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A role for preparatory midfrontal theta in autism as revealed by a high executive load brain–computer interface reverse spelling task

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Midfrontal theta oscillations have been linked to executive function, yet their role in autism—where this function is often compromised—remains unclear. We hypothesized that preparatory increases in theta power may help normalize performance in autism. To test this, we used a challenging interactive executive function task designed to impose a high working memory load and require constant error monitoring. An electroencephalogram (EEG)-based brain–computer interface (BCI) was used to maximize cognitive load and engagement. Neural activity from autistic and non-autistic adults was compared while participants were asked to mentally reverse pseudowords (engaging working memory) and write them using the BCI, which provided real-time performance feedback (maximizing error monitoring). The study focused on theta power modulation during the preparatory (pre-response) and feedback (post-response) periods but also explored the role of posterior alpha oscillations. Results showed similar task performance between groups, but distinct recruitment of brain resources, particularly during the preparatory period. The finding of an increased preparatory theta in autism favors the hypothesis of compensatory recruitment of cognitive control and attentional mechanisms to achieve accurate results.

Keywords Autism, Executive function, Midfrontal theta, Error monitoring, EEG-based BCI

Autism is a neurodevelopmental condition characterized by atypical social communication and interaction skills, along with restrictive and repetitive patterns of behavior and interests[1]. It is often related to alterations in executive function[2], which are not yet part of the diagnostic criteria.

Executive function comprises a set of interacting cognitive processes important for successful engagement in complex and goal-oriented actions[3], such as decision-making and abstract reasoning[2]. Individuals with executive function impairments tend to be less flexible and, consequently, face greater difficulty in handling situations that require creative solutions[3]. Based on a meta-analysis, Demetriou et al.[2] demonstrated moderate executive function alterations in autistic individuals, in line with reported differences in working memory, inhibition, error monitoring, and cognitive flexibility. The challenge of shifting mindsets to new concepts has been linked to repetitive behaviors, potentially leading to cognitive rigidity, perseverance to routines, and stereotypies in those with autism. More broadly, atypical executive function processes have been shown to impact social cognition and mental health. However, current research is still far from understanding the neural correlates of executive function alterations in autism[3].

Midfrontal theta activity has been associated with error monitoring and working memory, which are processes at the core of executive function[4]. Error monitoring enables the detection, processing, and signaling

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of errors upon action, playing a crucial role in learning and adaptive behavior by signaling when performance improvements are needed[5]. Increased midfrontal theta power has been consistently found immediately after erroneous actions in neurotypical individuals[6–8], which is thought to reflect the allocation of cognitive control resources to improve performance[9,10]. We recently showed that while theta power increases following errors, a reduction in theta can be observed prior to erroneous actions, compared to correct ones[11,12]. This absence of midfrontal theta during response preparation before errors suggests that theta may indicate the ability to establish adequate response control under challenging situations[13]. Here, we investigated whether theta activity could differentiate error monitoring mechanisms in autism, particularly during the preparatory phase.

Theta activity has also been described to increase by working memory load[14]. Working memory entails the storage and processing of information within a short period[15], and theta oscillations are believed to represent increased recruitment of other brain regions for effective memory encoding[16]. In addition to the midfrontal theta, the posterior alpha band was previously linked to error monitoring[8,13], working memory processes[17] and, most consistently, attention[18,19]. Therefore, we also analyzed alpha modulation in our task. This frequency band is thought to reflect cortical deactivation, as its activity is highest during rest and decreases with attentional engagement in a task[20–22]. We previously proposed that dysregulation of alpha oscillations is a hallmark of a set of neurodevelopmental disorders[18].

Previous studies have already suggested some error monitoring and working memory alterations in autism. Autistic individuals seem to experience greater difficulty in perceiving erroneous actions and are less likely to engage in compensatory mechanisms after error occurrence[23]. Such challenges have been further associated with alterations in error-related electroencephalographic (EEG) signals, including error-related potentials[5,24–27] and theta band oscillations[28]. Buzzell et al.[28] found a reduced error-related late theta power in autistic children, which was a significant predictor of poorer academic and social skills. Moreover, Larrain-Valenzuela et al.[14] revealed alterations in the link between frontal theta and posterior alpha activity and memory load in autism. In that study, only non-autistic participants showed a theta and alpha power modulation by memory load, and theta alterations were correlated with autistic traits. In another study[19], autistic children, contrary to non-autistic children, did not show alpha suppression in response to behaviorally relevant targets.

In this study, we tested the hypothesis that executive function mechanisms related to working memory and error monitoring—during task preparation and response feedback periods—are altered in autism and that these alterations are reflected at the level of midfrontal theta power. To investigate this, we employed an interactive brain–computer interface (BCI) task requiring participants to memorize and mentally reverse pseudowords. This task was designed to recruit executive function processes by maximizing participants' attention and engagement of both behavioral and neural resources. It included distinct cognitive/memory load levels, problem-solving stages, and error sources that had to be constantly monitored (both participants' own errors and BCI decoding errors—hereinafter referred to as system errors). We aimed to understand whether executive function processes are recruited differently in autism during response preparation and following performance feedback, while accounting for the influence of cognitive/memory load[29], distinct sources of errors[6,7], and task practice[30] on theta modulation.

Contributions and novelties

To our knowledge, this is the first study to use a BCI-based approach to investigate the role of theta oscillations in executive function in autism. BCI systems translate neural activity patterns into commands for interactive applications, thereby decoding users' intentions from brain activity[31]. Originally designed for communication, these approaches have also been proposed for interactive brain training, while investigating brain function[32]. By integrating BCI with a working memory and error monitoring task, we:

(i) Introduced and applied a novel framework to assess executive function alterations in autism;
(ii) Explored the feasibility of using this BCI task as a potentially gamified brain training approach for autism, where innovative therapeutic methodologies are desirable[33].

Our results revealed similar task performance across groups but distinct recruitment of neural resources during task preparation. Specifically, autistic individuals exhibited increased midfrontal theta during the preparatory period, which may reflect a compensatory engagement of cognitive control mechanisms to achieve similar performance to non-autistic individuals. Additionally, we observed enhanced posterior alpha activity in autistic individuals. This study advances the understanding of executive function alterations in autism while demonstrating the feasibility of a new BCI gamified task.

Methods

Participants

Ten non-autistic (seven females, 28.20 ± 2.58 years) and fourteen autistic volunteers (one female, 25.00 ± 1.93 years) participated in this study. All participants had normal or corrected-to-normal visual acuity, as well as sufficient reading and listening comprehension skills to perform the task. All participants provided written informed consent in accordance with the Declaration of Helsinki before participation. The study followed the safety guidelines for research on humans and was approved by the Ethics Committee of the Faculty of Medicine of the University of Coimbra.

The Portuguese Association for Developmental Disorders and Autism of Viseu and Coimbra (APPDA-Viseu and APPDA-Coimbra) supported participant recruitment. Psychologists who work daily with autistic individuals identified potential volunteers interested in participating, ensuring they had the required reading and listening comprehension skills for the task. As we used a portable EEG system by g.tec, data acquisition took place at the respective Associations, contributing to participants' comfort. Data acquisition occurred during participants' usual schedules in familiar rooms.

The diagnosis for autism was previously assigned based on gold standard instruments, such as parental or caregiver interview with the Autism Diagnostic Interview—Revised (ADI-R)[34], direct structured subject assessment with the Autism Diagnostic Observation Schedule (ADOS)[35], and the current diagnostic criteria for autism according to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5)[1].

Data regarding the Full-Scale Intelligence Quotient (FSIQ)[36] was collected for autistic individuals (except one) to evaluate its influence on the capability of interacting with the BCI and performing the task. Out of the fourteen participants in the autistic group, only ten (all males, 26.30 ± 2.58 years) were able to interact with the BCI (four could not do it due to calibration problems or difficulty in understanding the system functioning). Considering the autistic participants that could perform the task, the mean FSIQ was 101.11 ± 4.46 and it ranged from 86 to 120. The mean FSIQ for the remaining four autistic individuals was 70.50 ± 5.17, ranging from 62 to 83. In addition to these four participants who did not perform the task, four other autistic participants did not fully complete the entire task due to fatigue.

Experimental design overview

This study used a BCI-based pseudoword reversal task to assess executive function in autistic and non-autistic individuals using EEG signals. In each trial, participants were presented with a five- or seven-letter pseudoword (i.e., a sequence of letters that mimics a real word in terms of its orthographic and phonological structure but does not exist in the language). They were then instructed to memorize the pseudoword, reverse its order, and finally write it down using a BCI speller, as detailed below.

BCI system: P300-based speller

We used the P300-based lateral single-character (LSC) speller developed by Pires et al.[37], previously validated in non-clinical and clinical (motor disabled) groups[38,39], which allowed participants to write their responses into a computer using their EEG signals.

Whenever there is a sequence of events such that one of them is rare, that infrequent event generates a P300. The P300 is an event-related potential detected over central and parietal regions elicited from 300 to 500 ms after the onset of the relevant and rare stimulus[40]. In the speller here used, the target letter is the infrequent event and the non-target letters constitute the frequent event. LSC speller contains the letters of the alphabet and the space symbol, spatially arranged as shown in Fig. 1b.

To use this BCI system, an individual calibration session was required. During the calibration phase, the participants attended the letters of the word "INTERFACE". For each calibration letter, all symbols flashed nine times for 75 ms each. In total, the calibration session took approximately 5 min[37]. These data were then used to obtain the optimal classification model to be applied by the interface. The classification was performed following the methodology proposed by Pires et al.[41]. It employs a statistical spatial filter to improve the signal-to-noise ratio (SNR) and reduce the dimension of the data. Spatial filter projections are then classified by a naïve Bayes classifier and the optimal number of repetition rounds are determined.

Following the calibration phase, during the online interaction with the BCI, the conditions were similar: the letters and symbols flashed individually and randomly for 75 ms, and each letter flashed once in each repetition round; the P300 component was averaged across these repetitions to improve the SNR. Features were extracted from the averaged signal and the speller system detected the target letter through automatic recognition of the P300 component. The detected letter was then fed back to the user for 1000 ms and, following the letter detection, all letters and symbols flashed again after 4000 ms. The frequency of feedback varied across participants, as each had an optimal number of repetition rounds. In each round, all 28 letters and symbols flashed individually, taking a total of 2.1 s per round (28×0.075 s)[37]. On average, participants completed approximately five rounds, resulting in a total of 10.5 s to write each letter and receive feedback.

Task: pseudoword reversal game

All participants performed a pseudoword reversal gamified task, which required memorizing and mentally reversing pseudowords to further write them using a BCI speller. Each session included 20 trials of pseudowords reversal. To assess different levels of cognitive and memory load, the task included 10 five-letter pseudowords and 10 seven-letter pseudowords. Each trial (Fig. 1) began with a preparation time of 3000 ms before the instruction was given, during which the speller display/virtual keyboard was already visible. Then, the instruction (i.e., a pseudoword) was shown for 2000 ms. After the instruction disappeared, during the encoding phase, participants had 6000 ms to mentally prepare to "write" the reversed version of the pseudoword. These three periods (preparation, instruction, and encoding) constituted the pre-response stage. Subsequently, participants interacted with the speller to "write" letter by letter the reversed pseudoword. During this stage, all symbols flashed repeatedly, and then the letter selected (decoded) by the BCI algorithm was highlighted for 1000 ms (response feedback). Participants were informed to keep writing the response independently of detecting a typing error. At the end of the five or seven letters, the correct and recorded responses were shown one above the other during 1000 ms (outcome).

Considering the two possible sources of error—participant errors and system errors (errors caused by the participant and by the incorrect decoding of the user's intentions by the BCI system, respectively), we used a short debriefing period at the end of each trial to understand the source of the errors (around 1 min long). In these debriefings, we asked the participants whether each error in the outcome was elicited by the participant or the system. The most common participant errors were exchanges of two consecutive letters (e.g., ODAMRIF instead of ODAMIRF). System errors were usually exchanges of neighbor letters in the LSC speller (e.g., if the "B" letter was flashing and a participant was paying attention to the "A"—a neighbor letter —, the participant

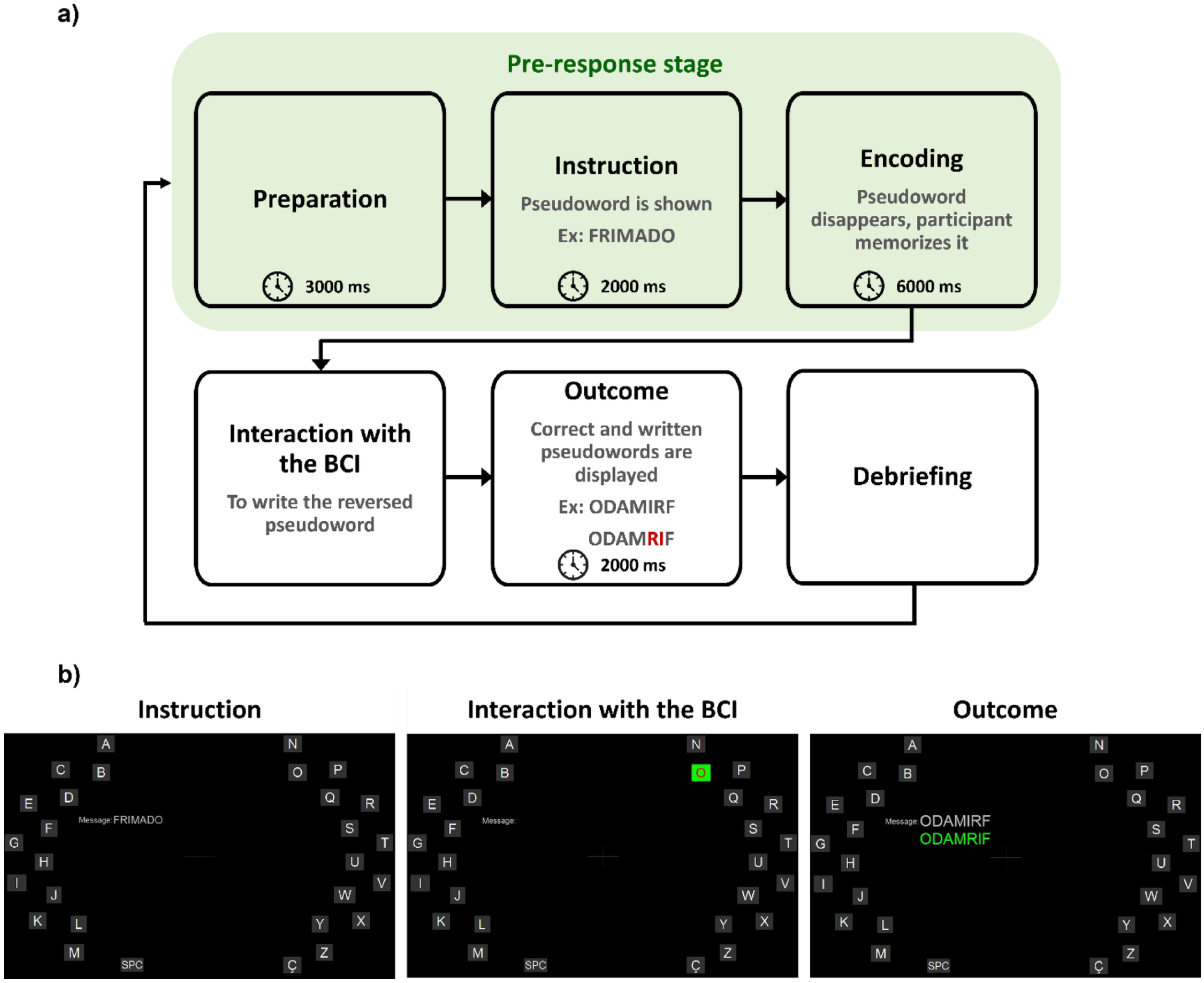

Fig. 1. Experimental protocol overview. (**a**) Each trial began with a preparation period of 3000 ms, after which the pseudoword (instruction) was shown for 2000 ms (e.g., "FRIMADO"). The instruction then disappeared, and participants had 6000 ms to prepare for writing down the reversed pseudoword (encoding). These three periods (preparation, instruction, and encoding) constituted the pre-response stage. Subsequently, participants wrote their responses using the BCI speller. In the end, the outcome was provided: the correct (in white) and written/recorded response (in green) words were shown. Each trial ended with a short debriefing phase. (**b**) Screenshot of the BCI speller during instruction presentation, interaction with the BCI/response, and outcome.

could react not only to "A" but also to "B", and the system could incorrectly select "B"). The order of pseudowords was pseudo-randomly distributed mixing five-letter with seven-letter words, although the first one was always a five-letter pseudoword for task habituation purposes. The complete list of pseudowords used in this task is detailed in the supplementary Table S1.

At the beginning and end of each experimental session, the participants were asked to use the BCI system to copy two words separated by a space for control purposes: CORAGEM-TALENTO (meaning COURAGE-TALENT). This step was used to assess each participant's online speller performance at the beginning and end of the task. The task was programmed in MATLAB (version R2012b MathWorks). The stimuli were presented on a 1440 × 900 resolution monitor with a refresh rate of 60 Hz. Figure 2 displays a photograph taken during an experimental session.

EEG data recording and offline pre-processing

EEG data were acquired using a g.tec gUSBamp amplifier with a sampling rate of 256 Hz. Sixteen active Ag/AgCl channels (with application of conductive gel) were recorded at positions FPz, F1, Fz, F2, FCz, C3, Cz, C4, CPz, P3, Pz, P4, PO7, POz, PO8, and Oz of the international extended 10–20 standard system with a g.tec cap. The ground channel was placed at the AFz position. Figure 3 illustrates the EEG electrode placement. We used the left ear lobe as the reference, due to the low number of electrodes, which were not evenly distributed, and because we were interested in midline channels[42]. EEG impedances were kept below 20 kΩ as much as possible.

The EEG system used is portable, which provided the possibility of collecting data in a comfortable environment for the participants. Moreover, the EEG system features flat electrodes integrated into the cap,

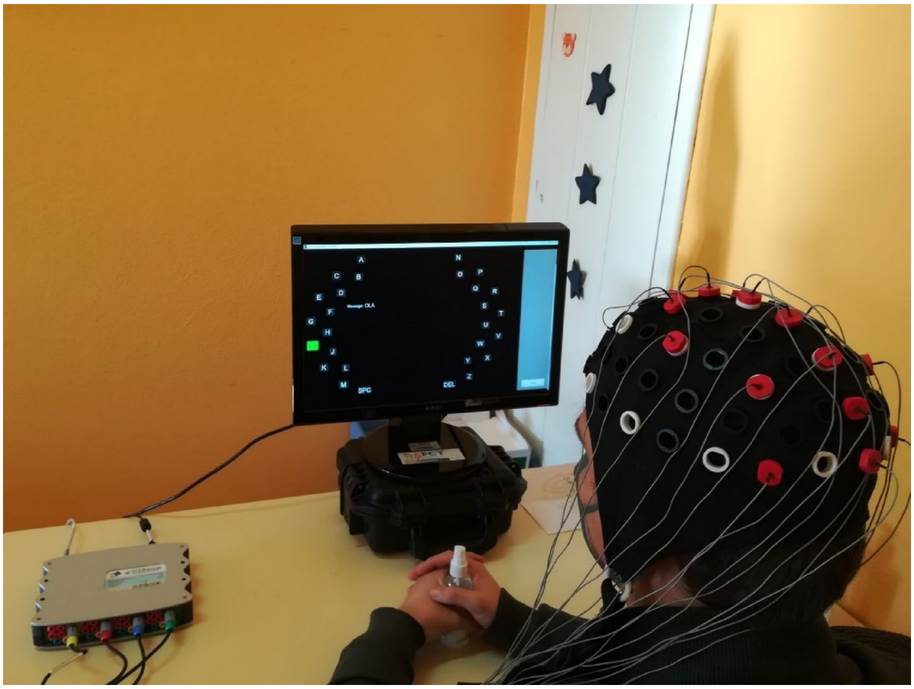

Fig. 2. Photograph taken at APPDA-Viseu during an experimental session.

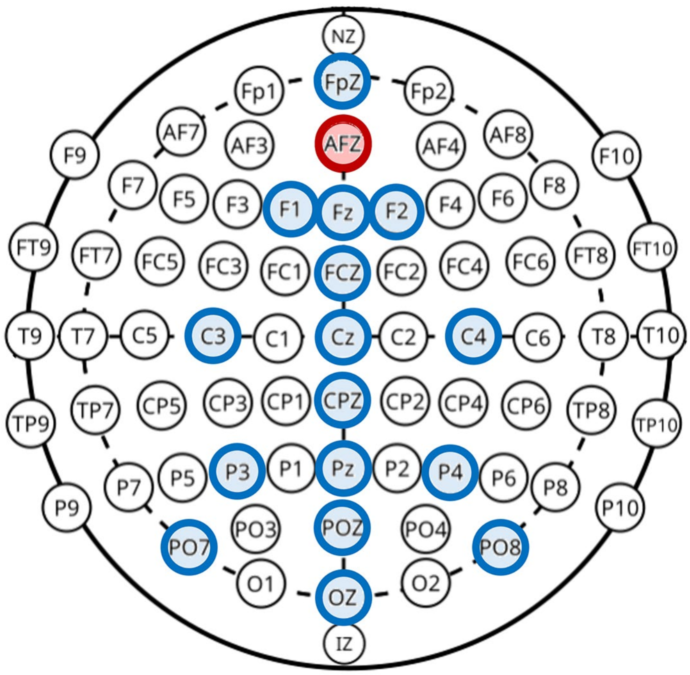

Fig. 3. EEG electrode placement based on the extended 10–20 international system. The electrodes used for data acquisition are marked with solid blue circles, while the ground electrode is represented by a solid red circle.

enhancing comfort. Although the application of conductive gel is not entirely comfortable, it ensures higher signal quality than dry electrode systems[43], without compromising BCI feasibility for individuals with autism.

Offline pre-processing started with a zero-phase non-causal finite impulse response filter between 0.5 and 45 Hz to remove non-neural fluctuations and power line interference noise. Moreover, we applied Independent Component Analysis (ICA), and IClabel (iclabel.ucsd.edu/tutorial) was used to support the manual identification of muscular artifacts, blinks and saccade-related components to be removed from data[44]. Data were segmented into different intervals of interest, and noisy intervals were removed through visual inspection. Segments where the signal exceeded ± 100 µV were identified and removed. EEG offline pre-processing and analyses were conducted using EEGLAB toolbox functions (version 2021.0) based on a custom MATLAB script (version R2018b, MathWorks).

Participants' performance and BCI feasibility

We assessed the participants' error rate (i.e., the ratio between the number of letters with participant errors and the total number of letters). The participants' error rate was compared between groups (autistic and non-autistic) considering two cognitive/memory load levels (five-letter and seven-letter pseudowords) and practice/learning stage (considering four learning stages with five trials each: initial—trials 1 to 5 –, intermediate 1—trials 6 to 10–, intermediate 2—trials 11 to 15 –, and final—trials 16 to 20).

We also explored the correlation between the FSIQ and participants' performance (measured by the participants' error rate) within the autistic group to investigate whether their ability to execute the task depended on FSIQ.

Moreover, we performed a feasibility analysis to understand whether the applied BCI-based gamified task was suitable for autistic individuals. First, we compared the BCI system error rate (i.e., the ratio between the number of letters with system errors and the total number of letters) during the task between groups, considering the practice/learning stages. Then, we analyzed the relation between the users' FSIQ and BCI system error rate to evaluate whether the speller performance depended on FSIQ.

Offline EEG data analysis

Pre-response analysis

Firstly, we analyzed midfrontal theta power modulation during pre-response. We investigated whether midfrontal theta activity differs in autism and if it is affected by participants' performance, cognitive/memory load, task period, and practice/learning effects over the session.

Mean theta (4–8 Hz) PSD was computed using the Welch's method[45] (with the *pwelch* MATLAB function) at the FCz and POz channels during the temporal segments described below. The FCz electrode was chosen due to its link to executive function[46], error monitoring[6,11], and working memory[16]. Theta power at FCz was compared to that at POz to assess the specificity of midfrontal theta.

Data were segmented into epochs starting at the beginning of preparation, instruction, and encoding intervals with durations of 3000 ms, 2000 ms, and 6000 ms, respectively. On average we analyzed 9.10 ± 0.23 five-letter and 9.00 ± 0.42 seven-letter pseudoword trials for the non-autistic group, and 7.10 ± 0.93 five-letter and 7.10 ± 0.91 seven-letter pseudoword trials for the autistic group. Theta power modulation was thus estimated in both groups (autistic and non-autistic) at the FCz and POz channels, considering the cognitive/memory load (five- and seven-letter pseudowords), pre-response period (preparation, instruction, and encoding), practice/learning stages (initial, intermediate 1, intermediate 2, and final), and participant performance (upcoming correct and incorrect pseudoword reversal).

Additionally, we analyzed the posterior alpha band (8–12 Hz), which was previously linked to error monitoring[8,13], attention[22], and working memory processes[17]. Mean alpha PSD was similarly computed using the Welch's method[45] at both FCz and POz channels during the same temporal segments. We selected the same electrodes as in the theta power analysis; however, here the focus was on POz, with FCz serving as a control to evaluate the specificity of posterior alpha.

Response feedback analysis

Midfrontal theta was also analyzed during the feedback to the response writing (i.e., during letter decoding by the BCI). We investigated whether the neural response to errors differed between groups and depended on error origin (caused by the participant or the BCI system) or practice/learning effects. In this analysis, we did not include the cognitive/memory load factor since it was not hypothesized to be relevant for the neural response to the letter decoding feedback.

We computed mean theta and alpha bands PSD at FCz and POz channels for epochs of 1000 ms, locked to the moment when the letter was detected by the BCI system. On average 116.40 ± 0.95 and 95.70 ± 9.16 epochs were analyzed for the non-autistic and autistic groups, respectively. Note that during pre-response stage, we analyzed one epoch per pseudoword (since each pseudoword only had one pre-response moment) but, in this case, we analyzed one epoch per letter (as we assessed the moment following the decoding of each letter by the BCI speller).

Statistical analysis

Autistic and non-autistic groups' performance was compared using a linear mixed-effects model analysis. We tested the effect of group, cognitive/memory load, practice/learning stage, and respective interactions on participants' error rates. Moreover, the correlation between participants' FSIQ and error rate was tested based on a Spearman correlation analysis.

The theta and alpha modulation (both during the pre-response and response feedback moments) were analyzed based on linear mixed-effects modelling to account for the several factors we were interested in while considering an unequal number of repetitions. In case of resulting factors and interactions without a significant effect, these were removed, and the mixed-effect analyses were rerun to simplify the model, as suggested by Seltman[47]. We ran one model per channel and frequency band of interest. Due to multiple testing, we used Bonferroni correction for multiple comparisons. In addition, we analyzed significant interactions using post hoc comparisons, with adjusted significance levels set by applying the Bonferroni correction.

In the pre-response analysis, we considered the factors group (autistic and non-autistic), performance (upcoming correct and incorrect pseudoword reversal), cognitive/memory load (five- and seven-letter pseudowords), pre-response period (preparation, instruction, and encoding), and practice/learning stage (initial, intermediate 1, intermediate 2, and final). We also included all possible interactions between factors and a random intercept for each subject and trial. As every participant performed several trials that included distinct periods (preparation, instruction, and encoding), participant and trial ID were considered random variables.

In the response feedback analysis (following the letter decoding by the BCI system), we considered the factors group, practice/learning stage, and performance (correct letters, system errors, and participant errors) and all possible interactions. The participant ID was considered as a random variable (each participant had several epochs with distinct EEG power values).

BCI feasibility was evaluated using a mixed ANOVA to evaluate the impact of group (between-subjects factor), practice/learning stage (within-subjects factor), and respective interaction on BCI system error rate. We used a different statistical test since here there is only one within-subject factor (we did not include cognitive/memory load since it was not hypothesized to be relevant for BCI performance). Moreover, a Spearman correlation analysis between participants' FSIQ and the BCI system error rate was conducted.

All statistical tests were performed with a 95% confidence interval and the results were considered significant for $p < 0.05$. Besides, we controlled all analyses for age and sex by including them as covariates in our statistical tests. We used MATLAB (version R2018b, MathWorks) to conduct correlation analyses. The remaining statistical analyses were run on IBM SPSS Statistics 27 software. Throughout this document, the numbers that follow the ± sign correspond to the SEM.

Results

Participants' performance and BCI system feasibility

When analyzing the responses of both autistic and non-autistic participants, we found that 5.79 ± 1.90% of five-letter pseudoword characters (letters) and 12.20 ± 3.03% of seven-letter pseudoword characters (letters) were incorrectly written. The linear mixed-effects model revealed a significant impact of cognitive/memory load on participants' error rate ($F(1,144.03) = 12.75$, $p = 4.83 \times 10^{-4}$). The error rate was higher for seven-letter than five-letter pseudowords ($t(1,144.03) = 3.57$, $p = 4.83 \times 10^{-4}$), but it was not influenced by group (demonstrating performance matching) or practice/learning stage, as detailed in supplementary Fig. S1. Moreover, there was no significant correlation between autistic individuals' FSIQ[36] and the number of incorrect responses.

Regarding the feasibility of the BCI task, the overall average accuracy of the online BCI speller, considering both autistic and non-autistic participants, was 70.30 ± 3.43%. Moreover, performance was similar across both groups (a comparison of the BCI system error rate between groups considering the practice/learning effect revealed no significant differences). Additionally, a correlation analysis between the FSIQ of the autistic participants and the BCI error rate showed no significant impact of the FSIQ on their capacity to interact with this system. However, four autistic participants (out of 14) were not able to interact with the BCI system. In three cases, this was due to poor classification accuracy during the calibration session, and in one case, due to the task's demands. These four participants had the lowest FSIQ scores, with values < 85 (supplementary Fig. S2).

Although we were concerned about potential discomfort due to sensory hyper-reactivity in autism[3], participants did not report significant issues. The EEG system featured flat electrodes integrated into the cap, enhancing comfort. Importantly, conducting data acquisition in familiar rooms at APPDA-Viseu and APPDA-Coimbra likely contributed to participants' satisfaction. It was also important to show and explain the materials used and their purpose.

Neurophysiological results

Distinct midfrontal theta and posterior alpha modulation during pre-response

Midfrontal theta power was analyzed in different pre-response periods (preparation, instruction, and encoding) considering performance (upcoming erroneous and correct responses), cognitive/memory load (five- and seven-letter pseudowords), practice/learning stage (initial, intermediate 1, intermediate 2, and final), and group (autistic and non-autistic) as factors. Figure 4 illustrates the main observed effects. The linear mixed-effects model revealed a significant effect of the pre-response period ($F(2, 646) = 10.96$, p-corr. $= 8.40 \times 10^{-5}$) and group ($F(1, 323) = 6.85$, p-corr. $= 0.04$) on midfrontal theta (measured at the FCz channel). It also revealed a significant interaction between the pre-response period and group ($F(2, 646) = 8.45$, p-corr. $= 9.52 \times 10^{-4}$). No significant effect was found related to the remaining factors tested. Given the significant interaction found, we ran post hoc tests to compare theta power between groups during each pre-response period (preparation, instruction, and encoding). We found that theta power was 1.23 ± 0.27 dB higher in the autistic than non-autistic group during the preparation period (p-corr. $= 2.40 \times 10^{-5}$).

All these analyses were also run for the POz channel (for comparison purposes). It showed a significant impact of the group on the parieto-occipital theta ($F(1, 323) = 18.04$, p-corr. $= 1.12 \times 10^{-4}$). Theta power at POz was 0.68 ± 0.16 dB higher in autistic individuals ($t(323) = 4.25$, p-corr. $= 1.12 \times 10^{-4}$). Supplementary Table S2 details the fixed effects estimates and post hoc results for theta power at FCz and POz channels.

We also analyzed alpha oscillations during the periods of pre-response (preparation, instruction, and encoding) at FCz and POz. Alpha power at FCz was modulated by the group ($F(1, 323) = 12.75$, p-corr. $= 0.002$) and pre-response period ($F(2, 646) = 16.85$, p-corr. $= 2.95 \times 10^{-7}$). It was 0.94 ± 0.26 dB higher in autistic individuals ($t(323) = 3.57$, p-corr. $= 0.002$) and 0.92 ± 0.17 dB lower during the encoding than the preparation period ($t(646) = -5.44$, p-corr. $= 3.01 \times 10^{-7}$). At the POz channel, group ($F(1, 323) = 36.34$, p-corr. $= 1.81 \times 10^{-8}$), performance ($F(1, 323) = 6.56$, p-corr. $= 0.044$), pre-response period ($F(2, 646) = 27.70$, p-corr. $= 1.15 \times 10^{-11}$), and the interaction between group and pre-response period ($F(2, 646) = 5.38$, p-corr. $= 0.02$) significantly impacted alpha power (Fig. 5). Alpha activity was 1.77 ± 0.69 dB lower during pre-erroneous events ($t(323) = -2.56$, p-

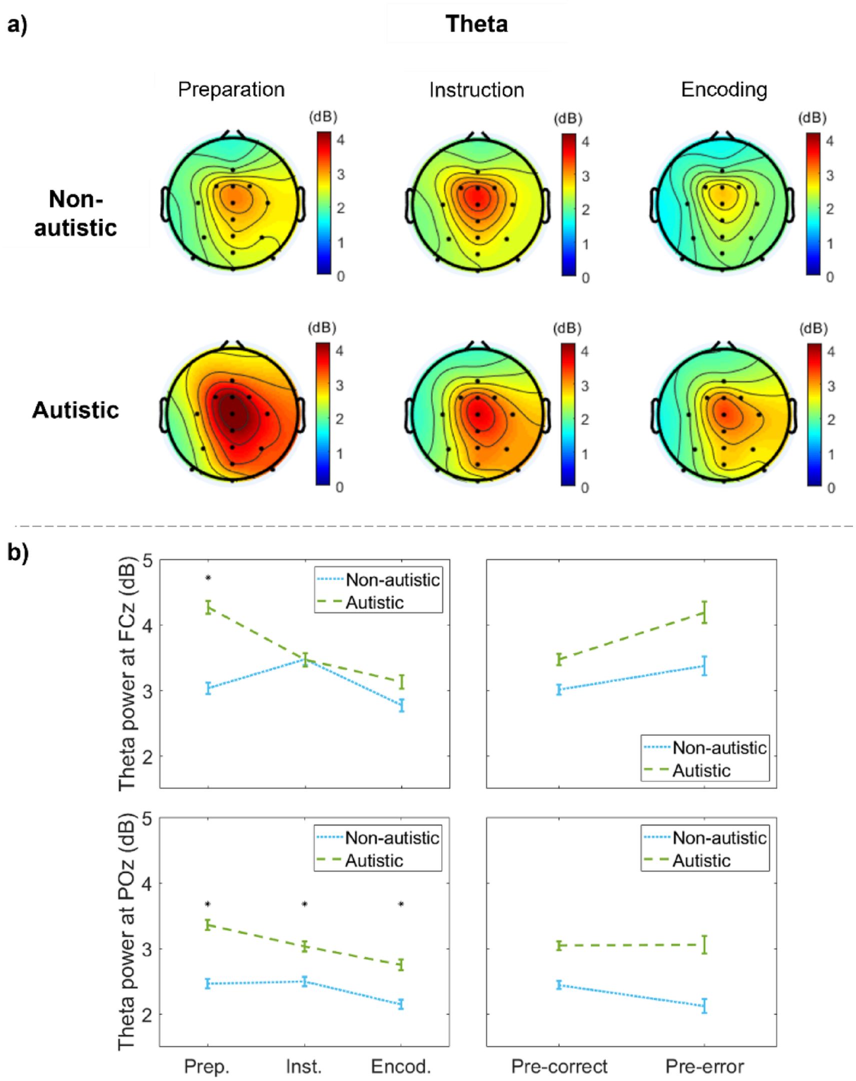

Fig. 4. Estimated marginal means of theta power spectral density (PSD) in non-autistic and autistic groups during pre-response. (**a**) Topographic maps of theta power distribution during preparation, instruction, and encoding. (**b**) Theta power at FCz and POz during each pre-response period and considering pre-correct and pre-erroneous pseudoword reversal. Error bars represent the standard error of the mean (SEM). While there was a significant interaction between the group and the pre-response period on the midfrontal theta, the activity in the parieto-occipital theta was increased in the autistic group independently of the period. Significant differences ($p < 0.05$, Bonferroni-corrected) between groups in each period are signaled with an asterisk. Theta power did not significantly differ between pre-correct and pre-erroneous events.

corr. = 0.044). Given the significant interaction found, we ran post hoc tests to compare alpha power at POz between groups during each pre-response period (preparation, instruction, and encoding). We found that posterior alpha power was higher in the autistic than the non-autistic group regardless of the pre-response period (with differences of 4.96 ± 0.75 dB, 3.11 ± 0.75 dB, and 2.33 ± 0.75 dB during preparation, instruction, and encoding, respectively). Alpha activity appears to be lateralized, but we did not test it because it was outside the scope of the study. Supplementary Table S3 details these results.

Similar error monitoring patterns between groups during feedback on response performance

We analyzed error-related neural patterns during feedback on response performance, i.e., when the BCI speller decoded and highlighted the selected letter to be written. We started by analyzing midfrontal theta oscillations considering group (autistic and non-autistic), performance (correct letters, system errors, and participant errors), and practice/learning stage (initial, intermediate 1, intermediate 2, and final). The linear mixed-effects modeling analysis revealed that theta power at FCz was significantly influenced by performance ($F(2, 2110.96) = 50.91$, p-corr. $= 1.02 \times 10^{-21}$). Midfrontal theta was increased by 1.81 ± 0.18 dB following system errors than correct letters ($t(2110.61) = 10.04$, p-corr. $= 1.31 \times 10^{-22}$) for both groups. Theta at POz was also affected by performance ($F(2, 2110.18) = 7.31$, p-corr. $= 0.003$), being 0.50 ± 0.13 dB higher following system errors than correct letters

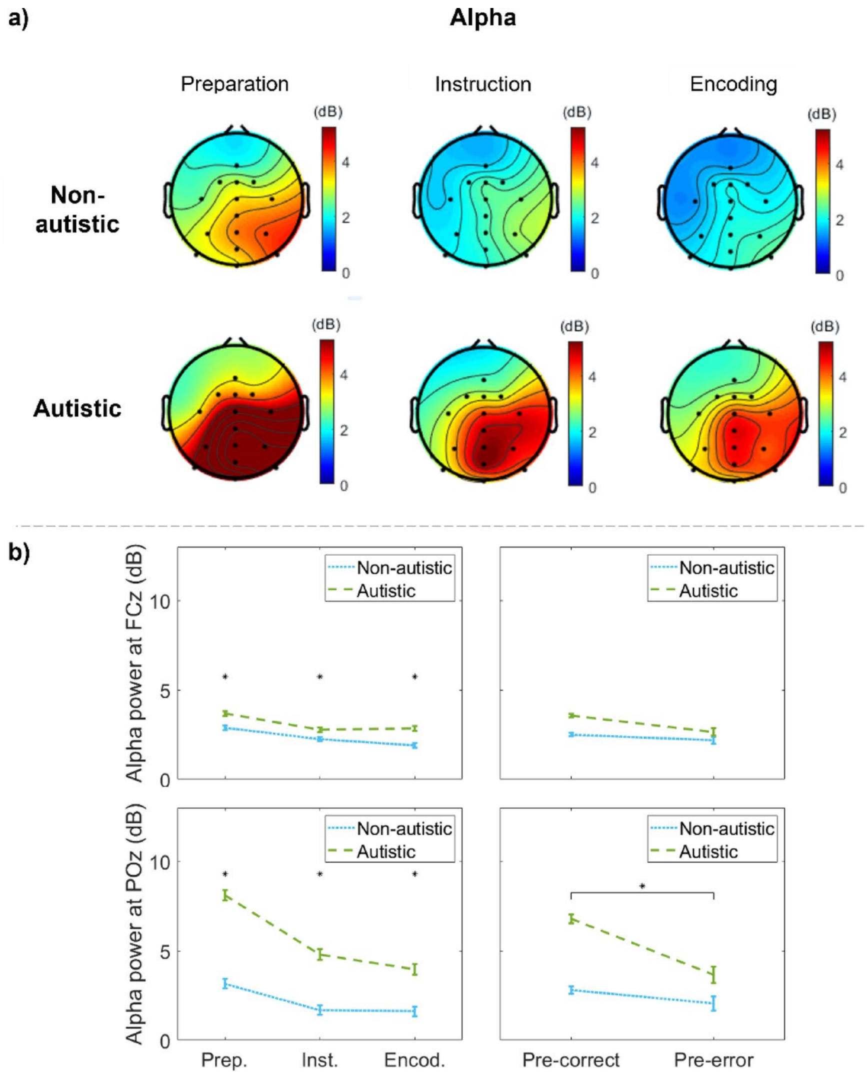

Fig. 5. Estimated marginal means of alpha PSD in non-autistic and autistic groups during pre-response. (**a**) Topographic maps of alpha power distribution during preparation, instruction, and encoding. Parieto-occipital alpha was found to be increased in the autistic group regardless of the pre-response period, and decreased from preparation to encoding. (**b**) Alpha power at FCz and POz during each pre-response period and considering pre-correct and pre-erroneous pseudoword reversal. Error bars represent the SEM. Significant differences ($p < 0.05$, Bonferroni-corrected) are signalized with an asterisk.

($t(2109.84) = 3.77$, p-corr. $= 6.64 \times 10^{-4}$). Figure 6 illustrates theta power per group, for correct letters, system errors, and participant errors, and supplementary Table S4 details these results.

We also analyzed alpha oscillations during this period (supplementary Table S5). Our results revealed a significant effect of performance on alpha power at FCz ($F(2, 2110.26) = 9.53$, p-corr. $= 3.04 \times 10^{-4}$) and POz ($F(2, 2109.56) = 6.93$, p-corr. $= 0.001$). Alpha power was higher following system errors than correct trials, both at FCz (difference of 0.50 ± 0.12, $t(2109.92) = 4.36$, p-corr. $= 5.6 \times 10^{-5}$) and POz (difference of 0.52 ± 0.14, $t(2109.24) = 3.65$, p-corr. $= 0.001$). Posterior alpha power in this period appears larger in the autistic group, but only at a trend level. Figure 7 illustrates these results.

Discussion

In this study, we investigated the neural correlates of executive function in autistic individuals using an interactive task involving the integration of error monitoring and working memory processes. The task required communication through a BCI interface forcing large engagement of behavioral and neural resources to signal the pseudowords to be written in the interface, with constant error monitoring. Midfrontal theta was evaluated over time considering the cognitive/memory load, participants' performance, and practice/learning effects. Data were analyzed for two distinct periods: during pre-response and following feedback on response performance.

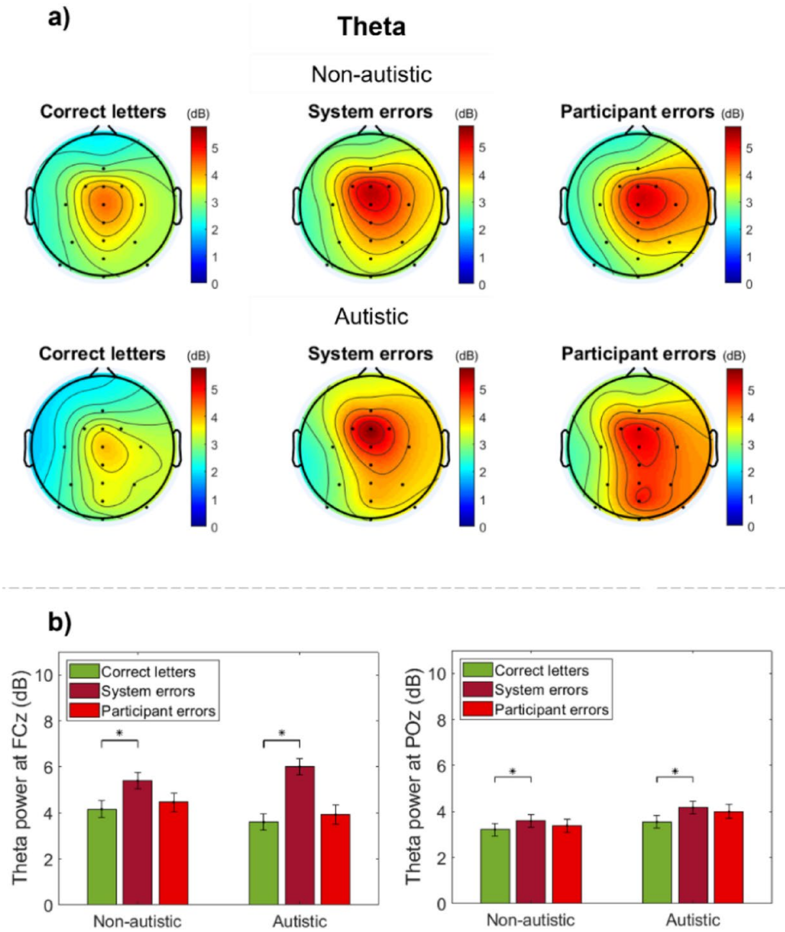

Fig. 6. Estimated marginal means of theta PSD during response feedback for correctly selected letters, system errors, and participant errors. (**a**) Topographic maps of theta power distribution. (**b**) Theta power at FCz and POz with error bars representing the SEM. Significant differences between correct letters, system errors, and participant errors are signalized with an asterisk ($p < 0.05$, Bonferroni-corrected).

Similar behavioral performance in autistic and non-autistic groups

Both autistic and non-autistic groups were able to perform the proposed pseudoword reversal task with similar performance. The number of erroneous responses was higher at the highest cognitive/memory load level (seven-letter pseudowords), as expected, but it did not differ between groups. This result suggests that both autistic and non-autistic individuals had a comparable ability to perform the proposed gamified BCI task. Although many studies revealed higher error rates in autism[24,26,28,48,49], many others showed similar task performance in autistic and non-autistic individuals[5,23,25,27,50]. The inconsistency in findings may be attributed to distinct task designs, involving different difficulty levels, as well as variations in motivation and engagement levels. We have prior evidence that BCI interfaces are engaging in autistic people[51], which may explain matched performance across groups. The absence of differences in error rates between groups allows for an unbiased comparison of error monitoring skills. Moreover, we did not find any effect of practice on the error rate, as it remained constant from the start to the end of the session. While we initially expected the error rate to decrease with practice[52], it is also possible that attention and focus became less efficient over time due to fatigue[53]. In this work, the lack of a practice effect on error rate may result from the simultaneous influence of these opposing factors.

Distinct neurophysiological response patterns during preparation in autism

The first part of our paradigm allowed us to investigate midfrontal theta and posterior alpha during the initial preparation period to perform the task, pseudoword presentation (instruction), and preparation to write the reversed version of the pseudoword previously presented (encoding). Theta and alpha modulation were examined across these periods for each group considering the possible influence of cognitive/memory load, performance, and practice/learning.

Autistic participants exhibited heightened midfrontal theta power during the initial preparation period, suggesting anticipatory recruitment of executive function mechanisms that may underlie their preserved performance. This finding aligns with our previous work in neurotypical participants, where preparatory increases in theta were linked to correct performance[11,12]. Midfrontal theta activity is linked to the recruitment of cognitive control[9,10] and heightened theta power has been consistently found following errors in neurotypical

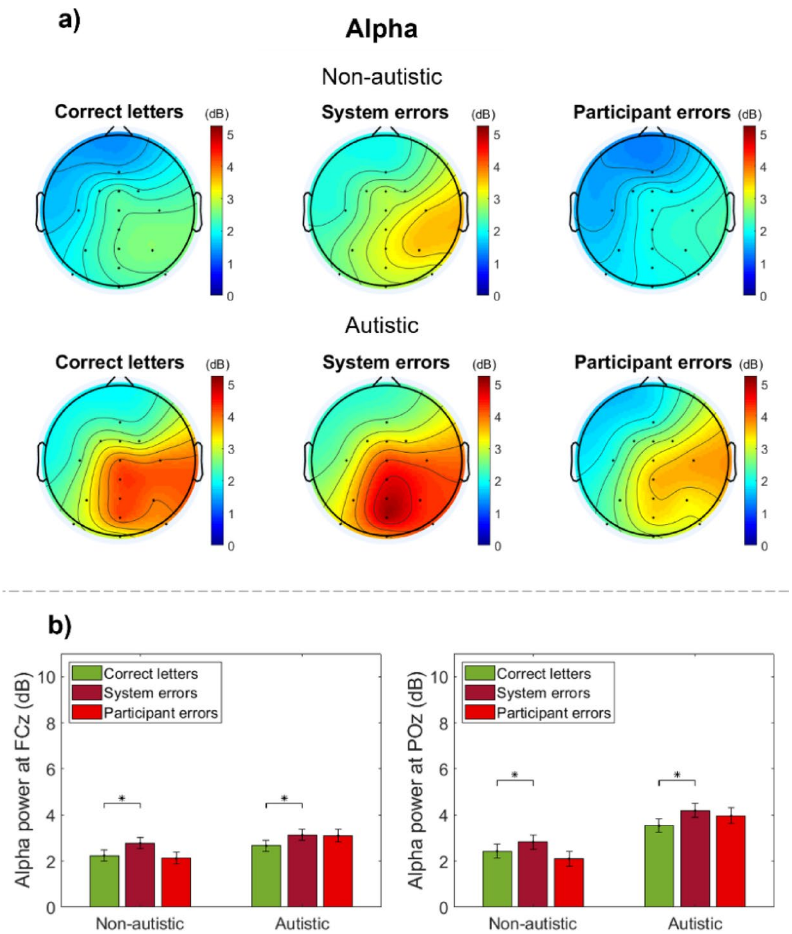

Fig. 7. Estimated marginal means of alpha PSD during response feedback for correctly selected letters, system errors, and participant errors. (**a**) Topographic maps of alpha power distribution. (**b**) Alpha power at FCz and POz with error bars representing the SEM. Significant differences between correct letters, system errors, and participant errors are signalized with an asterisk ($p < 0.05$, Bonferroni-corrected).

individuals[6–8,54,55]. Elevated theta power during a preparatory period may thus reflect the allocation of cognitive control resources needed for successful task execution. In this study, the enhanced theta activity observed in autism during task preparation could indicate a greater reliance on cognitive control mechanisms to achieve similar performances to the non-autistic group. These results may hence suggest that autistic individuals spend more neural resources during the preparatory period than non-autistic individuals. Alternatively, it is possible that autistic participants experience heightened anxiety during preparation, which could also contribute to increased theta activity, as previous studies have linked theta power with anxiety[56].

Although theta power differed between groups in the initial preparatory period, it tended to converge as the task progressed. No differences were found in the midfrontal theta between groups during the pseudoword presentation (instruction) or during the encoding phase. In the non-autistic group, theta power increased with the attention given to the instruction, whereas in the autistic group, it decreased, likely because it was already elevated during the preparation phase. Previous studies have demonstrated that theta power increases during engagement in working memory and cognitive control tasks[9,10,14,29]. However, this increase was not observed in autistic participants, despite their similar task performance to the non-autistic participants.

Along with theta oscillations, we analyzed the alpha band over the pre-response period. It has been consistently demonstrated that posterior alpha power decreases with attentional engagement[20–22]. In line with this, our results showed a decrease in alpha activity from the preparatory phase (similar to a resting state) to the encoding phase (with higher attentional demands), regardless of the group. Notably, alpha was distinctly elevated in the autistic group regardless of the pre-response period.

While alpha suppression was observed in both groups, a more pronounced alpha decrease was observed from the preparation to the encoding period in autism compared to the non-autistic group. The extent of alpha suppression during a task is thought to reflect the allocation of attentional resources needed for performing it[57,58], suggesting a higher demand for attentional resources in autistic compared to non-autistic individuals. This is consistent with our previous study, where we observed a greater alpha suppression in Neurofibromatosis Type 1, in a task requiring focused covert attention[18]. It is worth noting that, contrary to our results, some studies have reported reduced task-related alpha suppression in autism[19,20], but in these, participants performed simple visual tasks. Different task demands and attentional states may lead to distinct patterns of alpha modulation in autism.

As mentioned above, alpha activity has long been described to decrease with attentional demands and engagement, and this finding was so consistent that alpha power has been considered an inverse measure of activation[20–22]. Consistent with this, increased alpha activity has been related to unfocused states and attentional deficits[59]. Therefore, the observed enhanced alpha activity in autism during pre-response may be linked to attentional difficulties[60]. However, despite these difficulties, autistic individuals had similar performance levels to the non-autistic group. Possibly, an increase in theta power during task preparation[11,12] and greater task-related alpha suppression in autism are compensatory mechanisms for achieving accurate results.

Theta activity has been proposed to act as an alarm signal that engages cognitive control to adjust behavior, modulate motor responses, and redirect attention[9,10,61]. Additionally, its neural source has been shown to predict attentional focusing[62]. The observed increase in preparatory theta may therefore reflect a compensatory response to attentional difficulties in autism, as indicated by elevated preparatory alpha. These difficulties may amplify the need for enhanced cognitive control, thereby driving attentional focusing, as revealed by alpha suppression.

Moreover, we found higher alpha power before correct responses compared to errors. Studies have been inconsistent regarding the relationship between preparatory alpha and performance. While many studies revealed enhanced alpha before lapses of attention[13], others demonstrated higher alpha power before correct responses than errors[63,64]. Firstly, whereas lapses of attention may be linked to increased pre-error alpha, there is no evidence reporting that other errors (for instance, errors resulting from increased complexity) are related to higher pre-error alpha. Additionally, previous studies have shown that increased alpha before a task allows for enhanced alpha suppression during the same task[57,65]. Consistent with this, van Driel et al.[8] demonstrated that different types of errors are associated with distinct patterns of midfrontal theta and posterior alpha activity.

Similar error-related patterns in autistic and non-autistic individuals during response feedback

In addition to investigating how theta oscillations are modulated during pre-response, we also analyzed the response feedback moment (post-response). Theta and alpha activity were increased following system errors compared to correct letters in both groups. Theta activity has been demonstrated to increase not only following error commission[6,7,11,12] but also when an individual receives error feedback[9,13,66] or while observing errors[6,67] namely BCI errors[7,68]. Nonetheless, we did not find differences between correct letters and participant errors. This might be explained by the fact that, in this study, system errors were more evident and frequent than participant errors. In many cases, participants were unable to perceive their own errors from response feedback (letter decoded by the BCI system). If a participant incorrectly memorized the instruction (for instance, FIRMADO instead of FRIMADO), the error could only be recognized during the final outcome.

We believe that the lack of midfrontal theta differences between groups during response feedback may be due to the fact that most errors in this study were system errors. While previous literature has suggested alterations in error-related neural responses in autism, the findings have been inconsistent: most authors reported decreased EEG error-related potentials in autism[25–27,69], but some did not find differences when comparing to non-autistic individuals[48,70] and others noted increased error-related potentials in autism[5,24]. These error-related potentials have been linked to theta band oscillations[66], and Buzzel et al.[28] demonstrated a reduced error-related late theta power in autistic children. Besides, van Noordt et al.[71] showed a reduced inter-trial coherence of midfrontal theta during feedback processing in autism. Two fMRI studies also revealed differences between these groups concerning error monitoring processes. Still, while Goldberg et al.[50] observed increased error-related neural activity, Thakkar et al.[49] identified a decreased differentiation between erroneous and correct responses. Moreover, most studies assessed the neural responses to self-committed errors[5,24–27,69], some evaluated reward and performance feedback[48], and errors made by others[70]. In our study, we assessed the error-related theta response to BCI errors, and, to the best of our knowledge, this is the first study comparing neural responses (more specifically, oscillatory responses in the theta and alpha bands) to BCI errors between autistic and non-autistic individuals. This result might suggest that, although autistic individuals have altered neural responses to self-committed errors, autistic and non-autistic people similarly process BCI errors.

We also found greater alpha activity following system errors than correct responses, regardless of the group. Similarly, previous studies have reported increased alpha power after error observation[6,67]. As mentioned earlier, previous studies have shown that increased preparatory alpha allows for a more pronounced alpha suppression during a task[57,65], potentially indicating a greater allocation of attentional resources in post-error trials[57,58].

BCI speller feasibility in autism and future work

The BCI speller used in this study was previously developed by Pires et al.[37] and tested in non-clinical[38] and some clinical groups, such as individuals with motor disabilities[37,72]. As far as we are aware, this is the first study to assess the feasibility of a P300-based speller in autism. However, Amaral et al. previously developed[73] and validated[51] a P300-based BCI (not a speller) in autistic individuals, reporting online accuracy similar to ours. Their dataset was later published[74] and further analyzed in other studies[75–77]. Here, we found that not only was the speller feasible in autism, but also its incorporation in a more complex gamified task.

Only three participants were unable to interact effectively with the BCI speller. In these cases, the classification model obtained during the calibration session was not accurate enough to detect the user's intention, possibly due to artifacts caused by factors such as blinks and movement[78,79]. Additionally, one participant could not perform the word reversal task due to its complexity. Upon examining the FSIQ values, we found that all these participants scored lower than the remaining autistic individuals. This suggests an important consideration for the feasibility of the proposed BCI task: it might be necessary to establish an FSIQ threshold to determine the suitability of the proposed approach. In our case, it seems appropriate to recommend the BCI approach for autistic individuals with an FSIQ > 85. The average FSIQ is 100 with a standard deviation of 15[36], suggesting that only individuals with average or above average FSIQ values are capable of using the BCI. However, the correlation between the number of system errors and FSIQ was not statistically significant, indicating that, once the threshold is met, the BCI performance is not influenced by the FSIQ. The speller performance was also found to be independent of the group and remained stable over time. Nonetheless, some autistic participants did not complete the entire task due to fatigue, which is an important consideration for future optimization. Lastly, we emphasize the importance of conducting data collection in environments where autistic individuals feel comfortable.

In the future, we aim to adapt and generalize this BCI gamified task to different autism subtypes, particularly individuals with major executive function alterations or those who experience anxiety or frustration in response to errors, for the purpose of brain training. BCI systems have been shown to enhance behavioral, neurophysiological, executive function, and social skills in autism[51,80]. Our findings suggest that autistic individuals recruit more neural resources than non-autistic individuals during the preparatory period, as reflected in the theta and alpha activity. These neural alterations could be targeted in brain training approaches. Future research should examine whether long-term training with this task leads to executive function improvements in autism, as well as changes in theta and alpha power. Consistent with this, previous neurofeedback studies have focused on these frequency bands to improve executive function, mainly in non-autistic[46] but also in autistic individuals[81]. Besides, the alpha/theta neurofeedback protocol is widely used but not yet fully understood[82]. Our findings suggest that this ratio varies across task periods and appears to be related to the allocation of cognitive control and attentional resources. However, more studies are needed to comprehend the underlying mechanism of this protocol. Finally, given consistent findings of atypical functional connectivity in autism[83], future studies should also explore alterations in theta and alpha coherence.

Limitations of the study

The main limitation of our study is the sample size. Moreover, it included only one autistic female participant who was unable to interact with the BCI due to calibration issues. Although all analyses were controlled for age and sex, observed group differences may still be influenced by sex-related factors. Therefore, future research should replicate this work with a larger dataset including female participants. Moreover, we aim to include participants from diverse age groups and autism subtypes. Understanding differences in autistic individuals across the lifespan, as well as the relationship between alterations in executive function and autistic traits, is crucial. In a future study, we also plan to test a wider range of cognitive/memory load levels to determine more effectively whether cognitive load affects theta and alpha oscillations.

Conclusions

Our results revealed similar task performance and error-related midfrontal theta modulation during response feedback in autism but suggested distinct recruitment of brain resources during the preparatory phase. We found increased midfrontal theta during preparation to perform the task in autism, which might indicate an increased need for active cognitive control mechanisms to obtain similar performance. Additionally, overall alpha power was higher in autistic individuals, accompanied by larger task-driven suppression, suggesting a greater demand for attentional resources compared to non-autistic individuals.

Data and code availability

Raw EEG data and triggers have been deposited at zenodo.org/records/13367018 and are publicly available as of the date of publication. Moreover, the code used for EEG offline processing and analysis has been deposited at https://github.com/CIBIT-UC/BCI_autism and is publicly available as of the date of publication.

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References

1. American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders* (American Psychiatric Association, 2013).
2. Demetriou, E. A. et al. Autism spectrum disorders: A meta-analysis of executive function. *Mol. Psychiatry* **23**, 1198–1204 (2018).
3. Demetriou, E. A., DeMayo, M. M. & Guastella, A. J. Executive function in autism spectrum disorder: History, theoretical models, empirical findings, and potential as an endophenotype. *Front. Psychiatry* **10**, 1–17 (2019).
4. Best, M. W., Gale, D., Tran, T., Haque, M. K. & Bowie, C. R. Brief executive function training for individuals with severe mental illness: Effects on EEG synchronization and executive functioning. *Schizophr. Res.* **203**, 32–40 (2019).
5. Kim, S. H., Grammer, J., Benrey, N., Morrison, F. & Lord, C. Stimulus processing and error monitoring in more-able kindergarteners with autism spectrum disorder: A short review and a preliminary event-related potentials study. *Eur. J. Neurosci.* **47**, 556–567 (2018).
6. Pavone, E. F. et al. Embodying others in immersive virtual reality: Electro-cortical signatures of monitoring the errors in the actions of an avatar seen from a first-person perspective. *J. Neurosci.* **36**, 268–279 (2016).
7. Chavarriaga, R., Sobolewski, A. & del Millán, J. R. Errare machinale est: The use of error-related potentials in brain-machine interfaces. *Front. Neurosci.* **8**, 208 (2014).
8. van Driel, J., Richard Ridderinkhof, K. & Cohen, M. X. Not all errors are alike: Theta and alpha EEG dynamics relate to differences in error-processing dynamics. *J. Neurosci.* **32**, 16795–16806 (2012).
9. Cavanagh, M. & Frank, M. J. Frontal Theta as a mechanism for cognitive control. *Trends Cogn. Sci.* **18**, 414–421 (2014).
10. McLoughlin, G., Gyurkovics, M., Palmer, J. & Makeig, S. Midfrontal theta activity in psychiatric illness: An Index of cognitive vulnerabilities across disorders. *Biol. Psychiatry* **91**, 173–182 (2022).
11. Dias, C. et al. A neuronal theta band signature of error monitoring during integration of facial expression cues. *PeerJ* **10**, e12627 (2022).

12. Estiveira, J. et al. An action-independent role for midfrontal theta activity prior to error commission. *Front. Hum. Neurosci.* https://doi.org/10.3389/fnhum.2022.805080 (2022).
13. van Noordt, S. J. R., Desjardins, J. A., Gogo, C. E. T., Tekok-Kilic, A. & Segalowitz, S. J. Cognitive control in the eye of the beholder: Electrocortical theta and alpha modulation during response preparation in a cued saccade task. *Neuroimage* **145**, 82–95 (2017).
14. Larrain-Valenzuela, J. et al. Theta and alpha oscillation impairments in autistic spectrum disorder reflect working memory deficit. *Sci. Rep.* **7**, 14328 (2017).
15. Cai, D., Deng, M., Yu, J., Nan, W. & Leung, A. W. S. The relationship of resting-state EEG oscillations to executive functions in middle childhood. *Int. J. Psychophysiol.* **164**, 64–70 (2021).
16. White, T. P. et al. Theta power during encoding predicts subsequent-memory performance and default mode network deactivation. *Hum. Brain Mapp.* **34**, 2929–2943 (2013).
17. de Vries, I. E. J., Slagter, H. A. & Olivers, C. N. L. Oscillatory control over representational states in working memory. *Trends Cogn. Sci.* **24**, 150–162 (2020).
18. Silva, G. et al. Peripheral attentional targets under covert attention lead to paradoxically enhanced alpha desynchronization in neurofibromatosis type 1. *PLoS ONE* **11**, e0148600 (2016).
19. Keehn, B., Westerfield, M., Müller, R. A. & Townsend, J. Autism, attention, and alpha oscillations: An electrophysiological study of attentional capture. *Biol. Psychiatry Cogn. Neurosci. Neuroimag.* **2**, 528–536 (2017).
20. Mathewson, K. J. et al. Regional EEG alpha power, coherence, and behavioral symptomatology in autism spectrum disorder. *Clin. Neurophysiol.* **123**, 1798–1809 (2012).
21. Knyazev, G. G., Slobodskoj-Plusnin, J. Y., Bocharov, A. V. & Pylkova, L. V. The default mode network and EEG alpha oscillations: An independent component analysis. *Brain Res.* **1402**, 67–79 (2011).
22. Ray, W. J. & Cole, H. W. EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. *Science (80-)* **228**, 750–752 (1985).
23. McMahon, C. M. & Henderson, H. A. Error-monitoring in response to social stimuli in individuals with higher-functioning autism spectrum disorder. *Dev. Sci.* **18**, 389–403 (2015).
24. Henderson, H. et al. Response monitoring, the error-related negativity, and differences in social behavior in autism. *Brain Cogn.* **61**, 96–109 (2006).
25. Santesso, D. L. et al. An event-related source localization study of response monitoring and social impairments in autism spectrum disorder. *Psychophysiology* **48**, 241–251 (2011).
26. South, M., Larson, M. J., Krauskopf, E. & Clawson, A. Error processing in high-functioning autism spectrum disorders. *Biol. Psychol.* **85**, 242–251 (2010).
27. Vlamings, P. H. J. M., Jonkman, L. M., Hoeksma, M. R., Van Engeland, H. & Kemner, C. Reduced error monitoring in children with autism spectrum disorder: An ERP study. *Eur. J. Neurosci.* **28**, 399–406 (2008).
28. Buzzell, G. A., Thomas, H. R., Choi, Y. B. & Kim, S. H. Atypical mediofrontal theta oscillations underlying cognitive control in kindergarteners with autism spectrum disorder. *Biol. Psychiatry Cogn. Neurosci. Neuroimag.* **7**, 566–575 (2021).
29. Castro-Meneses, L. J., Kruger, J. L. & Doherty, S. Validating theta power as an objective measure of cognitive load in educational video. *Educ. Technol. Res. Dev.* **68**, 181–202 (2020).
30. Kelly, A. M. C. & Garavan, H. Human functional neuroimaging of brain changes associated with practice. *Cereb. Cortex* **15**, 1089–1102 (2005).
31. Lotte, F. et al. A review of classification algorithms for EEG-based brain–computer interfaces: A 10 year update. *J. Neural Eng.* **15**, 031005 (2018).
32. Datko, M., Pineda, J. A. & Müller, R. A. Positive effects of neurofeedback on autism symptoms correlate with brain activation during imitation and observation. *Eur. J. Neurosci.* **47**, 579–591 (2018).
33. Trzmiel, T., Purandare, B., Michalak, M., Zasadzka, E. & Pawlaczyk, M. Equine assisted activities and therapies in children with autism spectrum disorder: A systematic review and a meta-analysis. *Complement. Ther. Med.* **42**, 104–113 (2019).
34. Lord, C., Rutter, M. & Le Couteur, A. Autism diagnosis interview-revised: a revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *J. Autism Dev. Disord.* **24**, 659–685 (1994).
35. Lord, C. et al. Austism diagnostic observation schedule: A standardized observation of communicative and social behavior. *J. Autism Dev. Disord.* **19**, 185–212 (1989).
36. Wechsler, D. *WAIS–III Escala de Inteligência de Wechsler para Adultos* (Cegoc-Tea, 2008).
37. Pires, G., Nunes, U. & Castelo-Branco, M. Comparison of a row-column speller versus a novel lateral single-character speller: Assessment of BCI for severe motor disabled patients. *Clin. Neurophysiol.* **123**, 1168–1181 (2012).
38. Cruz, A., Pires, G. & Nunes, U. J. Double ErrP detection for automatic error correction in an ERP-based BCI speller. *IEEE Trans. Neural Syst. Rehabil. Eng.* **26**, 26–36 (2017).
39. Cruz, A., Pires, G. & Nunes, U. J. Spatial filtering based on Riemannian distance to improve the generalization of ErrP classification. *Neurocomputing* **470**, 236–246 (2022).
40. Farwell, L. A. & Donchin, E. Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials. *Electroencephalogr. Clin. Neurophysiol.* **70**, 510–523 (1988).
41. Pires, G., Nunes, U. & Castelo-Branco, M. Statistical spatial filtering for a P300-based BCI: Tests in able-bodied, and patients with cerebral palsy and amyotrophic lateral sclerosis. *J. Neurosci. Methods* **195**, 270–281 (2011).
42. Yao, D. et al. Which reference should we use for EEG and ERP practice?. *Brain Topogr.* **32**, 530–549 (2019).
43. Liu, Q. et al. The feature, performance, and prospect of advanced electrodes for electroencephalogram. *Biosensors* **13**, 101 (2023).
44. Chaumon, M., Bishop, D. V. M. & Busch, N. A. A practical guide to the selection of independent components of the electroencephalogram for artifact correction. *J. Neurosci. Methods* **250**, 47–63 (2015).
45. Solomon, Jr, O. M. *PSD computations using Welch's method. [Power Spectral Density (PSD)]*. (1991). https://doi.org/10.2172/5688766
46. Viviani, G. & Vallesi, A. EEG-neurofeedback and executive function enhancement in healthy adults: A systematic review. *Psychophysiology* https://doi.org/10.1111/psyp.13874 (2021).
47. Seltman, H. J. Mixed models. in *Experimental Design And Analysis* 357–378 (2018).
48. Groen, Y. et al. Error and feedback processing in children with ADHD and children with autistic spectrum disorder: An EEG event-related potential study. *Clin. Neurophysiol.* **119**, 2476–2493 (2008).
49. Thakkar, K. N. et al. Response monitoring, repetitive behaviour and anterior cingulate abnormalities in autism spectrum disorders (ASD). *Brain* **131**, 2464–2478 (2008).
50. Goldberg, M. C. et al. Children with high functioning autism show increased prefrontal and temporal cortex activity during error monitoring. *Dev. Cogn. Neurosci.* **1**, 47–56 (2011).
51. Amaral, C. et al. A Feasibility clinical trial to improve social attention in autistic spectrum disorder (ASD) using a brain computer interface. *Front. Neurosci.* https://doi.org/10.3389/fnins.2018.00477 (2018).
52. McDougle, S. D. Post-error slowing during instrumental learning is shaped by working memory-based choice strategies. *Neuroscience* **486**, 37–45 (2022).
53. Wascher, E. et al. Frontal theta activity reflects distinct aspects of mental fatigue. *Biol. Psychol.* **96**, 57–65 (2014).
54. Cohen, M. X. Error-related medial frontal theta activity predicts cingulate-related structural connectivity. *Neuroimage* **55**, 1373–1383 (2011).
55. Cavanagh, J. F., Zambrano-Vazquez, L. & Allen, J. J. B. Theta Lingua Franca: A common mid-frontal substrate for action monitoring processes. *Psychophysiology* **49**, 220–238 (2012).

56. Cavanagh, J. F. & Shackman, A. J. Frontal midline theta reflects anxiety and cognitive control: Meta-analytic evidence. *J. Physiol.: Paris* **109**, 3–15 (2015).
57. Knyazev, G. G., Savostyanov, A. N. & Levin, E. A. Alpha synchronization and anxiety: Implications for inhibition versus alertness hypotheses. *Int. J. Psychophysiol.* **59**, 151–158 (2006).
58. Zhu, Y., Wang, Q. & Zhang, L. Study of EEG characteristics while solving scientific problems with different mental effort. *Sci. Rep.* **11**, 23783 (2021).
59. Cañigueral, R. et al. Alpha oscillatory activity during attentional control in children with Autism Spectrum Disorder (ASD), Attention-Deficit/Hyperactivity Disorder (ADHD), and ASD + ADHD. *J. ofChild Psychol. Psychiatry* **63**, 745–761 (2022).
60. Ames, C. & Fletcher-watson, S. A review of methods in the study of attention in autism. *Dev. Rev.* **30**, 52–73 (2010).
61. Cavanagh, J. F., Cohen, M. X. & Allen, J. J. B. Prelude to and resolution of an error: EEG phase synchrony reveals cognitive control dynamics during action monitoring. *J. Neurosci.* **29**, 98–105 (2009).
62. Danielmeier, C., Eichele, T., Forstmann, B. U., Tittgemeyer, M. & Ullsperger, M. Posterior medial frontal cortex activity predicts post-error adaptations in task-related visual and motor areas. *J. Neurosci.* **31**, 1780–1789 (2011).
63. Klimesch, W. EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Res. Rev.* **29**, 169–195 (1999).
64. Mathewson, K. E., Gratton, G., Fabiani, M., Beck, D. M. & Ro, T. To see or not to see: Prestimulus alpha phase predicts visual awareness. *J. Neurosci.* **29**, 2725–2732 (2009).
65. Wang, J. et al. The effects of pre-cue posterior alpha on post-cue alpha activity and target processing in visual spatial attention tasks with instructional and probabilistic cues. *Cereb. Cortex* **33**, 4056–4069 (2023).
66. Koban, L. & Pourtois, G. Brain systems underlying the affective and social monitoring of actions: An integrative review. *Neurosci. Biobehav. Rev.* **46**, 71–84 (2014).
67. Somon, B., Campagne, A., Delorme, A. & Berberian, B. Brain mechanisms of automated conflict avoidance simulator supervision. *Psychophysiology* https://doi.org/10.1111/psyp.14171 (2022).
68. Zhang, H. et al. EEG-based decoding of error-related brain activity in a real-world driving task. *J. Neural Eng.* **12**, 066028 (2015).
69. Sokhadze, E. M. et al. Event-related potential study of attention regulation during illusory figure categorization task in ADHD, autism spectrum disorder, and typical children. *J. Neurother.* **16**, 12–31 (2012).
70. Clawson, A. et al. How about watching others? Observation of error-related feedback by others in autism spectrum disorders. *Int. J. Psychophysiol.* **92**, 26–34 (2014).
71. van Noordt, S. et al. Inter-trial coherence of medial frontal theta oscillations linked to differential feedback processing in youth and young adults with autism. *Res. Autism Spectr. Disord.* **37**, 1–10 (2017).
72. Pires, G., Nunes, U. & Castelo-Branco, M. Evaluation of brain–computer interfaces in accessing computer and other devices by people with severe motor impairments. *Proc. Comput. Sci.* **14**, 283–292 (2012).
73. Amaral, C. P., Simões, M. A., Mouga, S., Andrade, J. & Castelo-branco, M. A novel Brain Computer Interface for classification of social joint attention in autism and comparison of 3 experimental setups: A feasibility study. *J. Neurosci. Methods* **290**, 105–115 (2017).
74. Simões, M. et al. BCIAUT-P300: A Multi-session and multi-subject benchmark dataset on autism for P300-based brain–computer-interfaces. *Front. Neurosci.* https://doi.org/10.3389/fnins.2020.568104 (2020).
75. Peketi, S. & Dhok, S. B. Machine learning enabled P300 classifier for autism spectrum disorder using adaptive signal decomposition. *Brain Sci.* **13**, 315 (2023).
76. Das, M. & Manjunatha, M. Enhancing ASD cognitive assessment with P300 classification using EMD-based qEEG Wavelet Features. in *2023 7th International Conference on Computer Applications in Electrical Engineering-Recent Advances (CERA)* (IEEE, 2023). https://doi.org/10.1109/CERA59325.2023.10455596
77. Tasnim, N., Halder, J., Ahmed, S. & Fattah, S. A. An approach for analyzing cognitive behavior of autism spectrum disorder using P300 BCI Data. in *2022 IEEE Reg. 10 Symp.* 1–6 (2022). https://doi.org/10.1109/TENSYMP54529.2022.9864339
78. Mak, J. N. et al. Optimizing the P300-based brain–computer interface: Current status, limitations and future directions. *J. Neural Eng.* **8**, 025003 (2011).
79. Rahmani, M., Mohajelin, F., Khaleghi, N., Sheykhivand, S. & Danishvar, S. An automatic lie detection model Using EEG signals based on the combination of type 2 fuzzy sets and deep graph convolutional networks. *Sensors* **24**, 3598 (2024).
80. Kouijzer, M. E. J., van Schie, H. T., de Moor, J. M. H., Gerrits, B. J. L. & Buitelaar, J. K. Neurofeedback treatment in autism. Preliminary findings in behavioral, cognitive, and neurophysiological functioning. *Res. Autism Spectr. Disord.* **4**, 386–399 (2010).
81. Holtmann, M. et al. Neurofeedback in autism spectrum disorders. *Dev. Med. Child Neurol.* https://doi.org/10.1111/j.1469-8749.2011.04043.x (2011).
82. Lee, Y.-J. et al. The analysis of electroencephalography changes before and after a single neurofeedback alpha/theta training session in university students. *Appl. Psychophysiol. Biofeedback* **44**, 173–184 (2019).
83. Khaleghi, N. et al. EEG-based functional connectivity analysis of brain abnormalities: A systematic review study. *Inform. Med. Unlock.* **47**, 101476 (2024).

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Author contributions

T. Sousa, A. Cruz, G. Pires, and M. Castelo-Branco conceived and designed the experiments. C. Dias, T. Sousa, A. Cruz, D. Costa, and G. Pires performed the experiments and acquired the EEG data. S. Mouga performed the neuropsychological evaluation for the ASD group. C. Dias, T. Sousa, A. Cruz, D. Costa, J. Castelhano, G. Pires, and M. Castelo-Branco contributed to the analysis and interpretation of the data. C. Dias wrote the first draft of the manuscript and prepared figures and tables. All authors reviewed drafts of the paper and approved the final manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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