trials were conducted to ensure that the children clearly understood the task to be performed during the test. The MABC-2 was administered and scored by a trained researcher who was not involved in delivering the intervention, minimizing bias.

2.2.2.2. Cognitive test. A simple response task (SRT) requiring visual detection and motor responses was conducted during the EEG recording. The participants sat 114 cm from a computer monitor and kept a response box in their right hand. A central fixation point on a black background was present during the entire run. Four visual stimuli, each with an equal probability, were randomly presented for 250 ms with a variable interstimulus interval from 1200 to 2200 ms. The stimuli were square configurations measuring 4 × 4° made up of vertical and/or horizontal bars. The task was to press the response button as soon as possible when any visual stimuli were detected. The run included 60 trials, and the duration was 102 s. The session included 5 runs with pauses requiring about 15 min. The response time and accuracy (expressed as the percentage of omitted responses) were used for statistical analysis. Also, in this case, one or two familiarization trials were conducted to ensure that the children clearly understood the task to be performed during the test. Cognitive and EEG recording were administered by a trained experimenter independent from the instructors, ensuring blinding to intervention progress.

2.2.2.3. EEG recording and ERP analysis. EEG data were recorded using a 32-channel EEG system (BrainAmp™ amplifiers) with active electrodes (Acticap™) and software (Recorder 1.2 and Analyzer 2.2) all by BrainProducts GmbH (Gilching, Germany). The electrodes were fitted according to the 10-20 international system and referenced to the average of the M1–M2 electrodes. The EEG was amplified, digitized at 250 Hz, band-pass filtered using a Butterworth zero-phase filter (0.01–60 Hz and 50 Hz notch filter; second order), and stored for offline analyses. The eye movements were controlled by electrooculograms (EOG) recorded by a second BrainAmp amplifier (ExG type) in bipolar modality. Horizontal EOG was recorded with an electrode pair over the left and right outer canthi of the eyes, while vertical EOG (VEOG) was recorded with an electrode pair below and above the left eye. Electrode impedances were kept below 5 KΩ. The correction of blink and vertical eye movement artifacts was automatically performed using independent component analysis. Data were then submitted to automatic artifact rejection, excluding EEG with amplitudes exceeding the threshold of ±70 μV. On average, 2.5% of trials were rejected. To evaluate pre-stimulus activity, EEG was segmented into 1300 ms epochs, starting 1100 ms before and ending 200 ms after stimulus onset. The baseline was fixed from −1100 to −900 ms. To evaluate post-stimulus activity, EEG was segmented into 1000 ms epochs, starting 100 ms before and ending 900 ms after stimulus onset. The baseline was fixed from −100 to 0 ms. Two different baselines were necessary since, to be appropriate, they have to precede the ERPs of interest, as usually done in the literature (e.g., Di Russo et al., 2019; Polich, 2007).

To select the intervals and electrodes to be taken into consideration in statistical analysis, the "collapsed localizer" method was used (Luck & Gaspelin, 2017) in which a localizer ERP is obtained by collapsing (averaging) all experimental conditions. To identify the intervals of analysis, the global field power (GFP) was calculated. The GFP describes the ERP spatial variability at each time point, considering all scalp electrodes simultaneously, resulting in a reference-independent descriptor of the potential field. The pre- and post-stimulus intervals in which the one-sample t-tests against zero were significant ($p < 0.05$ after Bonferroni correction) were used for further analysis. This approach selected one pre-stimulus interval from −620 ms to 0 ms, and the following three post-stimulus intervals: 116-160, 192-224, and 294-352. To identify the electrodes to be included in the statistical analysis, we selected those that had a mean amplitude in the mentioned intervals significant ($p < 0.05$ after Bonferroni correction) in the one-sample t-tests against zero executed on the localizer ERP. This procedure identified in the pre-stimulus interval two foci of activity. A medial central activity, including the FCz and Cz electrodes representing the BP component, and a bilateral occipital activity, including the PO7, O1, O2, and PO8 electrodes representing the vN component. In both the first two post-stimulus intervals, the procedure selected the PO7, O1, O2, and PO8 electrodes representing the P1 and N1 components. The later interval, the Cz and CPz electrodes were selected, representing the P3 component.

Fig. 3 shows the GFP of the pre- and post-stimulus ERPs and the intervals selected based on the *t*-test against zero. In addition, the figure shows the scalp topography at the selected intervals.

2.2.3. Statistical analysis

Before statistical analyses, the normality assumption for all variables was assessed using the Shapiro–Wilk test. None of the distributions deviated significantly from normality. For all the measures used in the screening, mixed (between-within) 2x2 analyses of variance (ANOVA) were used. The within-factor was the Time (pre-test vs. post-test). The between factor was the Group (ASD vs. TD). The alpha level was set at 0.05, and partial eta-squared (ηp^2) was calculated as an effect size measure. Post-hoc analyses were performed using the Bonferroni correction. Cohen's d was also reported to quantify the effect size for post-hoc tests. Analyses were performed using the "Statistica" software version 15 (StatSoft Inc, Tulsa, OK USA).

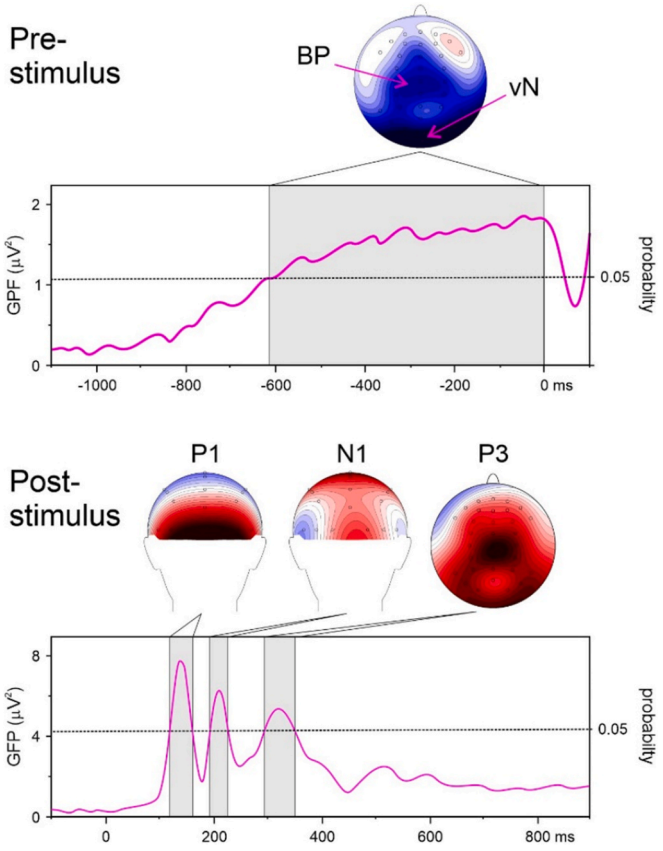

Fig. 3. Global field power (GFP) of the pre-stimulus and post-stimulus collapsed localizer ERP, and the intervals selected based on the *t*-test against zero. The scalp topographies are relative to the indicated intervals which are highlighted by grey shadows.

3. Results

3.1. Motor test

The ANOVA on the M-ABC2 total score showed a significant main effect of both Group ($F_{(1,19)} = 53.8$, $p < 0.01$, $\eta p^2 = 0.74$) and Time ($F_{(1,19)} = 133.0$, $p < 0.01$, $\eta p^2 = 0.87$) factors, indicating a larger score in the TD group and in the post-test. The interaction between Group and Time was also significant ($F_{(1,19)} = 20.4$, $p < 0.01$, $\eta p^2 = 0.52$). Post-hoc analyses showed that both groups improved their score in the post-test ($t_{(18)}$>8.1, $p < 0.01$, $d > 0.88$), but while in the pre-test, the TD group (11.9, SD = 2.3) obtained a larger score of 8.1 (SD = 1.2) points ($t_{(18)} = 8.6$, $p < 0.01$, $d = 4.0$) than the ASD group (3.8, SD = 1.7). In the post-test, this difference ($p < 0.01$, $d = 0.86$) was 5.2 points (SD = 0.8). However, even in the post-test, the TD group (14.2, SD = 2.7) obtained a larger score ($t_{(18)} = 7.9$, $p < 0.01$, $d = 2.2$) than the ASD group (9.0, SD = 1.9). Fig. 4 shows this interaction.

3.2. Cognitive test

The ANOVA on the response time showed a significant main effect of both the Group ($F_{(1,18)} = 5.1$, $p < 0.05$, $\eta p^2 = 0.22$) and the Time ($F_{(1,18)} = 8.0$, $p < 0.05$, $\eta p^2 = 0.31$) factors, indicating shorter response time in the TD group and in the post-test. The interaction between Group and Time was also significant ($F_{(1,18)} = 6.5$, $p < 0.05$, $\eta p^2 = 0.27$). Post-hoc analyses showed that the ASD group only improved the response time in the post-test (difference = 43 ms, SD = 7, $t_{(18)} = 6.8$, $p < 0.01$, $d = 0.96$), while the TD group remained stable. In addition, while in the pre-test the ASD group had a slower response time than the TD group (difference = 81 ms, SD = 24, $t_{(18)} = 5.5$, $p < 0.05$, $d = 0.63$), in the post-test the difference between groups was not significant.

The ANOVA on the accuracy showed a significant main effect of Group ($F_{(1,18)} = 4.4$, $p < 0.05$, $\eta p^2 = 0.20$) with higher accuracy in the TD than the ASD group. The effect of time and the interaction were not significant ($F < 1$). Fig. 5 shows those interactions.

3.3. ERP data

Fig. 6 shows the pre-stimulus ERP waveforms in the two groups and conditions. The BP component peaked over the medial central scalp. The vN component peaked over bilateral occipital scalp areas.

The ANOVA on the BP component showed non-significant effects of the Group ($F_{(1,18)} = 3.3$, $p = 0.08$, $\eta p^2 = 0.16$) and the Time ($F_{(1,18)} = 2.9$, $p = 0.11$, $\eta p^2 = 0.13$) factors; however, the interaction was significant ($F_{(1,18)} = 6.1$, $p < 0.05$, $\eta p^2 = 0.27$). Post-hoc comparisons showed

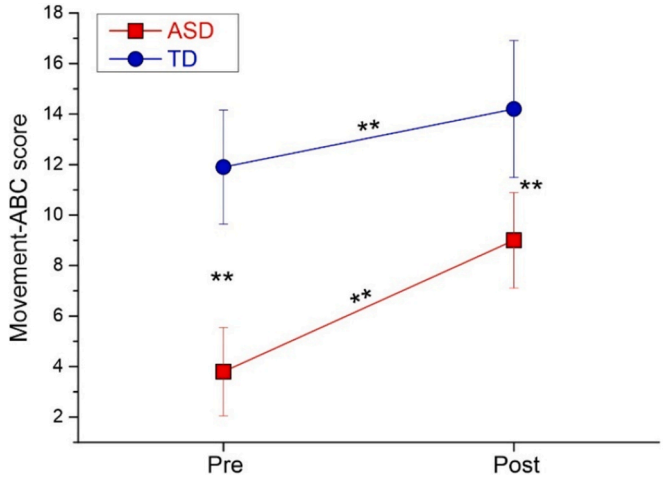

Fig. 4. Result of the motor test. The vertical lines represent the 95% confidence interval. **p < 0.01.

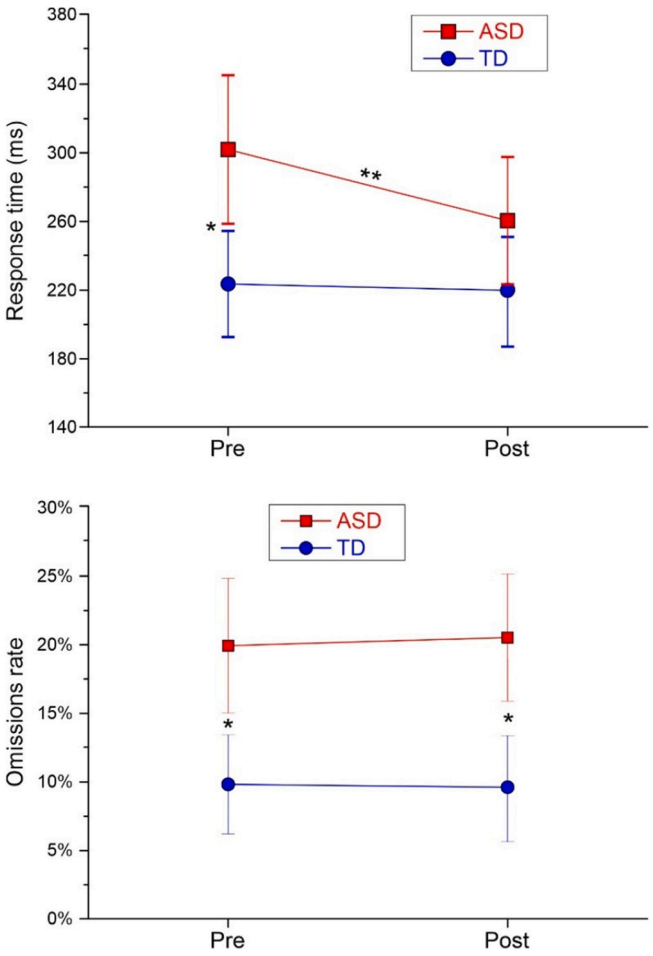

Fig. 5. Result of the cognitive tests. Above the mean response time and below the error rate. The vertical lines represent the 95% confidence interval. *p < 0.05, **p < 0.01.

that in the pre-test, the BP amplitude of the ASD group was lower ($t_{(18)} = 2.5$, $p < 0.05$, $d = 0.52$) than the TD group, but in the post-test, the two groups did not statistically differ. In the ASD group, the BP amplitude in the post-test was larger than in the pre-test ($t_{(18)} = 2.6$, $p < 0.05$, $d = 0.55$).

The ANOVA on the vN component showed non-significant effects of the Group ($F_{(1,18)} = 3.6$, $p = 0.07$, $\eta p^2 = 0.18$) and the Time ($F_{(1,18)} = 3.1$, $p = 0.09$, $\eta p^2 = 0.15$) factors; however, the interaction was significant ($F_{(1,18)} = 6.8$, $p < 0.05$, $\eta p^2 = 0.33$). Post-hoc comparisons showed that in the pre-test, the vN amplitude of the ASD group was lower ($t_{(18)} = 2.2$, $p < 0.05$, $d = 0.44$) than the TD group, but in the post-test, the two groups did not statistically differ. In the ASD group, the vN amplitude in the post-test was larger than the pre-test ($t_{(18)} = 2.3$, $p < 0.05$, $d = 0.51$).

Fig. 7 shows those interactions.

Fig. 8 shows the post-stimulus ERP waveforms in the two groups and conditions. The P1 and N1 components peaked at bilateral occipital scalp areas, and the P3 at medial parietal areas.

The ANOVA on the P1 component showed non-significant main effects and interaction ($F > 1$) with a mean amplitude of 10.79 μV, SD = 1.86.

The ANOVA on the N1 component showed a significant effect of the Group ($F_{(1,18)} = 12.2$, $p < 0.01$, $\eta p^2 = 0.67$) and the Time ($F_{(1,18)} = 5.6$, $p < 0.05$, $\eta p^2 = 0.44$) factors, with larger amplitude in the ASD than the TD group and larger amplitude in the post-test than the pre-test. The interaction was also significant ($F_{(1,18)} = 7.3$, $p < 0.05$, $\eta p^2 = 0.51$). Post-hoc comparisons confirmed the main effects but additionally showed that only in the ASD group the N1 amplitude in the post-test was

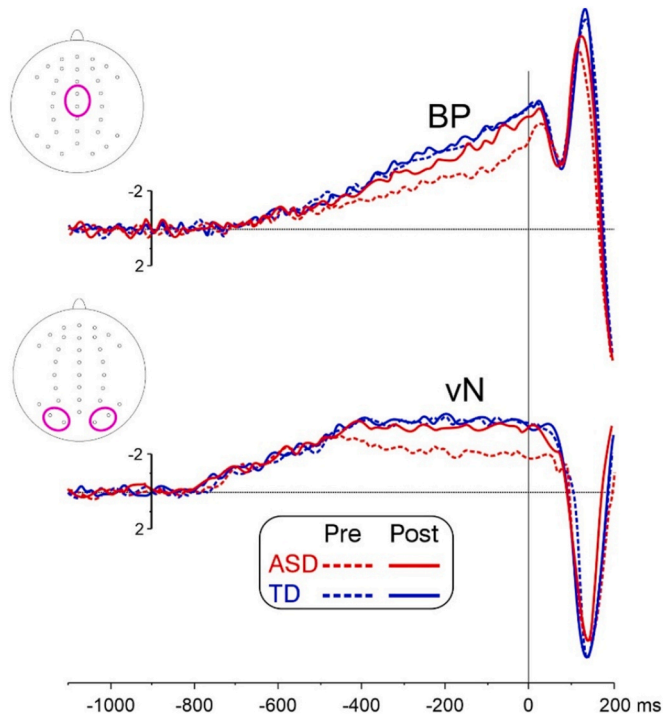

Fig. 6. Pre-stimulus ERP waveforms at central and occipital groups of electrodes indicated in the head representations on the left.

larger ($t_{(18)} = 2.2$, $p < 0.05$, $d = 0.48$) than in the pre-test.

The ANOVA on the P3 component showed significant effects of the Group ($F_{(1,18)} = 18.5$, $p < 0.01$, $\eta p^2 = 0.71$) and the Time ($F_{(1,18)} = 7.8$, $p < 0.05$, $\eta p^2 = 0.58$) factors, with larger amplitude in the TD than the ASD group and larger amplitude in the post-than pre-test. The interaction was also significant ($F_{(1,18)} = 8.2$, $p < 0.05$, $\eta p^2 = 0.66$). Post-hoc comparisons confirmed the main effects but additionally showed that in the ASD group, only the P3 amplitude was larger ($t_{(18)} = 4.7$, $p < 0.01$, $d = 0.98$) in the post-than pre-test.

Fig. 9 shows the interactions of the N1 and P3 components.

4. Discussion

The present pilot study aimed to determine the feasibility of CMDT training on neurological disorders, such as ASD, measuring motor and cognitive skills, and on anticipatory and reactive brain processing during a visuomotor response task.

According to existing literature documenting motor impairments and lower MABC-2 performance in ASD populations (e.g., Bo et al., 2019; Gandotra et al., 2020), before the training, the ASD group showed lower motor and cognitive performance than the TP group. The ASD group obtained a score on the Movement-ABC test that was 8 points lower than the TD group. This means that children with ASD have less motor coordination than the TD group, such as manual and body dexterity, balance, and hand-eye coordination. This pattern may be associated with altered connectivity between prefrontal and motor areas, which has been reported in ASD populations. Additionally, altered sensorimotor connectivity between the somatosensory cortex and motor cortex may contribute to inefficient sensory-motor integration, resulting in hypo- or hyper-responsiveness to sensory input (Sharer et al., 2015; Migò et al., 2022). According to the Bayesian theory, this discrepancy between sensory input and perceived sensory information is called prediction error, which is tried to be minimized by the brain. In ASD children, this mechanism has been proposed to be imbalanced, with greater weighting of sensory prediction errors reported in the literature (Pellicano & Burr, 2012; Van de Cruys et al., 2014). Indeed, rigid prior beliefs cause

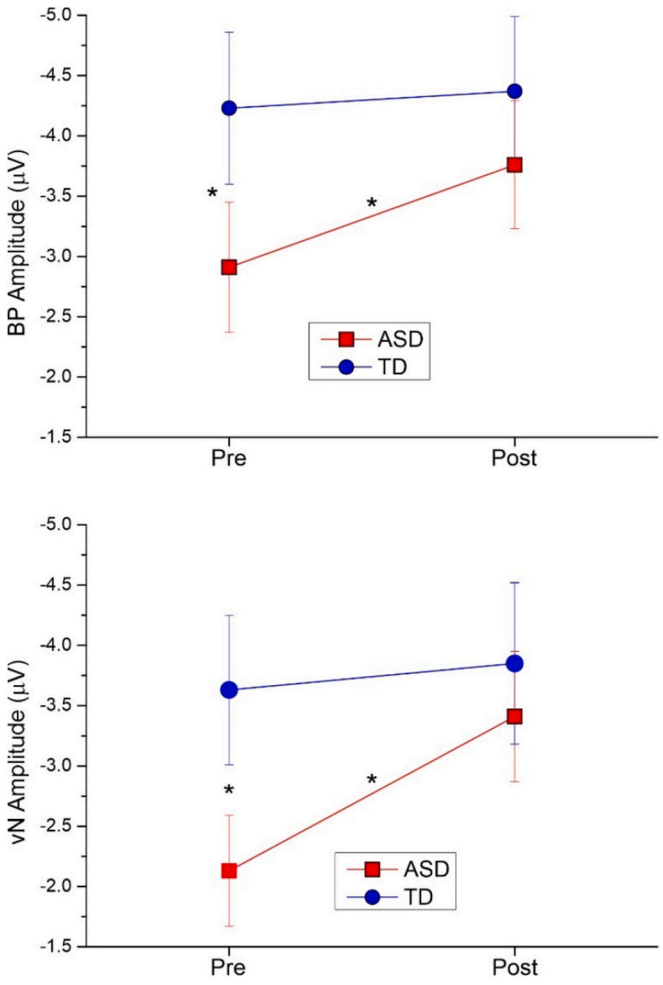

Fig. 7. Result of the pre-stimulus ERP. Above the mean the BP amplitude and below the vN amplitude. The vertical lines represent the 95% confidence interval. *$p < 0.05$.

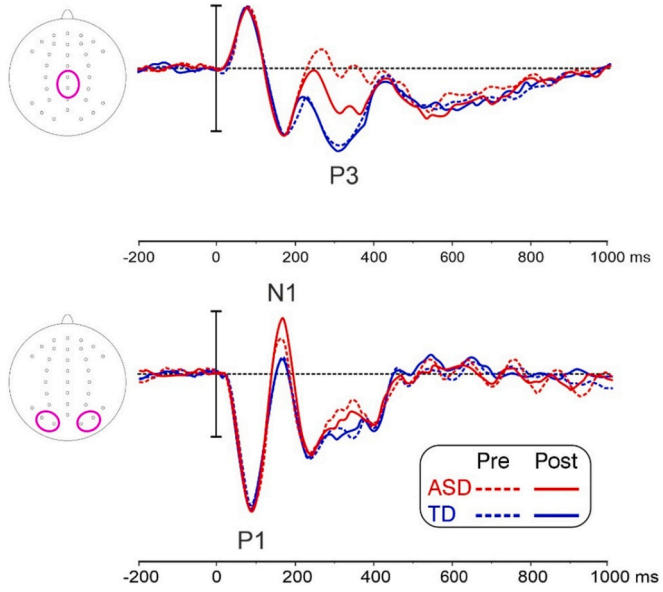

Fig. 8. Post-stimulus ERP waveforms at parietal and occipital groups of electrodes indicated in the head representations on the left.

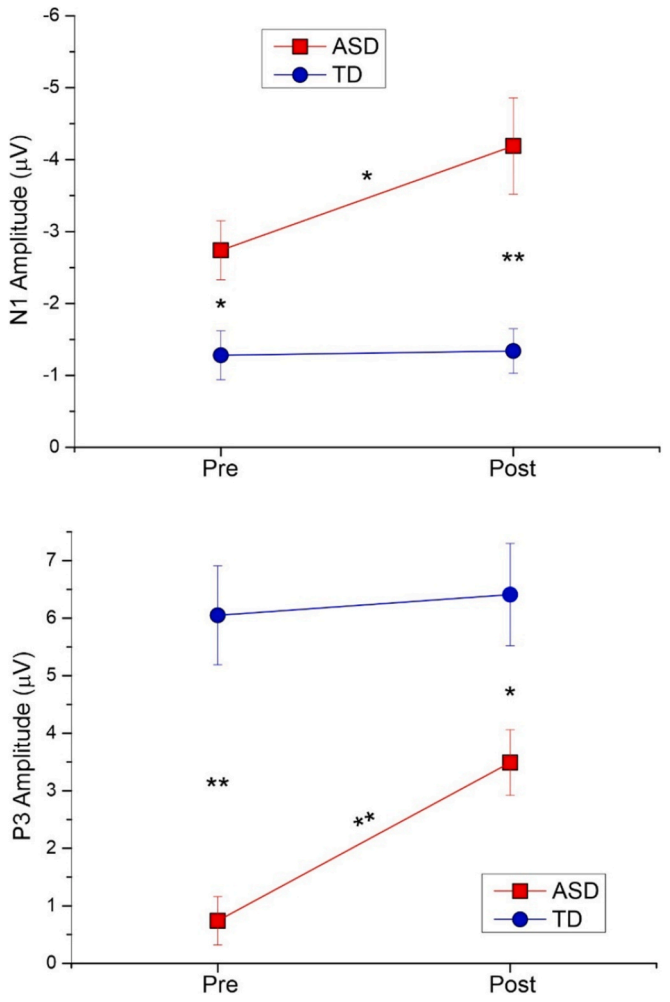

Fig. 9. Result of the post-stimulus ERP. Above the mean N1 amplitude and below the P3 amplitude. The vertical lines represent the 95% confidence interval. *p < 0.05, **p < 0.01.

difficulty in updating beliefs, which result in repetitive behaviors such as obsessive-compulsive disorders in ASD.

In the visuomotor response task, the ASD group was slower and less accurate than the TD group, indicating possible perceptual or cognitive impairments. Indeed, at the brain level, during this task, several anomalies were detected. Before the stimulus onset, both motor and visual readiness (the BP and vN components) were reduced. The low BP activity may reflect reduced engagement of neural processes involved in motor preparation (e.g., Di Russo et al., 2019). The reduced vN may be associated with altered sensory readiness and has been interpreted, within predictive-coding frameworks, as reflecting differences in top-down anticipatory processing (Häger et al., 2024).

Brain activity in response to visual stimuli showed that early visual processing in extrastriate areas (the P1 component) was comparable between the two groups. Anyway, the subsequent attentional processing indexed by the N1 component was enhanced in the ASD group. As previously found for the auditory P3a (e.g., Goncalves & Monteiro, 2023), this effect may reflect a stronger attentional focus on the stimulus that just appeared and, therefore, heightened sensitivity for visual events. Alternatively, the increased N1 could reflect compensatory mechanisms or increased neural effort as found for auditory processing (e.g., Linke et al., 2018) or less efficient neural processing as found for visual tasks (e.g., Faja et al., 2016) due to increased thalamocortical activity. However, the absence of P1 effects makes these possibilities unlikely. Finally, the P3 component was almost absent, possibly reflecting differences in post-perceptual task-related neural processing (e.g., Polich et al., 2007), although alternative mechanisms cannot be excluded.

Following CMDT training, the ASD group showed pre-to post-training changes across several measures, with some outcomes descriptively approaching those observed in the TD group. In the motor test, the ASD group's performance remained inferior to that of the TD group. However, the group differences were smaller at post-test compared to pre-test. In the cognitive test, the response speed of the ASD group increased, approaching that of the TD group. Response accuracy was not affected by the training. At the electrophysiological level, pre-stimulus anticipatory activity increased in the ASD group, partially overlapping with the range observed in the TD group. Post-stimulus activity also increased in the ASD group, but while the N1 became even larger, the P3 remained lower than that of the TD group.

These pilot results seem to confirm the literature, showing that CMDT training may be associated with changes in sensorimotor processing (Wu et al., 2024; Wollesen et al., 2014), which could influence the engagement of higher-order task demands. In addition to motor-related changes, behavioral results in the cognitive task were consistent with our hypothesis; in the ASD group, response time diminished, and the time difference with the TD group was reduced after training, as shown in previous studies as well. Participants who underwent CMDT training exhibited higher accuracy and faster response in cognitive tasks than before the intervention (Brezis et al., 2017). However, here the accuracy was not modulated by the training. This can be explained by the simplicity of the task, which just required visual detection and an indiscriminate motor response. Alternatively, the increased response speed may have prevented improvement in accuracy due to the speed/accuracy trade-off. The use of more complex tasks requiring discrimination from alternative responses, such as in go/no-go inhibition, or selective attention tasks, may better assess executive functioning and indicate whether the found gains may be attributed to differences in response conservativeness rather than in stimulus discriminability (e.g., Pirrone et al., 2020).

This study has some limitations. First, the small sample size; therefore, further studies should include larger sample sizes to enhance the generalizability of the findings. The ASD sample had a male-biased composition, but this mirrors ASD prevalence patterns and recruitment constraints. Moreover, a follow-up assessment will be relevant to verify the duration of the training effect. In addition, given the absence of an ASD active control group, causal inference is not possible. Improvements may reflect maturation, practice, or non-specific effects such as instructor attention or social engagement. To allow causal inference, future works should adopt a randomized, multi-group design within the ASD population that compares CMDT training to standard motor training interventions, controlling non-specific factors such as increased attention from instructors and social engagement.

5. Conclusion

One of the key contributions of this study was the investigation of the effects of CMDT training and its evaluation through neural activity associated with visual stimuli during pre- and post-sensory processing, instead of focusing on only post-stimulus processing and auditory stimuli, which already had a broad literature. Results showed that CMDT training was associated with motor, cognitive, and neural changes in children with ASD, although the study was not powered to test effectiveness.

As practical implications, if confirmed, CMDT may support improvements in motor, behavioral, and cognitive domains relevant to daily functioning. Such improvements are critical for enhancing their quality of life, particularly in areas such as social interactions and academic achievement. In addition, considering that CMDT training is a non-pharmacological ASD treatment, its use represents a promising trend to alleviate the costs of healthcare expenditures for drugs, and it

could provide clinicians with a powerful tool to help with this complex pathology.

CRediT authorship contribution statement

Merve Aydin: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Data curation. **Giulia Di Martino:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Formal analysis, Data curation. **Carlo Della Valle:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Enzo Iuliano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Alessandra Di Cagno:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luca Boccacci:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Andrea Casella:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Elona Dybeli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Data curation. **Francesco Di Russo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

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Data availability

Data will be made available on request.

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