The inhibitory control characteristic of children with attention-deficit/hyperactivity disorder with emotional dysregulation: evidence from event-related potentials (ERPs)

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Research Article

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Abstract

Objective

Attention-deficit/hyperactivity disorder (ADHD) is the most prevalent neurodevelopmental condition in children. Emotion dysregulation (ED) exacerbates functional impairment severity in children with ADHD, and previous research suggests that ED may be linked to inhibition control deficits.

Method

We utilized the Anxiety/Depression, Aggression, and Attention scales of the CBCL (CBCL-DESR) to categorize participants into three groups: ADHD with emotion dysregulation (ADHD with DESR, n = 15), ADHD without emotion dysregulation (ADHD without DESR, n = 22), and Typical Development Children (TDC, n = 35). The Two-Choice Oddball task was employed to assess inhibitory control characteristics and record synchronous ERP. Repeated measures ANOVA and multiple linear regression was used to analysis the relationship between inhibition control deficit and emotion dysregulation.

Results

In the measurement of behavioral inhibit control functioning, we found that ADHD patients had a lower overall response accuracy than TDC. ADHD patients with emotion dysregulation had even longer overall response time than ADHD without emotion dysregulation and TDC. The original waveform analysis showed the larger amplitude for deviant stimuli than for standard stimuli in ADHD with emotional dysregulation group and lower amplitude for ADHD with emotional dysregulation than for ADHD without emotional dysregulation and TDC groups in deviant stimuli. The deviation-standard difference wave analysis showed that the N2 difference wave of ADHD with emotion dysregulation group was significantly larger that of ADHD without emotional dysregulation and TDC groups and we find inhibitory control-related EEG indicators (N2, P3) in predicting emotional dysregulation in ADHD patients.

Conclusions

ADHD children with emotional dysregulation showed more severe inhibitory control impairment on behavioral indicators, and differential N2 amplitude together with differential P3 amplitude can predict ADHD children with emotional dysregulation independently. The results could provide enlightening evidence for early detection and intervention targets in this subtype of children with ADHD.

Introduction

Attention-deficit/hyperactivity disorder (ADHD) is the most common neurodevelopmental disorder in children and adolescents worldwide[1, 2], with a global prevalence of 5.29%[3]. A meta-analysis found a prevalence of 6.3%[4] in Chinese children and adolescents. Diagnosis of ADHD is based on identifying age-inappropriate symptoms of inattention, hyperactivity, and impulsivity, which can cause impairment in two or more areas of daily functioning[5]. Children with ADHD often struggle in educational settings, achieving lower academic performance compared to their peers without ADHD. These challenges also affect their social interactions, leading to disruptive behaviors, peer disapproval, and low self-esteem[6].

Emotion dysregulation (ED) refers to the inability to effectively manage one's own emotions, leading to excessively intense or inappropriate reactions that are not in line with one's developmental stage[7]. In the early conceptualization of ADHD as "minimal brain damage," emotion dysregulation was considered a primary symptom, alongside inattention[8]. However, with the introduction of DSM-III, emotion dysregulation shifted from being a diagnostic criterion to being an "associated feature" of ADHD. Despite ongoing debates about the role of emotion dysregulation in ADHD diagnosis, their importance is undeniable. Research indicates that a substantial proportion of individuals with ADHD, ranging from 24–45% in children, also experience comorbid emotion dysregulation (ED) [9]. In Christiansen's study, emotion dysregulation is highly prevalent and associated with increased impairment and negative outcomes throughout the life span[10]. Individuals with both ADHD and ED experience greater impairment in overall functioning[9], as well as a higher risk of involvement in criminal activities[11], substance misuse[12], psychiatric hospitalizations[13], and even premature mortality[14] compared to those with ADHD alone[15]. A recent longitudinal study revealed that emotion dysregulation serves as a unique predictor of ADHD persistence into adulthood in seven out of ten key domains of impairment from childhood[16].

Neurocognitive dysfunction especially the behavior inhibit control (BIC) deficit has long been proposed in the etiology of ADHD. A substantial body of evidence supports the idea of compromised inhibitory control function in individuals with ADHD, as evidenced by reduced accuracy rates[17, 18], increased commission errors[19, 20] on No-Go trials, and elevated Stroop interference error scores on the SST[21]. Barkley et al. argue that inhibitory control, as the most central executive function, is closely related to emotional regulation, and its absence leads to deficits in emotional regulation[22]. According to Barkley's model, people with ADHD are more likely than healthy controls to have excessive emotional responses or difficulty regulating emotions when faced with emotion-inducing situations because of impaired inhibitory control[23, 24]. In a recent investigation directly examining the relationship between ADHD and emotional dysregulation (ED) symptoms, Banaschweski found that mean reaction time (MRT), standard deviation of individual reaction times (RTV), commission and omission errors in the go/no-go task significantly predicted ADHD and ED symptoms with moderate to low regression coefficients. However, the association between neuropsychological parameters and ED disappeared entirely when the influence of ADHD symptoms was considered[25]. Notably, prior studies have not explored the neurocognitive dysfunction in ADHD with emotion dysregulation. Therefore, it is worthwhile investigating the behavioral inhibitory control function in individuals with ADHD, particularly those with emotion dysregulation.

Inhibit control functions can be assessed synchronously and precisely by event-related potentials (ERPs) derived from EEG data by subtracting the amplitude of the deviant stimulus from that of the standard stimulus[26]. Event-related potential (ERP) components closely associated with inhibitory control processes include the N2 and P3 components[27]. The amplitude of the P3 waveform reflects the level of cognitive effort exerted by the individual in effectively restraining impulsive behavior, with a higher amplitude indicating stronger inhibitory control processes[28]. Previous studies have shown that children with ADHD consistently display N2 and P3 amplitudes[29], suggesting a potential association between N2 and P3 amplitudes and ADHD. Despite the significance of these ERP components in ADHD, research focused on understanding the neurocognitive basis of emotional reactivity and regulation in ADHD is limited; and to date, N2 and P3 characteristics of ADHD with ED patients have not been studied.

Researchers have employed the two-choice oddball task to investigate inhibitory control in those with substance abuse[30, 31] and nonsuicidal self-Injury (NSSI)[32]. In patients with substance abuse, research found that the RTs of the tendencies towards cybersex addiction (TCA) group to deviant stimuli were much slower than those of the HC group; individuals with TCA demonstrated smaller N2 and P3 amplitude differences for deviant than standard stimuli. In patients with NSSI, research found that in the NSSI group, the P3 amplitude with self-injury cues was significantly larger than that with neutral cues. As there has been etiologically associations between ADHD and substance abuse[33] and there is also etiologically associations between emotion dysregulation and NSSI[34], it is reasonable to investigate whether there is any behavioral or ERPs deviation in inhibitory control in patients with ADHD and emotion dysregulation.

In this study, we utilized the two-choice Oddball task (1) to assess the proficiency of behavioral inhibitory control in individuals with ADHD. Additionally, we aimed (2) to investigate the characteristics of inhibitory control, specifically focusing on N2 and P3 amplitudes, and their relationship within a subgroup of ADHD individuals with emotion dysregulation (ED), comparing them to ADHD individuals without ED and typically developing controls (TDC). Finally, we tried (3) to elucidate the interplay between N2 and P3 amplitudes, behavioral inhibitory control, and ADHD symptoms that may contribute to the expression of ED in individuals with ADHD.

Method

Participants

The study included 37 children aged 6 to 12 years who had been diagnosed with ADHD, along with 35 healthy control subjects matched for age and gender. To be eligible for inclusion, both groups needed to have an intelligence quotient (IQ) estimate of 80 or higher, which was assessed using the Chinese-Wechsler Intelligence Scale for Children-III (C-WISC-III) [35]. Exclusion criteria for both groups included physical brain injury, neurological disorders, serious medical or genetic conditions, and substance dependence. Healthy control subjects were also excluded if they had been diagnosed with any mental health disorder. The diagnostic process for ADHD and other mental disorders involved using the Schedule for Affective Disorders and Schizophrenia for School-age Children (K-SADS-PL), which was administered to parents by clinical psychologists or trained interviewers with equivalent qualifications[36].

To assess the emotional dysregulation challenges faced by the participating children, the Child Behavior Checklist-Deficient Emotional Self-Regulation scale (CBCL-DESR) was employed. A T-score within the range of 180 to 210 on the CBCL-DESR scale indicated a deficit in emotional self-regulation[37]. ADHD participants were categorized into two groups based on their CBCL-DESR scores: those with ADHD and DESR, and those with ADHD without DESR. The functional impairment of the tested children was evaluated using the Weiss Functional Impairment Scale-Parent form (WFIRS-P), with higher scores indicating more significant impairment[38]. The severity of attention deficit/hyperactivity symptoms was assessed using the K-SADS-PL, with higher scores reflecting more severe symptoms[36].

Two-choice Oddball Task

The two-choice Oddball paradigm was implemented using E-Prime 2.0.8 software. As shown in Fig. 1, this task involved stimuli categorized into two types: standard stimuli and deviant stimuli, with an 80% standard to 20% deviant stimuli ratio. In the stimuli set, numbers other than "3" were considered standard stimuli, while the number "3" was designated as the deviant stimulus. The stimuli were presented in a random order, and each stimulus had a maximum presentation time of 800 milliseconds, ending when the participant pressed a key. During the inter-stimulus interval, a cross-shaped fixation point (" ") was displayed at varying intervals of 1000ms, 1200ms, or 1400ms.Participants were required to respond quickly and accurately to the stimuli using the keyboard. The response rules were as follows: Press "F(J)" for the key labeled "3," and press "J(F)" for keys other than "3." Key assignments were evenly distributed among the participants. Before the formal experiment, participants underwent a practice session consisting of 30 trials. The formal experiment began once participants achieved an accuracy rate exceeding 90%. The formal experiment was divided into three blocks, each containing 80 trials.

Past studies investigating the behavioral inhibition control in individuals with ADHD have often used the Go/No Go paradigm and the Stop Signal Task (SST) as experimental tasks. The former requires participants to quickly respond to a "Go" signal while refraining from responding to a "No go" signal. In contrast, the latter includes both Go and Stop trials, assessing inhibitory control function by examining reaction times and response accuracy[39–42]. Essentially, inhibitory control involves the ability to restrain ongoing behaviors, serving as a mechanism for managing behavioral and cognitive regulation by suppressing inappropriate behaviors or cognitive processes[43].Yuan et al.'s revised two-choice oddball task requires participants to respond quickly and accurately to both high-probability standard stimuli and low-probability deviant stimuli[44].

Data Acquisition and Preprocessing

EEG data acquisition was conducted using the ERP recording system from Brain Products (Munich, Germany). A 64-lead silver/silver chloride (Ag/AgCl) electrode cap was employed, arranged in adherence to the international 10–20 lead system. The impedance of each electrode was vigilantly maintained below 5kΩ. The electrode FCz was used as the online reference, and the AFz electrode was used as the grounding electrode. Vertical electrooculogram (VEOG) was recorded by an electrode placed under the right eye. The resistance of all electrodes was less than 5 kΩ. EEG and EOG were amplified with a 0.01

~250 Hz bandpass and digitized at 500 Hz/channel. The accuracy and RT were recorded for each response. Trials with RTs less than 100ms were excluded from the analysis, and solely correct responses were considered for subsequent analysis involving reaction times and EEG activity.

Offline analyses were conducted using the EEGLAB toolbox in MATLAB 2020a[45]. We resampled all EEG data at 500Hz. The offline bandpass filter was set at 0.1–35Hz. All EEG data were rereferenced to the average of the TP9 and TP10 electrodes. EEG data were epoched to include 200ms of the pre-stimulus and 800ms of the post-stimulus periods. Epochs with an incorrect response were removed. Epochs with large artifacts were rejected, and bad channels were interpolated using the spherical method. Then, we ran independent component analysis (ICA) to remove artifact components, which mainly included blinking, horizontal eye movements, and some muscle artifacts[46]. For each condition, epochs were overlapped and averaged separately. The 200-ms pre-stimulus baseline was subtracted by the post-stimulus wave to correct the baseline. The mean amplitude of N2 (180–300ms) and P3 (350–450ms) components was derived from both standard and deviant stimuli. N2 is typically largest in anterior areas, and P3 is typically largest in parietal or posterior areas [47–49]. As in previous studies[50, 51], FCz was chosen as the electrode of interest for N2, and Cz was chosen as the electrode of interest for P3.

Statistical Analysis

Questionnaire data were analyzed using univariate ANOVA analysis. Repeated measures analysis of variance (ANOVA) was applied to analyze the ERP indices of BIC (N2 and P3) and behavioral measurements (accuracy and RTs). This resulted in a Group (ADHD with DESR, ADHD without DESR,TDC) × Stimulus (standard and deviant conditions) ANOVA for N2 and P3 amplitudes related to BIC, and a Group×Stimulus ANOVA for behavioral measures. Stimulus were within-subject factors, and Group was the between-subject factor. Post-hoc analyses using pairwise comparisons with Least Significant Difference (LSD) adjustments were applied. All statistical values were reported with Greenhouse–Geisser corrections, and the partial eta-square ($\eta^2 p$) value was reported to have significant effects. An alpha level of 0.05 was used for all statistical tests. We further performed a hierarchical multiple regression analyses to explore complex relationships between the behavioral measurements and ERP indices of BIC with the DESR score for the ADHD group.

Results

Demographic and clinical characteristics

Our study included a total of 72 participants, consisting of 35 healthy control individuals and 37 patients diagnosed with ADHD. Within the ADHD group, 21 cases predominantly exhibited attention deficit symptoms (ADHD-I) (accounting for 56.76% of the ADHD group), 5 cases primarily displayed hyperactivity and impulsivity symptoms (ADHD-H) (13.51%), and 11 cases had a mixed presentation of symptoms (ADHD-C) (29.73%). A comprehensive overview of the demographic characteristics across the three groups is presented in **Table 1**. Specifically, there were no statistically significant differences in age, sex distribution, or IQ among the groups. Furthermore, there were no significant differences in ADHD core symptom scores between the ADHD group with DESR and the ADHD group without DESR.

Table 1 Sample Characteristics

	ADHD with DESR (N=15)	ADHD without DESR (N=22)	TDC (N=35)	χ^2/F	*p*
Gender					
Male	14	16	21	5.70	0.06
Female	1	6	14		
Age	7.73±1.16	8.59±2.20	9.14±2.34	2.38	0.10
IQ	117.52±13.46	106.65±13.46	110.78±15.28	2.56	0.09
K-SADS-attention deficit	17.67±2.72	17.10±2.36	-	0.67	0.51
K-SADS-hyperactive/impulsive	21.40±5.28	20.62±5.20	-	0.44	0.66
K-SADS-total	39.07±5.99	37.71±6.21	-	0.65	0.52

Note ADHD: Attention-deficit/hyperactivity disorder; DESR: Deficient Emotional Self-Regulation; TDC: Typical Development Children; K-SADS: Schedule for Affective Disorders and Schizophrenia for School-age Children.

Function impairment

As shown in **Figure 2**, we conducted a univariate ANOVA analysis to identify potential differences of functional impairment among the three groups: ADHD with DESR, ADHD without DESR and TDC. The results of this analysis revealed statistically significant differences (P < 0.05). The post-hoc analysis yielded that ADHD patients with DESR exhibited significantly more extensive functional impairments across family, study/school, life skills, social activities and risky activities domains compared to both the

ADHD without DESR and TDC groups. For ADHD patients without DESR, the observed functional impairments were primarily concentrated within the study/school domain compared to the TDC group.

FIGURE2 | Functional impairment of ADHD with DESR, ADHD without DESR and TDC groups.

Behavioral Neurocognitive Functioning

Accuracy As illustrated in **Figure 3**, the analysis of accuracy (ACC) revealed a significant main effect of group ($F(2,69) = 5.65$, $p = 0.005$, $\eta 2p = 0.15$). ACC across conditions were lower for the ADHD with DESR group ($M = 0.67$, $SD = 0.03$) and the ADHD without DESR group ($M = 0.71$, $SD = 0.03$) compared to TDC group ($M = 0.80$, $SD = 0.02$). There was also a significant main effect of stimulus type ($F(1,69) = 143.71$, $p < 0.001$, $\eta 2p = 0.69$), indicating that ACC was significantly lower for deviant stimuli ($M = 0.59$, $SD = 0.03$) compared to standard stimuli ($M = 0.86$, $SD = 0.01$) across all groups. However, there was no significant interaction between group and stimulus type ($F(2,69) = 1.23$, $p = 0.30$, $\eta 2 = 0.04$).

FIGURE 3 | Accuracy for ADHD with DESR, ADHD without DESR and TDC groups of standard and deviant stimuli.

Reaction Time As illustrated in **Figure 4**, the analysis of reaction time (RT) revealed a significant main effect of group($F(1,69) = 5.01$, $p = 0.009$, $\eta 2p = 0.13$). RT across conditions were longer for the ADHD with DESR group ($M = 591.86$, $SD = 16.84$) compared to the ADHD without DESR group ($M = 543.41$, $SD = 13.44$) and the TDC group ($M = 528.89$, $SD = 10.65$). There was also a significant main effect of stimulus type ($F(1,69) = 319.65$, $p < 0.001$, $\eta 2 = 0.83$), indicating that RT was significantly longer for deviant stimuli ($M = 602.37$, $SD = 8.05$) compared to standard stimuli ($M = 507.07$, $SD = 8.82$) across all groups. However, there was no significant interaction between group and stimulus type ($F(2,69) = 2.02$, $p = 0.14$, $\eta 2p = 0.06$).

FIGURE 4 | Reaction time for ADHD with DESR, ADHD without DESR and TDC groups of standard and deviant stimuli.

Test the Effect of BIC (Original Waveform)

N2 Amplitude A repeated measures variance analysis was conducted on the N2 amplitude. The result revealed that there was no significant main effect of group ($F(2,69) = 0.27$, $p = 0. 76$, $\eta 2p = 0.01$). There was a significant main effect of stimulus type ($F(1,69) = 4.04$, $p = 0.04$, $\eta 2p = 0.06$), post hoc(LSD) analysis found the average amplitude for deviant stimuli (5.05 ± 0.70) was significantly larger than that of standard stimuli (3.80 ± 0.58). In addition, there was a significant interaction effect of stimuli type and group ($F(2,69) = 4.54$, $p = 0.02$, $\eta 2p = 0.13$), the simple effect analyses of two-way interaction showed a stimuli effect in group types, with larger amplitude for deviant stimuli (7.06 ± 1.47) than for standard stimuli (3.02 ± 1.23) in ADHD with DESR group, and there was no difference between the two stimuli in ADHD without DESR and TDC groups.

P3 Amplitude A repeated measures variance analysis was conducted on the P3 amplitude. The result revealed that there was no significant main effect of group ($F(2,69) = 2.17$, $p = 0.12$, $\eta 2p = 0.07$). There was a significant main effect of stimulus type ($F(1,69) = 21.31$, p 0.001, $\eta 2p = 0.26$), post hoc(LSD) analysis found the average amplitude for deviant stimuli (7.36 ± 0.87) was significantly larger than that of standard stimuli (3.88 ± 0.86) . In addition, there was a significant interaction effect of stimuli type and group ($F(2,69) = 3.42$, $p = 0.04$, $\eta 2p = 0.10$). A simple effect analysis indicated that with deviant stimuli, the P3 amplitude in the ADHD +DESR group was smaller than that in the ADHD-DESR group and TDC group (LSD-adjusted p=0.009). The P3 amplitude with deviant stimuli was significantly larger than that with standard stimuli In the ADHD-DESR group (LSD-adjusted p=0.009) and TDC group (LSD-adjusted $p < 0.001$), however, there was no such effect in the ADHD+DESR group. Grand mean ERPs were presented in **Figure 5**, and topographic maps were shown in **Figure 6**.

FIGURE 5 | Average of original ERPs of FCz and Cz for standard and deviated stimulation in ADHD with DESR ,ADHD without DESR and TDC group.

FIGURE 6 | Topographical maps of voltage amplitudes for original waveform at 180–300 ms and 350–450 ms in ADHD+DESR group ,ADHD-DESR group and TDC group.

Differences of BIC Processes in Group of ADHD with DESR, ADHD without DESR and TDC group (Deviation-Standard Difference Wave Analysis)

As illustrated in **Figure 7**, the N2 difference wave of ADHD with DESR group (4.04 ± 4.68) was significantly larger that of ADHD without DESR (-1.01 ± 4.91) and TDC groups (0.73 ± 4.28). The P3 difference wave of ADHD with DESR group (1.11 ± 6.34) was significantly small that of TDC groups (5.79 ± 5.13).

FIGURE 7 | Deviation-standard difference wave in ADHD with DESR, ADHD without DESR and TDC group.

Predictive effect of behavioral measurements and ERP indices of BIC

As illustrated in **Table 2**, we use the hierarchical multiple regression analysis to test whether the behavioral measurements and ERP indices of BIC are valid predictor indexes of DESR in ADHD group. In the first step, behavioral measurements (i.e. RT and ACC) were entered as predictors of DESR in ADHD group. The result indicated that there was no significant predictive effects of behavioral measurements on DESR ($p = 0.60$). In the second step, ERP indices (i.e. standard N2, standard P3, N2d and P3d) were entered as candidate predictors. The results indicated that both the N2d ($p = 0.003$**) and P3d (p

0.001***) had significant predictive effects on DESR and the total variance explained by the model was 20% (F[6, 29] = 2.50; p = 0.03).

Table 2 Summary of the multiple hierarchical regression analysis predicting DESR in ADHD participants (n = 37).

Block				Model 1				Model 2			
Predictor	R2adj	R2ch	p	b	SE	β	p	b	SE	β	p
(1)behavioral measurements	-0.02	0.02	0.60								
RT				0.00	0.02	0.001	0.99	-0.01	0.02	-0.05	0.74
ACC				-11.39	12.54	-0.13	-0.91	1.39	12.61	0.02	0.91
(2)ERP indices	0.13	0.20	0.03								
Standard N2								0.01	0.36	0.01	0.97
Standard P3								-0.11	0.27	-0.07	0.70
N2d								1.20	0.39	0.59	0.003**
P3d								-1.01	0.29	-0.64	＜0.001***

Note: N2d: differential N2 amplitude; P3d: differential P3 amplitude.

Discussion

This study aims to explore the inhibitory control characteristics and related event related potential in ADHD children with emotional dysregulation using two-choice oddball task. The result of the behavioral and the EEG analysis confirms our hypothesis that ADHD patients with emotional dysregulation (ADHD with DESR group) have poorer inhibitory control compared with ADHD without emotional dysregulation (ADHD without DESR group) and the healthy control group. Moreover, differential N2 amplitude(N2d) and differential P3 amplitude (P3d) had significant predictive effects on emotion dysregulation (DESR scores) in ADHD participants, suggesting their potential role in detection of emotion dysregulation in ADHD. To our knowledge, this is the first study on characteristics of inhibitory control and related ERP exclusively in ADHD children with emotional dysregulation, and the results could provide enlightening evidence for early detection and intervention targets in this subtype of children with ADHD.

In this study, emotion dysregulation was found to highly associated with impairment in areas of function requiring social interaction ,those function were home, social functioning and education), which were not accounted for by the severity of core symptoms. Barkley and Murphy (2010)[52]previously showed that emotion dysregulation in ADHD was associated with school/college problems, impairment in community activities, marital satisfaction and stress in parent-child relationships. Our result on function impairment of emotion dysregulation in ADHD is in line with the work by Barkley and Fischer (2010)[53], suggesting the key dimensional impairment being on social interaction.

In the measurement of behavioral inhibit control functioning, we found that both ADHD and TDC had lower accuracy and longer response time on deviant stimuli than on standard stimuli, which was consistent with the results of previous studies on substance addiction[30] and normal population[54]. Together with our results, it is indicated that in the two-choice Oddball task, the deviant stimulus can induce more intense inhibition control related behavioral processes than the standard stimulus, and the two-choice Oddball paradigm is suitable for ADHD children with emotion dysregulation.

This study found that ADHD patients had a lower overall response accuracy than TDC. ADHD patients with emotion dysregulation had even longer overall response time than ADHD without emotion dysregulation and TDC. A recent meta-analyses revealed that children with ADHD make significantly more omission and commission errors on the CPT compared with typically developing children (TDC)[55]. Combined with the results of this study, it can be inferred that ADHD patients, especially those with emotion dysregulation, are more severely impaired in behavioral inhibit control functioning.

The original waveform analysis showed that the main effect of stimuli in N2 and P3 amplitude was significant. The N2 and P3 amplitude of deviant stimuli was even larger than that of standard stimuli in the present study, which was consistent to previous studies [56, 57].N2 is a negative component in the ERP, peaking between 200 and 300ms over frontocentral scalp regions. It has been proposed to reflect conflict monitoring and cognitive control, processes in the early stages of response inhibition [58–61]. The P3, a positive component peaking between 300 and 600ms over central parietal scalp, reflecting conflict resolution through top-down inhibition processing in a later stage of response inhibition [58–60]. The analysis of the original waveform reflects the validity of the two-choice oddball paradigm in measuring behavior inhibition control(BIC). Previous studies have only used the two-choice oddball paradigm to measure inhibitory control in patients with substance-abuse, and found that individuals with tendencies towards cybersex addiction (TCA) demonstrated smaller N2 and P3 amplitude differences for deviant than standard stimuli. Given the etiologically associated relationship of substance-abuse and ADHD and together with the result of this study, it verified the role of inhibit control functioning in ADHD.

The present study revealed a significant Stimulus*Group interaction effect in the N2 amplitude. This interaction was expressed as the larger amplitude for deviant stimuli than for standard stimuli in ADHD with emotional dysregulation group, in ADHD without emotional dysregulation group and TDC group, N2 amplitude of deviation stimulus was not found to be larger than that of standard stimulus. Previous studies in ADHD patients have not grouped them according to whether they are accompanied by emotion dysfunction, and the findings are inconsistent: One study using the go/nogo paradigm suggests ADHD showed a much larger NoGo>Go effect[62], another study using the Flanker task paradigm also found the N2 amplitude was much smaller to Incongruent than Neutral stimuli for ADHD group which was opposite to controls[62]. At the same time, there is research found the ADHD group did not differ from the control group in the N2 effect[63];There are even studies that show the opposite, that is ADHD group showed a reduced central N2 Nogo-Go effect compared to controls[64], another study had similar results, hints the central N2 Nogo>Go effect was significantly reduced in the AD/HD group compared to controls[64]. Previous studies indicated that frontocentral N2 is closely related to the detection of conflicts[65, 66], and

N2 amplitude was larger with conflict detection than without conflict detection[66]. In the present study, ADHD with emotional dysregulation group displayed a pronounced deviant related N2 component. This suggests that ADHD with emotional dysregulation were better than ADHD without emotional dysregulation and TDC in detecting response conflicts.

The present study revealed a significant Stimulus*Group interaction effect in the P3 amplitude indicating the lower amplitude for ADHD with emotional dysregulation than for ADHD without emotional dysregulation and TDC groups in deviant stimuli. Previous studies on the deviant stimuli P3 amplitude of ADHD patients found that nogoP3 (or P3 to Incongruent stimuli) stimuli decreased compared with normal control stimuli[67–69]. Furthermore, studies in borderline personality disorder with severe emotional dysfunction also showed reduced Nogo-P3 amplitudes[70], which is consistent with our result, The P3 observed in the present study was widely accepted as relevant to later response decision making and inhibitory control processes[71, 72]. Usually, P3 amplitudes increase with the amount of cognitive resources recruited for response inhibition[71, 73]: Decreased NoGo-P3 amplitude during Go/NoGo tasks have been reported in various populations with impaired response inhibition, such as offspring of alcoholics[74], impulsive violent offenders [75], and smokers[76, 77]. Our results provide further evidence of deficient behavior inhibition control(BIC) process in the ADHD with emotion dysregulation group.

The deviation-standard difference wave analysis showed that the N2 difference wave of ADHD with emotion dysregulation group was significantly larger that of ADHD without emotional dysregulation and TDC groups. The previous studies using go/nogo task in ADHD patients have had inconsistent results, one study indicating the magnitude of the difference N2 amplitude for the ADHD group was significantly larger than the HC group[78], another study found that N2 difference wave did not differ between the ADHD adults and HC[79]. Reasons for the above difference may be related to gender, age, intelligence, type, severity of symptoms, paradigm used as well as subgrouping on emotional dysregulation. Combined with the results of this study, it is suggested that ADHD patients with emotional dysregulation may have impaired inhibitory control in terms of magnitude of the difference N2 amplitude.

Although we did not find inhibitory control-related behavior in predicting DESR in ADHD patients, we did find inhibitory control-related EEG indicators (N2, P3) in predicting emotional dysregulation in ADHD patients. Previous studies on ADHD patients were not divided according to their emotional dysregulation, but studies on diseases with emotional dysregulation such as borderline personality disorder, anxiety and depression disorder found that BPD patients showed reduced P3 amplitudes[70]. And the P3 amplitudes showed the negative relation to the scores of depression and anxiety[80]. Combined with the results of this study, it is suggested that the inhibitory control ability of ADHD patients is closely related to their accompanying emotional dysregulation, and the inhibitory control-related EEG indicators (N2, P3) could predict emotional dysregulation in ADHD patients.

There are limitations in our study that need to be acknowledged. First, the type of stimulus in the two-choice oddball paradigm that we used was poorly targeted no emotion, future studies need to further use emotion-related inhibition control tasks, such as emotion recognition and emotion regulation task, to make the research results more targeted and accurate. Nevertheless, our study still found that there were more serious inhibitory control deficit in ADHD with emotional dysregulation group, which may still have reasons to use tasks of inhibitory control. Secondly, we chose CBCL-DESR as a tool to measure emotional dysregulation. While we strategically choose this tool in alignment with prevailing conceptualizations of emotional dysregulation in ADHD, it remains unclear if our results would be replicated using alternative tools measuring emotion dysregulation. Third, our current study uses a cross-sectional design. The absence of a longitudinal dimension limits our ability to develop deeper into the dynamic interaction between emotional dysregulation and inhibitory control in ADHD patients. Future efforts include longitudinal investigations may help us unravel the complex relationships between these structures. Lastly, it is essential to highlight the relatively modest sample size utilized in our study. Future studies with larger samples will further expand the impact of our findings.

Conclusion

Behavioral and ERP inhibitory control indicators were assessed using two-choice oddball paradigm in ADHD children with emotional dysregulation, ADHD children with emotional dysregulation showed more severe inhibitory control impairment on behavioral indicators, and differential N2 amplitude together with differential P3 amplitude can predict ADHD children with emotional dysregulation independently. The results could provide enlightening evidence for early detection and intervention targets in this subtype of children with ADHD.

Declarations

Ethics approval and consent to participate: This study was conducted in accordance with the ethical guidelines set forth by West China Hospital. Ethics approval for the study was obtained from the West China Hospital Ethics Committee, and the study adhered to the principles outlined in the Declaration of Helsinki. Informed consent was obtained from all participants' parents prior to their participation in the study. Participant' parents was provided with detailed information about the study's purpose, procedures, and potential risks, and they voluntarily agreed to participate by signing a written informed consent form.

Consent for publication: Not applicable in the declaration section.

Availability of data and materials: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests: The authors declare that they have no competing interests relevant to this research.

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Authors' contributions:

L.S. and H.Y. contributed equally to this work and are considered co-first authors. They were involved in the conception, design, and execution of the study, as well as the analysis and interpretation of the data. Both authors contributed significantly to the drafting and revision of the manuscript.

Y.YP, W.Z, L.TT, W.MW, ST.MJ, and L.P contributed to the data collection, analysis, and interpretation. They were actively involved in the development of the experimental design and critically reviewed and revised the manuscript.

Y.JJ, and H.Y are corresponding authors. Y.JJ supervised the project, provided guidance on the study design and methodology, and played a key role in data interpretation. H.Y provided expertise in the field, oversaw the research process, and contributed to the critical review and revision of the manuscript.

All authors have read and approved the final version of the manuscript and have agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Figures

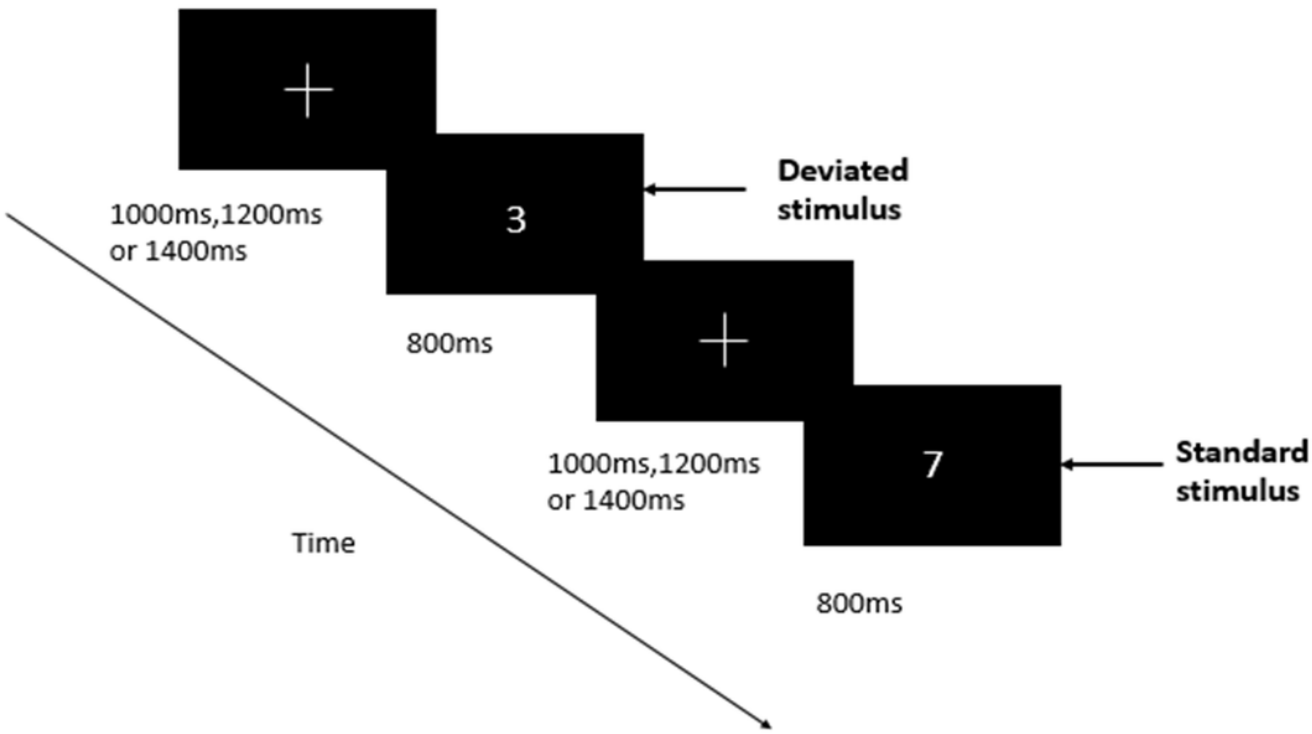

Figure 1. Two-choice oddball paradigm flow chart

Figure 1

See image above for figure legend.

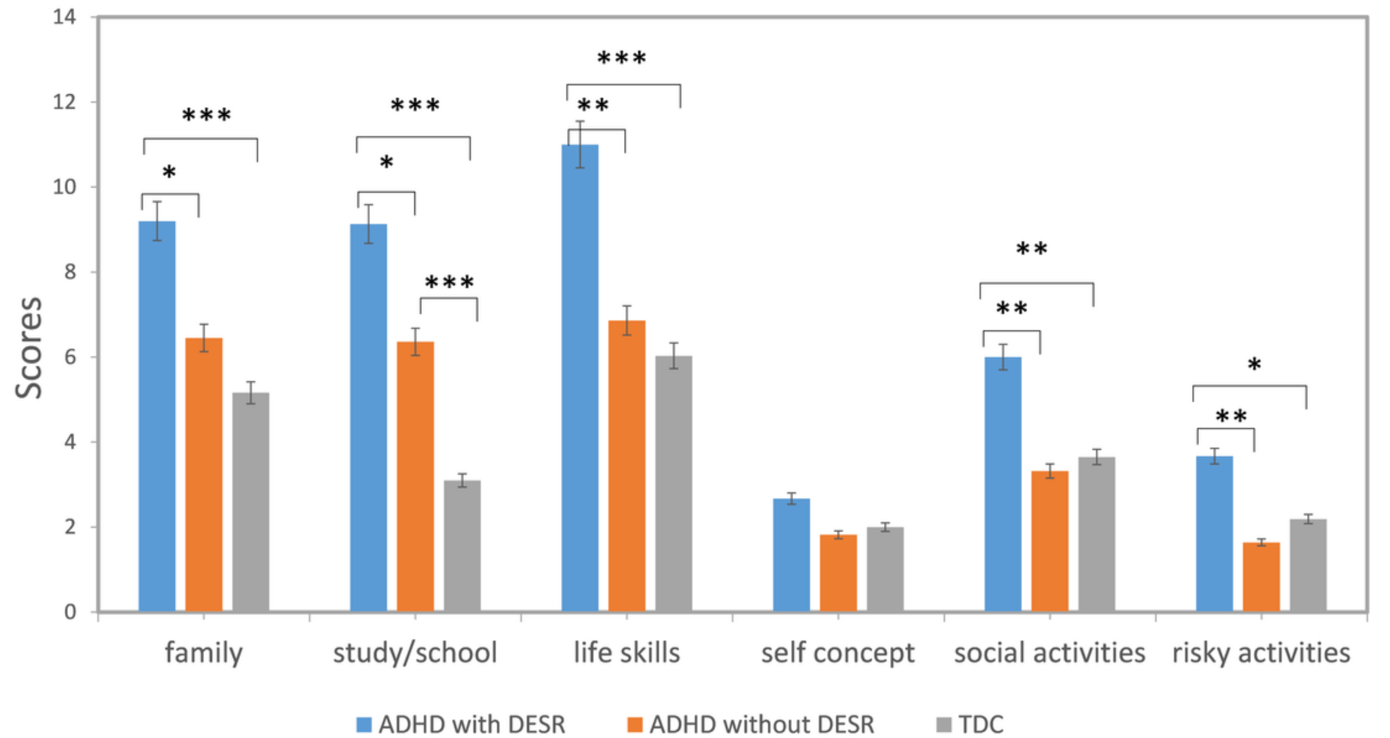

FIGURE2 | Functional impairment of ADHD with DESR,ADHD without DESR and TDC groups.

Figure 2

See image above for figure legend.

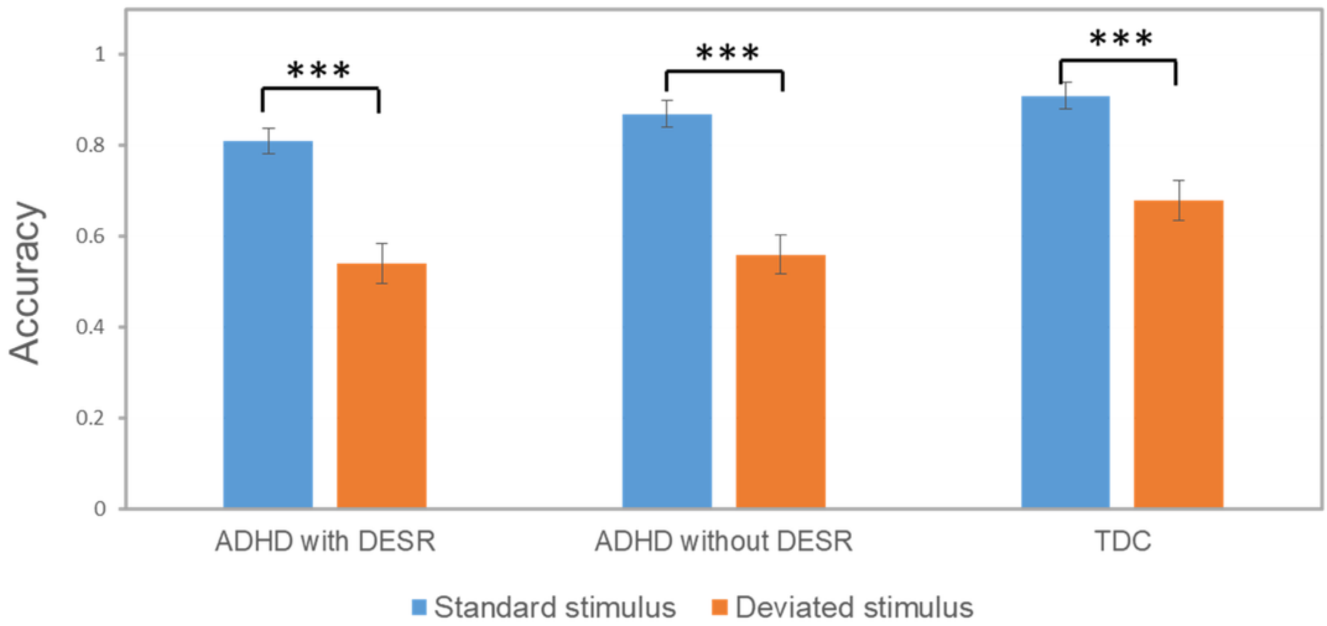

FIGURE 3 | Accuracy for ADHD with DESR 、ADHD without DESR and TDC groups of standard and deviant stimuli.

Figure 3

See image above for figure legend.

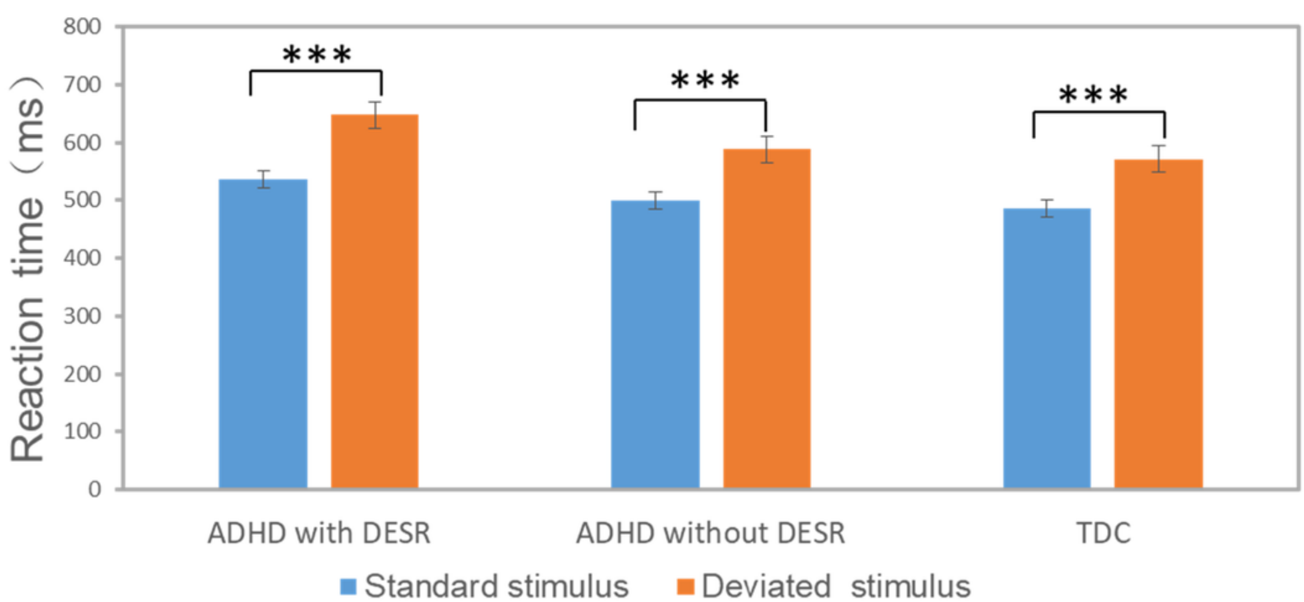

FIGURE 4 | RTs for ADHD+DESR 、ADHD-DESR and TDC groups of standard and deviant stimuli.

Figure 4

See image above for figure legend.

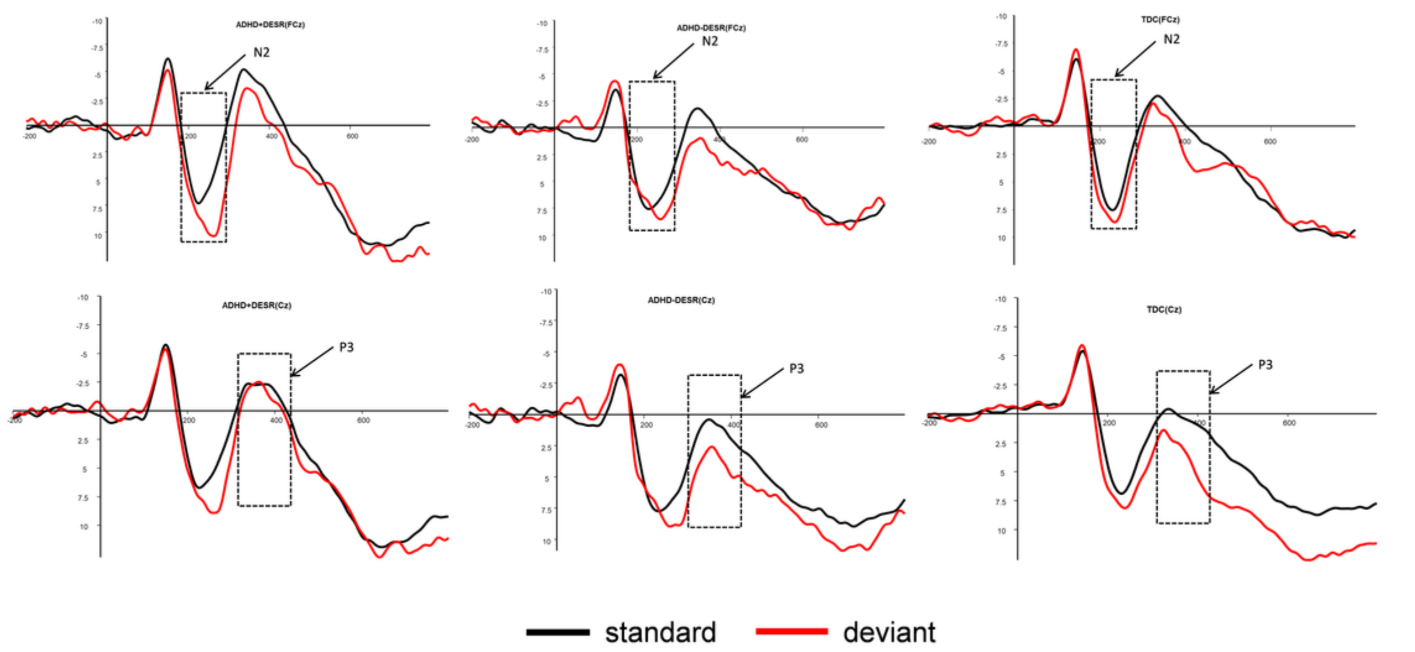

FIGURE 5 | Average of original ERPs FCz and Cz for standard ,deviated in ADHD with DESR ,ADHD without DESR and TDC group.

Figure 5

See image above for figure legend.

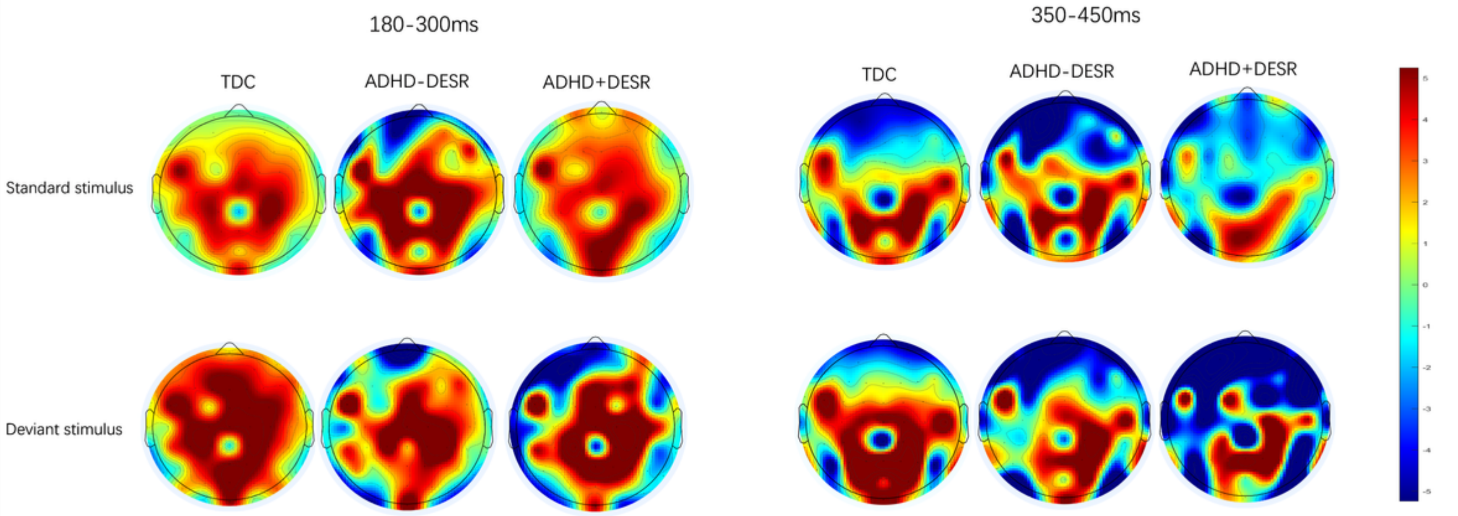

FIGURE 6 | Topographical maps of voltage amplitudes for original waveform at 180–300 ms and 350–450 ms in ADHD+DESR group ,ADHD-DESR group and TDC group.

Figure 6

See image above for figure legend.

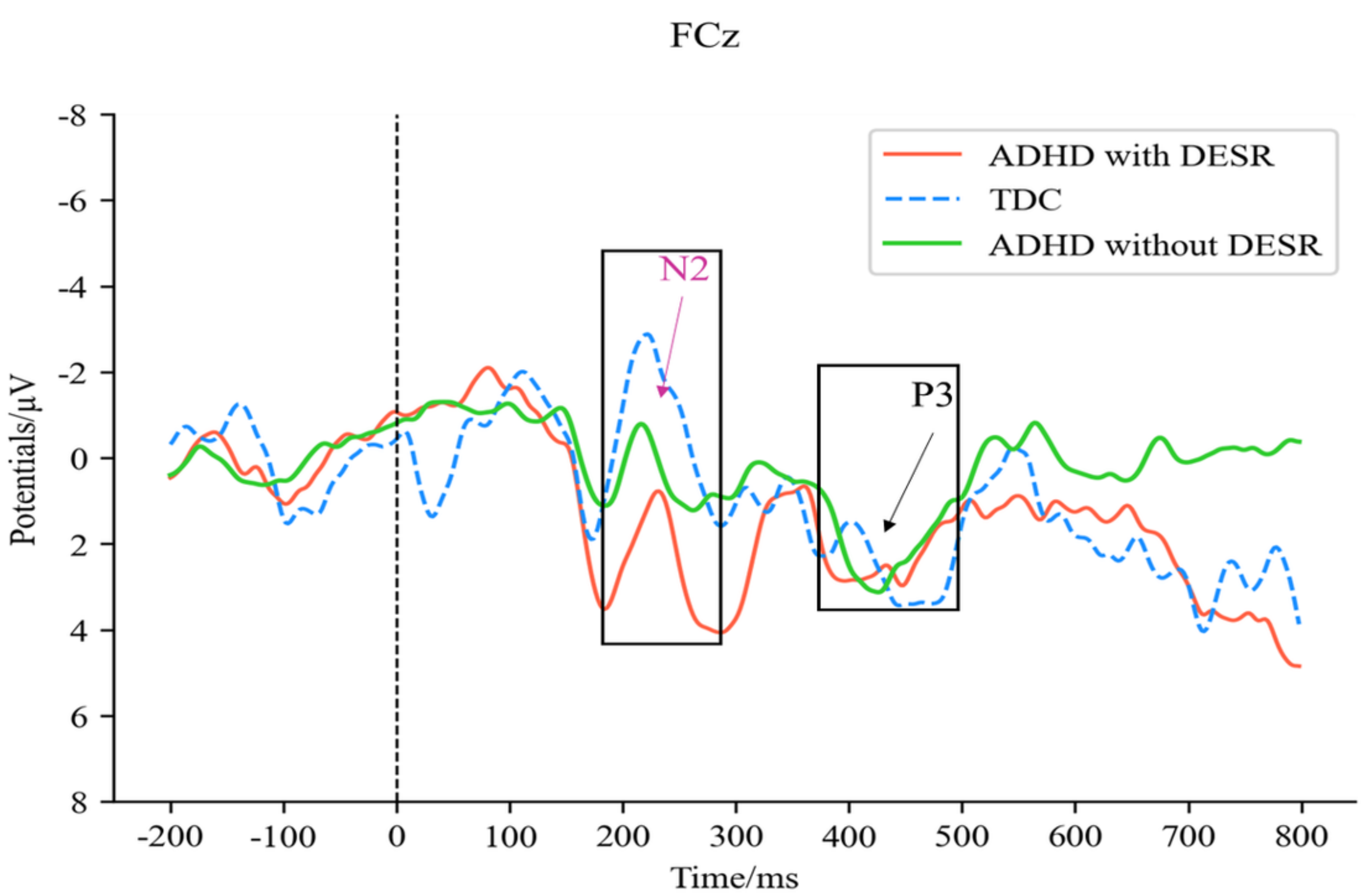

FIGURE 7 | Deviation-standard difference wave in ADHD with DESR ,ADHD without DESR and TDC group.

Figure 7

See image above for figure legend.