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Theta power and functional connectivity as neurophysiological markers of executive functions in individuals with cognitive complaints in daily life

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ABSTRACT

Impairments in executive functions (EFs) are common across psychological disorders. Research into the neural oscillations underlying EFs has the potential to help understand these impairments and contribute to the development of interventions. The aim of this study is to assess theta power and functional theta connectivity in the sensor space of the regions of the superordinate network for the core EFs: conflict monitoring, response inhibition, set-shifting, and working memory updating. We recruited adults with self-reported everyday EFs complaints and formed two groups: one with attention deficit hyperactivity disorder (ADHD) (n=27) and another without any diagnosis (n=22), and compared them to controls (n=21) on the Stroop, Stop-signal, Switching, and N-back task using EEG. Power and functional connectivity analyses were conducted for four regions of interest: frontal-midline, frontolateral left and right, and parietal region. For all four EFs, the groups showed a dynamical increase in theta power over time in the four regions of interest, as well as in functional theta connectivity between these regions. Group differences were found especially for conflict monitoring, with differences in theta power in the frontal-midline and frontolateral right region. These neural markers are also associated with behavioural performance and complaints in daily life. For set-shifting, group differences were less pronounced and for response inhibition and working memory updating no group differences were observed.

1. Introduction

Cognitive impairments occur across various psychological disorders (Abramovitch et al., 2021) and are associated with disturbed neural oscillations in underlying brain networks (Başar & Güntekin, 2008; Uhlhaas & Singer, 2006). Executive functions (EFs) are particularly affected and are considered a transdiagnostic dimensional feature and a key impairment across psychological disorders (Snyder et al., 2015). EFs is an umbrella term encompassing a broad range of separate, but interrelated higher mental processes (Friedman & Miyake, 2017; Karr et al., 2018). EFs enable us to successfully engage in adaptive, independent, and goal-driven behaviour (Diamond, 2013; Friedman & Miyake, 2017). Despite their broad nature, four core EFs have been established: conflict monitoring, response inhibition, set-shifting, and working memory updating (Miyake et al., 2000; Enriquez-Geppert et al., 2010). EFs are frequently referred to as cognitive control processes, as they facilitate other cognitive functions, such as memory and attention (e.g., Friedman & Miyake, 2017). Intact EFs are needed to set goals and adapt flexibly to changing circumstances (Burgess & Simons, 2005). Therefore, impaired EFs can greatly affect independence in daily life, functional outcomes, and quality of life (e.g., Vaughan & Giovanello, 2010; Zhang et al., 2021; Mohamed et al., 2019).

The largest meta-analysis to date by Niendam et al. (2012) shows that EFs rely on a superordinate fronto-cingulo-parietal network involving the midcingulate cortex (MCC; widely referred to as dorsal anterior cingulate cortex [Vogt, 2016]), dorsolateral prefrontal cortex (DLPFC), and parietal cortex. Other very similar and overlapping networks have been described in the literature (e.g., Duncan, 2010; Camilleri et al., 2018; Cole & Schneider, 2007; Vincent et al., 2008), and recently Menon and D'Esposito (2022) have identified six networks that play a role in EFs, confirming the relevance of these brain areas. In general, the highly interconnected MCC monitors and detects conditions that require cognitive control and signals this information to the parietal cortex and DLPFC (Niendam et al., 2012). The parietal cortex updates

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relevant stimulus-response associations and task representations (Brass et al., 2005) and provides the DLPFC with information about stimulus salience and learned stimulus-response associations (Niendam et al., 2012). Additionally, the parietal cortex in its turn also modulates the MCC during multisensory action monitoring (Vogt, 2016). The DLPFC interconnects neural networks to nearly all cortical sensory systems, motor systems, and many other subcortical structures (Miller & Cohen, 2001), and is involved in directing attention to task demands and reinforces processing of target information (Egner & Hirsch, 2005). As such, the MCC can be seen as a monitor and the DLPFC as a controller (Smith et al., 2019). In addition, depending on the specific task demands and required EFs, other brain areas also contribute to the superordinate network (Niendam et al., 2012), for example the right inferior frontal cortex in case of response inhibition (Aron et al., 2014).

Coordinated activity in networks of the brain during normal functioning is enabled by neural oscillations (Buzsáki & Draguhn, 2004; Buzsáki, 2006). Via oscillatory synchronisation, information can be processed locally within a neuronal assembly and contemporaneously exchanged between different neuronal assemblies in a network (Fries, 2005). Regarding EFs, theta oscillations (4-8 Hz) are of particular interest, and can be measured using electroencephalography (EEG). In response to events requiring EFs, theta oscillations are amongst others generated in the MCC (Cavanagh & Frank, 2014) and represent a phasic, task-related modulation of the background EEG (Mitchell et al., 2008). As such, theta oscillations can be considered as the neural 'working language' of EFs (Cavanagh & Frank, 2014).

Theta power and functional theta connectivity within the superordinate network are two potential neurophysiological markers of efficient EFs. First, increases in theta power are associated with stronger neuronal spike-field coupling within the theta band, which provides temporal windows for coincident neural activity that contribute to EFs (Cavanagh & Frank, 2014; Helfrich & Knight, 2016). In studies on healthy individuals, upregulation of theta power at the frontal-midline (FM) during EF tasks reflected the amount of cognitive control recruitment and was associated with better performance on conflict monitoring (e.g., Eschmann et al., 2018), response inhibition (e.g., Nigbur et al., 2011), set-shifting (e.g., Cooper et al., 2017), and working memory updating (e.g., Itthipuripat et al., 2013). Second, functional connectivity as measured by phase synchronization enables efficient information intake, processing, and exchange of information between regions in neural networks (Fries, 2015; Fell & Axmacher, 2011). Depending on the specific EF task, neuronal assemblies in different brain regions within the superordinate network (and additional regions) synchronise, thereby serving control mechanisms more efficiently (Cavanagh & Frank, 2014). In healthy individuals, increased theta functional connectivity has been observed in fronto-parietal brain regions during conflict monitoring (e.g., Cohen, 2014a), response inhibition (e.g., Harmony et al., 2009), set-shifting (e.g., McKewen et al., 2021), and working memory updating (e.g., Mizuhara & Yamaguchi, 2007). The distinction between the two neurophysiological markers is important, because an increase in power is considered to reflect engagement of a cortical region, whereas functional connectivity (i.e., phase synchronization) is thought to reflect communication between cortical hubs (Cooper et al., 2017).

Disturbed theta oscillations in the superordinate network (e.g., disrupted upregulation of theta power or disturbances in functional theta connectivity) can contribute to EFs impairments in various disorders (e.g., McLoughlin et al., 2021; Ryman et al., 2018). For instance, several studies in adults with attention deficit hyperactivity disorder (ADHD) have shown disturbances in task-related theta oscillations of EF (Cowley et al., 2022; Buyck & Wiersema, 2015; Missonnier et al., 2013). However, most studies assess one specific EF and focus on a single neurophysiological feature in patients from a specific diagnostic category. Consequently, the knowledge about the neural basis of EFs and the changes in theta oscillations associated with psychological disorders is still limited. Characterising the neural basis of different EFs tasks using multiple neurophysiological markers in individuals reporting EFs problems in daily life, regardless of diagnostic category, has the potential to contribute to understanding these impairments. In addition, this knowledge could support the development of new interventions that target the underlying pathophysiological mechanisms, such as neurofeedback, transcranial alternating current stimulation, and other neuroscientific approaches, enabling timely clinical treatment.

The aim of the current study is to take an integrative approach and systematically assess both theta power and functional theta connectivity in the sensor space of different regions of the superordinate network for the four core EFs (i.e., conflict monitoring, response inhibition, set-shifting, and working memory updating). We recruited participants with self-reported EFs complaints in daily life regardless of whether they had a psychological disorder or not. We then formed two groups, one with an ADHD diagnosis and one without any diagnosis, and compared them to controls without complaints. Our hypothesis is that individuals with subjective EF complaints and ADHD will have lower task-related increases in theta power and functional theta connectivity in the superordinate network, as well as poorer behavioural performance in the four core EFs tasks compared to controls. For the group with EF complaints without a diagnosis, we expect the neural measures of power and connectivity and behavioural performance to fall in between the other two groups.

2. Methods

2.1. Recruitment and inclusion criteria

In this study, participants were recruited with self-reported EF complaints in daily life and a control group without EF complaints. Self-reported EF complaints were defined as a score in the 90th percentile or higher (i.e., very high/impaired range) on the Behaviour Rating Inventory Executive Function-Adult version (BRIEF-A) total score ($\geq$ 128) or in at least two of the following subscales: Task monitor (score $\geq$ 12), Inhibit ($\geq$ 15), Shift ($\geq$ 12), and/or Working memory ($\geq$ 15). These subscales are considered to represent the four core EFs: conflict monitoring, response inhibition, set-shifting, and working memory updating, respectively. Exclusion criteria for this study were the presence or history of a severe neurological (e.g., brain tumour) or psychiatric disorder (e.g., schizophrenia) impairing functioning in daily life. Medication use was not an exclusion criteria.

2.2. Participants

The majority of the recruited participants with EF complaints reported a diagnosis of attention deficit hyperactivity disorder (ADHD) or no diagnosis. A small number of participants (n = 11) reported other types of diagnoses (e.g., autism spectrum disorder, eating disorder, mood disorder, post-traumatic stress disorder). To assess homogeneous and equally large groups, we formed the following three: participants with subjective EF complaints and ADHD (n = 27; mean age 30.0 years, *SD* = 7.3; ADHD group), participants with subjective EF complaints without any diagnosis (n = 22; mean age 35.0, *SD* = 10.5; No diagnosis group), and controls without subjective EF complaints (n = 21; mean age 32.0, *SD* = 12.1; controls), leaving the small number of participants with different reported diagnosis out. A total of 70 adults participated in this study.

In the ADHD group, 20 participants reported the predominantly inattentive subtype of ADHD (i.e., attention deficit disorder) and seven participants reported the combined ADHD subtype (i.e., attention deficit hyperactivity disorder). For most participants, their GP confirmed the diagnosis through a mental health care organisation. However, for six participants, the diagnosis was not officially confirmed because we had not received their permission to obtain this information. Before the start of the study, all participants gave written consent to the protocol. Participation was voluntary and there were no rewards provided. The

study was approved by the Ethical Committee Psychology of the University of Groningen and conducted in accordance with the Declaration of Helsinki.

2.3. Procedure

Participants were recruited through personal contacts of the researchers and appeals in social media (i.e., Facebook and LinkedIn). First, the participants filled out the questionnaires during which the EEG cap was placed. Followed by an EEG resting state measurement and administration of four computerised tasks (while EEG was measured) in a sound attenuated room. Conflict monitoring, response inhibition, set-shifting, and working memory updating were measured by the four tasks. In all tasks, the participant had to respond via a button press and had two answering options. A black background and white letters and symbols were used for all tasks unless otherwise stated. Two different lists were used, varying the task order and stimulus-response assignments. Before each task, participants received instructions and a short exercise to familiarise them with the task. All tasks were implemented using Presentation software (Neurobehavioral Systems version 14.8) and had a duration of ten to 18 minutes. Between the tasks, there were rest breaks, if requested by the participant. Participants were instructed to sit still and blink as little as possible while performing the tasks. For the ADHD and No diagnosis group this measurement served as a pre-measurement for a neurofeedback training.

2.4. Questionnaires

To assess eligibility to participate in the study, EFs in daily life were assessed by the BRIEF-A (Roth et al., 2005). Participants had to indicate on a 3-point scale (i.e., never to often) how often they experienced certain EF problems during the last month. The BRIEF-A consists of nine subscales, which together add up to a total score. In this study, the total score and the subscales Task Monitor, Inhibit, Shift, and Working Memory were used.

The presence of depressive symptoms was assessed using the Beck Depression Inventory II (BDI-II; Beck et al., 1996). Participants had to indicate which statements out of four options, referring to a specific symptom, best applied to them over the past two weeks. A total score of 0 - 13 is considered minimal, 14 - 19 mild, 20 - 28 moderate, and 29 - 63 severe.

To assess the presence of ADHD symptoms, the self-report questionnaire on attention problems and hyperactivity for adulthood and childhood (Dutch: Zelf-rapportage vragenlijst over aandachtsproblemen en hyperactiviteit voor volwassenheid en kindertijd [ZVAH]) was used. This is a rating scale based on the DSM-IV criteria for ADHD (Kooij et al., 2005). Participants had to indicate on a 4-point scale how often (i.e., rarely to very often) they showed certain behaviours in the past six months and during childhood. In this study, only the version for adulthood was used, which assesses nine criteria for attentional symptoms and nine for hyperactivity symptoms. For adults, the DSM-IV gives no information about the exact cut-off score for ADHD, however, there is research indicating that the cut-off score in adulthood is lower than in childhood; four of nine criteria (Kooij et al., 2005).

2.5. Tasks and stimuli

To assess conflict monitoring, the Stroop task was used for which colour words (i.e., red, yellow, blue, or green) were presented either in the same colour as the colour word (Congruent condition) or in a non-matching colour of the word meaning (Incongruent condition). Using button presses, participants had to indicate the colour of the colour word. In total there were 72 Incongruent trials and 72 Congruent trials. Every trial has an average length of 2700 ms and consists of a fixation cross presented for a random duration of 1200 - 1400 ms, followed by the presentation of the colour word for 500 ms, and a second fixation cross presented for a random duration of 100 - 500 ms. Trials were separated by an inter-trial interval of a random duration of 400 - 800 ms. After every 16 trials participants received feedback about their performance to stimulate fast and accurate responding. There were four types of feedback: (1) 'Respond more accurate', shown if less than 14 trials were correct, (2) 'Respond faster', shown if the average RT was more than 500 ms, (3) 'Respond faster and more accurate', shown if both condition (1) and (2) were met, and (4) 'Keep it up', shown if conditions (1) and (2) were not met.

To assess response inhibition, a visual Stop-signal task was used. In this task, left- and rightward pointing arrows were presented in a fixed starting colour that changed to a different colour during their presentation (three colour options). Participants had to press either the left or the right button according to the direction of the arrow immediately when the stimulus was displayed (Go condition). However, a change into a specific colour indicated that the participant had to inhibit the initiated response (Stop condition). The timing of the colour-change of the arrow was adjusted dynamically via a stop signal delay (SSD; Logan et al., 1997), to ensure that participants could stop their response in 75% of the stop-condition trials. In total, there were 300 trials, including 100 stop-condition trials. Every trial had a length of 2000 ms and started with a fixation cross with a random duration of 300-600 ms. Right after, an arrow was presented with an initial duration of 250 ms before the colour changed. This duration was adjusted by the SSD, by adding 50 ms after every second correct trial or subtracting 50 ms after a failed stop trial. The colour change remained on screen for another 200 ms. The trial ended with the presentation of a fixation cross.

To assess set-shifting, a Switching task was used, with number-letter pairs presented on a coloured background. The task consisted of two parts. The first part, included two unmix-blocks in which participants were instructed to only classify the numbers (even or odd) or the letters (vowel or consonant). In the second part, a mixed-block, participants classify either the number or letter cued by the background colour (red, pink, or orange vs. green, blue, or turquoise). This mixed-block includes a Switch condition where a switch between number and letter classification is required and a No switch condition where the classification category is the same as in the previous trial. Only the mixed-block was assessed in this study and consisted of 234 trials, including 70 switch trials. Trial length was 3000 ms and consisted of a fixation cross with the random duration of 250-500 ms, the presentation of the letter-number pair for 2200 ms, and the presentation of a black screen (i.e., filler period) for 300-550 ms to complete the total trial length.

To assess working memory updating, the N-back task was used with a No update condition (i.e., 0-back) and an Update condition (i.e., 3-back). In the No update condition, participants press a button each time a letter is presented that matches with a target letter presented at the beginning of the sequence. In all other cases, the participants do not have to react. In the Update condition, participants have to press a button each time a letter is presented that matches the letter presented exactly three positions earlier in the sequence. There were ten Update sequences and nine No update sequences, which were presented alternately. The total number of trials per sequence was 24, with each eight target letters. Every trial had a length of 2000 ms and started with a fixation cross for a duration of 1000 ms, followed by a letter presented for 1000 ms.

Mean accuracy (AC), reaction time (RT), and RT variability (RTV) were calculated for the correct trials of the four different tasks. For the Stop condition of the Stop-signal task, reaction times were estimated as the stop-signal reaction time (SSRT), which is an estimation of the time needed to inhibit a response that has already been initiated (Logan & Cowan, 1984). All tasks had a condition requiring EFs (i.e., Incongruent, Stop, Switch, and Update) and a control condition (i.e., Congruent, Go, No switch, and No update).

2.6. EEG recordings and processing

During the performance of the tasks, EEG was continuously recorded with a 64 Ag/AgCl electrodes Waveguard™ connect cap using an average reference Twente Medical Systems International B.V. (TMSi) REFA amplifier and Openvibe recording software (Renard et al., 2010). The electrodes were placed in accordance with the extended version of the international 10-20 system. The amplifier provided 24-bit resolution EEG data with a sampling rate of 256 Hz. The electro-oculogram was measured with two vertical electrodes on the dominant eye and two horizontal electrodes. The impedance level of the electrodes was initially put below 10 kΩ and checked after one or two tasks, if necessary action was taken to lower the impedance again.

EEG data was processed offline in MATLAB version R2019B using functions of the EEGlab toolbox (Brunner et al., 2013). Data was filtered with a 40 Hz low-pass and 0.1 Hz high-pass, down-sampled to 250 Hz, and re-referenced against two mastoid electrodes. Independent component analysis using the *runica* algorithm was applied to detect and correct for eye artifacts (i.e., blinks and horizontal eye-movements). Data was epoched from -1250 ms to 1250 ms with respect to stimulus onset, which is appropriate for time-frequency analysis focusing on theta (Cohen, 2014b). Remaining artifacts were discarded using a semi-automatic procedure with a threshold of 60 μV. Noisy electrodes were interpolated. In order to control for unequal numbers of correct trials between task conditions and to obtain a comparable signal-to-noise ratio, trials were randomly removed as necessary to allow a maximum difference of ten epochs between conditions in the same task for each participant. The minimum number of epochs required for a condition was 27. In the Stop-signal task, only twelve controls met the required number of correct epochs. Therefore, the minimum number of epochs for this task was reduced to 20 trials, resulting in four additional participants for the analysis. Table 1 shows the final sample sizes per group and task included in the EEG analyses. In order to reduce volume conduction effects in EEG sensor space, a spatial Laplacian filter was applied to transform the EEG data into estimates of scalp current density at each electrode. Scalp current density suppresses widespread EEG signals, while enhancing the sensitivity to focal activity in the cerebral cortex (Kayser & Tenke, 2006).

2.7. Time frequency analysis and data extraction

To decompose the EEG signal into frequency over time, event-related spectral perturbations (ERSPs) were calculated for the different conditions of the four EF tasks. ERSPs represent the log-transformed changes of power in dB relative to baseline (Delorme & Makeig, 2004). A Morlet wavelet transform was applied, with the number of cycles increasing in proportion to the frequency. The frequency range used was 2-30 Hz, starting with one cycle at 2 Hz and increasing by 0.5 cycles per 1 Hz increment, ending with fifteen cycles at 30 Hz. Single trial baseline correction was used to reduce the effect of potentially noisy trials. The average power across trials was divided by the frequency specific baseline values separately for each frequency in order to visualise power changes relative to the pre-stimulus activity. To assess the ERSP for each task condition, we automatically detect the maximum peak in power. Because FM theta power may also have a different time course in the group complaining of EFs compared to controls (Missonnier et al., 2013; Keute et al., 2019), we assess eight 200 ms time windows ranging from -100 ms to 800 ms after stimulus onset with a 50% overlap (i.e., sliding window). The average power in each time window was calculated for the maximum peak +/- 50 ms and +/- 1 Hz for four regions of interest (ROI) in the sensor space: frontal-midline (FM: Fz, FC1, FC2, Cz, FCz), frontolateral right (FLr: F8, FC6, F6, FT8), frontolateral left (FLl: F7, FC5, F5, FT7), and parietal (CP1, CP2, Pz, P1, P2) region. As a result of temporal leakage the time windows can contain power outside this window.

Table 1
Sample sizes per group and task included in the EEG analyses for theta power and functional theta connectivity.

Task	ADHD group (n = 27)	No diagnosis group (n = 22)	Controls (n = 21)
Stroop	27	22	21
Stop-signal	24	18	16
Switching	22	18	19
N-back	24	21	19

2.8. Connectivity analysis and data extraction

In order to investigate oscillatory synchronisation, while minimising artificial interaction at the electrode level, an imaginary coherence analysis was performed (Stam et al., 2007). Coherence is defined as the normalised cross-spectral correlation between two time series. To calculate imaginary coherence, the cross-spectrum between single-trial ERSP at the electrodes (j,k) of the four ROIs was calculated for each participant, condition, time (t), and frequency (f) (Eq. 1). Here, $\overline{P}_k(t,f)$ is the complex of the power at electrode k.

$$S_{jk}(t,f) = P_j(t,f) * \overline{P}_k(t,f) \quad (1)$$

To compute the coherence, the cross-spectrum between an electrode pair was divided by the root of the power of the auto-spectrum from each respective electrode (Eq. 2).

$$C_{jk}(t,f) = \frac{S_{jk}(t,f)}{\sqrt{S_{jj}(t,f)S_{kk}(t,f)}} \quad (2)$$

To finally extract the imaginary coherence, the complex component of coherence was extracted of $C_{jk}(t,f)$ (see Cooper et al., 2015). To assess theta connectivity within the EFs network, the imaginary coherence for theta was averaged across the same eight sliding time windows for five ROI pairs in the sensor space: FM-FLr, FM-FLl, FM-parietal region, FLr-parietal region, and FLl-parietal region.

2.9. Data preparation and statistical analyses

The study sample was divided into three groups: ADHD, No diagnosis, and controls. Comparing the No diagnosis group with controls indicates the sole effect of subjective EF complaints on task performance and related theta power and connectivity. Comparing the No diagnosis with the ADHD group indicates the additional effect of an ADHD diagnosis next to subjective EF complaints, and comparing the ADHD group with controls indicates the combined effects of both subjective EF complaints and an ADHD diagnosis. In each group a winsorizing approach was used on the amplitude, connectivity, and behavioural data to minimise the influence of outliers by replacing outliers by a less extreme value (i.e., mean +/- three x SD). For the amplitude and connectivity data, the mean per time window for each group was calculated and visualised in line charts, and for the behavioural data, the mean and standard error of the mean per group were calculated and visualised in bar plots.

Statistical analyses were only performed on the task conditions requiring EFs (i.e., Incongruent, Stop, Update, and Switch) in order to test our hypotheses and limit the number of tests. For the behavioural data, one-way ANOVAs were used to compare AC, RT, and RTV across the three groups. If significant, post-hoc comparisons were performed using Tukey's Honest Significant Difference (HSD) test. For the power and connectivity data, repeated measures (RM) ANOVAs were performed, with the within-subjects factor TIME (8 time windows) and between-subjects factor GROUP (three groups). In case of violations of sphericity, the Greenhouse-Geisser correction was applied and corrected degrees of freedom and p-values were reported. For significant interaction effects, a post-hoc ANOVA was performed to compare the groups in

Time Window 4, as the effects of EFs are specifically expected 200 to 400 ms after stimulus onset. If significant, post-hoc Tukey's HSD tests were performed to determine the exact group differences. Finally, to explore the neurocognitive associations between the neurophysiological markers (i.e., power and connectivity) and behaviour (i.e., AC, RT, RTV, and BRIEF-A questionnaire), Pearson correlation coefficients were calculated for all ROI (pairs).

For all tests, a p-value of $\leq$.05 was used to identify significant differences. Because of the clear a priori hypotheses about the effects, multiple test correction was not applied for the RM ANOVAs and one-way ANOVAs. However, the interpretation and discussion of the results did take into account the higher Type I error rate resulting from multiple testing. For the explorative correlation analyses, the Benjamini-Hochberg adjustment with a false discovery rate of.05 was applied as a multiple comparison correction for each task and neurophysiological marker separately (Chen et al., 2017). The effect size (ES) for RM ANOVA was indicated by partial eta squared (η_p^2) and for one-way ANOVA by eta squared (η^2) and interpreted as: <.06 is small, ≥.06 is medium, and ≥.14 is large. Pearson correlations were interpreted as: <.3 is small, ≥.3 is medium, and ≥.5 is large. All analyses were carried out using SPSS (IBM Corp., 2019). According to an a priori power calculation (G*Power 3.1.9.4), eighteen participants per group would be sufficient to detect a medium effect (η_p^2 =.06, i.e., smallest ES of interest) for a within-between interaction in RM ANOVA (α =.05, β =.95, non-sphericity correction ϵ =.4).

3. Results

3.1. Sample characteristics

Table 2 provides an overview of the demographics and questionnaire scores for the three groups. Educational level was rated on an eight level scale and classified into low (i.e., primary education [1] or preparatory secondary vocational education [2]), intermediate (i.e., secondary vocational education [3], senior general secondary education [4], or pre university education [5]), or high (i.e., higher vocational education [6], university bachelor [7], or university master [8]). There were no significant differences between groups regarding age, education, and sex. As expected, the controls scored significantly lower on the BRIEF-A total score and subscales Task monitor, Inhibit, Shift, and Working memory, in comparison to the ADHD and No diagnosis group. There were no significant differences between the two latter groups regarding BRIEF-A outcomes. Regarding ADHD symptoms, the controls reported significantly less attentional symptoms as compared to both the ADHD and No diagnosis group. The two latter groups showed a similar number of attentional symptoms, both exceeding the cut-off score of four out of nine criteria. For hyperactivity symptoms, all groups differed significantly from each other. Here only the ADHD group exceeded the cut-off score. As to depressive symptoms, the controls scored significantly lower than the ADHD and No diagnosis group. The number of depressive symptoms was similar for the ADHD and No diagnosis group. On average, all groups scored in the minimal range (≤ 13).

Regarding medication intake, thirteen participants in the ADHD group reported taking methylphenidate and five participants dexamphetamine, on a daily basis or when needed. Two of them voluntarily discontinued intake during the study. The remaining nine participants in the ADHD group, all diagnosed with the inattentive subtype of ADHD, reported not taking any medication. One participant in the ADHD group also reported taking Pregabalin, which is an anticonvulsant and anti-anxiety medication that can have mild negative cognitive effects (Salinsky et al., 2010). Seven participants in the No diagnosis group suspected a diagnosis of ADHD, but this was never officially confirmed. One participant in the No diagnosis group reported taking an antidepressant (i.e., Citalopram). The remaining participants in this group and all controls reported not taking any medication that could affect cognition and did not suspect or had any confirmed psychological or neurological diagnosis.

Table 2
Demographic characteristics and questionnaire scores per group.

	ADHD group (n = 27)	**No diagnosis group** (n = 22)	**Controls** (n = 21)
	n (%)	n (%)	n (%)
Education level (low / intermediate / high)	1 (3.7%) / 15 (55.6%) / 11 (40.7%)	0 (0%) / 9 (40.9%) / 13 (59.1%)	1 (4.8%) / 9 (42.9%) / 11 (52.4%)
Sex (female)	21 (78%)	14 (64%)	14 (67%)
Self-reported EFs (BRIEF-A)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Total score	162.7 (18.6)	154.7 (13.5)	97.0 (12.2)
Task monitor	15.7 (1.8)	15.0 (1.7)	9.0 (1.9)
Inhibit	17.3 (2.9)	16.7 (3.5)	11.4 (1.5)
Shift	13.4 (2.6)	12.5 (3.0)	8.7 (2.0)
Working memory	20.6 (2.4)	19.0 (2.5)	10.5 (2.1)
Depressive symptoms (BDI-II)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Total score	11.2 (7.2) *	8.7 (5.7) *	3.6 (3.2)
ADHD symptoms (ZVAH) (adulthood)	*M* (*SD*)	*M* (*SD*)	(*SD*)
Number of attentional symptoms	6.6 (2.3) * Range: 1-9	4.0 (2.7) * Range: 0-8	0.1 (0.4) Range: 0-1
Number of hyperactivity symptoms	4.5 (2.9) * Range: 0-9	2.6 (1.9) * Range: 0-6	1.0 (1.2) Range: 0-4

Note: BRIEF-A = Behaviour Rating Inventory Executive Function – Adult version, BDI-II = Beck Depression Inventory II, ZVAH = Self-report questionnaire on attention problems and hyperactivity for adult and childhood. * This information was not obtained for all participants; for the ADHD group information from five participants is missing (n = 22) and for the No diagnosis group information from one participant is missing (n = 21).

3.2. Behavioural data

Fig. 1 shows the mean AC, RT, and RTV of the correct responses on all conditions of Stroop, Stop-signal, Switching, and N-back task. In the following, the results of the one-way ANOVAs are described, for a full overview see Supplementary Table 1.

Regarding the Incongruent condition of the Stroop task, an ANOVA demonstrated a significant difference in RT between the three groups (F (2,67) = 3.206, p =.047, η^2 =.087). Tukey's HSD test showed a significantly higher RT for the ADHD group (M = 637, SD = 138) compared to controls (M = 550, SD = 116; p =.040, 95% confidence interval 3, 171). In the ADHD group, the RT of participants using stimulant medication (n = 16, M = 644, SD = 159) was similar to non-users (n = 11, M = 627, SD = 105). There were no significant differences in RT between the other groups. For RTV and AC there were no significant group differences on the Incongruent condition. For the Stop condition of the Stop-signal task, Switch condition of the Switching task, and Update condition of the N-back task, there were no significant group differences for any of the behavioural outcomes.

3.3. Theta power

Fig. 2 shows the mean power per time window and ROI of the correct responses for the conditions of Stroop, Stop-signal, Switching, and N-back task. In the following, the results of the RM ANOVAs for each task per ROI are described. For a full overview of the RM ANOVAs results and plots of the event-related potentials, ERSPs, and topographies see Supplementary Table 2 and Fig. 1-4.

For the Incongruent condition of the Stroop task, the RM ANOVAs showed significant large main effects of TIME for all four ROIs: FM (F (2.661,178.264) = 86.487, p <.001, η_p^2 =.563), FLr (F(2.765,185,277) =

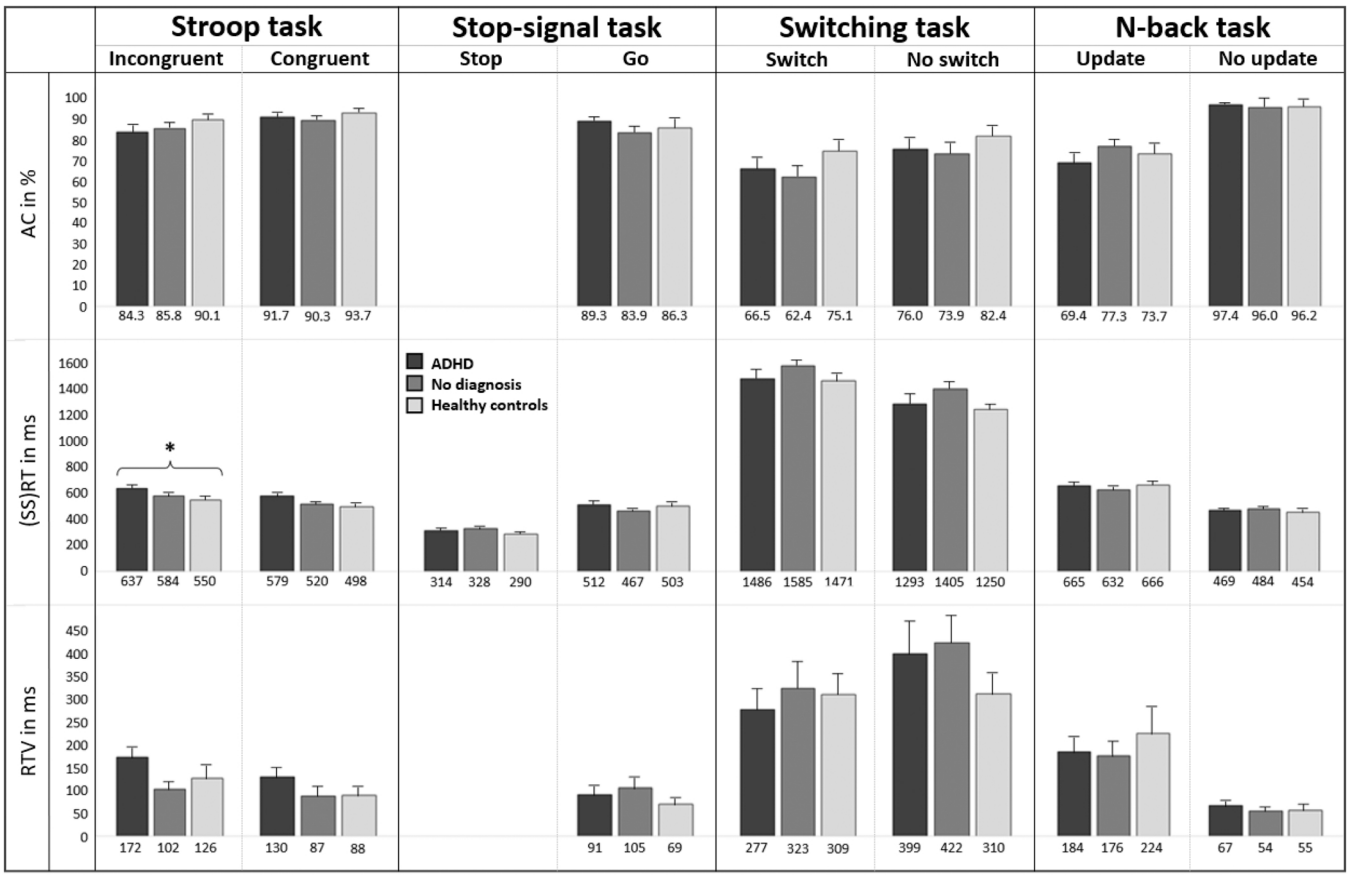

Fig. 1. Mean accuracy (AC), reaction time (RT), and RT variability (RTV) of the correct responses on all conditions of the Stroop, Stop-signal, Switching, and N-back task for the ADHD group, No diagnosis group, and controls. *Note: Error bars represent the standard error of the mean. * Significant difference ($p \leq .05$).*

99.274, $p < .001$, $\eta_p^2 = .597$), FLl ($F(3.024,202.629) = 53.484$, $p < .001$, $\eta_p^2 = .444$), and parietal region ($F(2.158,144.594) = 158.936$, $p < .001$, $\eta_p^2 = .703$). Furthermore, there was as expected a significant interaction effect of TIME x GROUP for FM ($F(5.321,178.264) = 2.769$, $p = .017$, $\eta_p^2 = .076$) and FLr ($F(5.531,185.277) = 3.060$, $p = .009$, $\eta_p^2 = .084$), indicating that in these ROIs power change over time differed between the groups. Post-Hoc one-way ANOVAs for FM and FLr, comparing power at Time window 4 across groups, revealed a medium significant group difference for FLr ($F(2,67) = 3.460$, $p = .037$, $\eta^2 = .094$), but not for FM ($F(2,67) = 2.645$, $p = .078$). Tukey's HSD test for FLr showed a significantly lower power in Time Window 4 for the ADHD group ($M = 3.734$, $SD = .851$) in comparison to controls ($M = 4.527$, $SD = 1.444$; $p = .042$, 95% confidence interval -1.565, -.023). In the ADHD group the results for power in the FLr of participants using stimulant medication (n = 16, $M = 3.812$, $SD = .961$) was similar to non-users (n = 11, $M = 3.620$, $SD = .688$). There were no significant power differences in this time window between the other groups. Lastly, there were no significant main effects of GROUP.

Similar large main effects of TIME in all ROIs were found for the three other task conditions: Stop condition of the Stop-signal task (FM: $F(2.659,146.269) = 95.530$, $p < .001$, $\eta_p^2 = .635$, FLr: $F(2.688,147.844) = 66.024$, $p < .001$, $\eta_p^2 = .546$, FLl: $F(2.586,142.234) = 47.998$, $p < .001$, $\eta_p^2 = .466$, and parietal region: $F(2.290,125.972) = 42.463$, $p < .001$, $\eta_p^2 = .436$), Switch condition of the Switching task (FM: $F(1.819,101.880) = 9.518$, $p < .001$, $\eta_p^2 = .145$, FLr: $F(2.288,128.149) = 19.272$, $p < .001$, $\eta_p^2 = .256$, FLl: $F(1.872,104.858) = 11.844$, $p < .001$, $\eta_p^2 = .175$, and parietal region: $F(1.717,96.134) = 100.096$, $p < .001$, $\eta_p^2 = .641$), and Update condition of the N-back task (FM: $F(2.714,165.554) = 43.160$, $p < .001$, $\eta_p^2 = .414$, FLr: $F(2.817,171.826) = 51.700$, $p < .001$, $\eta_p^2 = .459$, FLl: $F(2.818,171.891) = 50.768$, $p < .001$, $\eta_p^2 = .454$, and parietal region: $F(1.965,119.877) = 159.715$, $p < .001$, $\eta_p^2 = .724$). However, for the Stop, Switch, and Update condition there were no significant main effects of GROUP or interaction effects TIME x GROUP.

Overall, the FM, FLr, and FLl show a relatively similar progression over time for all tasks; power increases gradually until Time Window 4 or 5 (i.e., 200-400 or 300-500 ms), and then slowly decreases again, but not to the initial level. Only the Switch condition shows a different pattern in these three ROI, with a relatively small power increase in the first two Time Windows (i.e., —100-100 and 0-200 ms) and a stable level thereafter. In contrast, the parietal region shows a sharp increase from Time Window 1 to 2 for most tasks, remains relatively stable until Time Window 4 (i.e., 200-400 ms), and then drops to an even lower level than initial. The exception is the Stop condition, which did not show this steep increase in the first time windows, but did reach a lower level of power at the end as compared to the start.

3.4. Functional theta connectivity

Fig. 3 shows the mean connectivity per time window and ROI pair of the correct responses for the conditions of Stroop, Stop-signal, Switching, and N-back task. In the following, the results of the RM ANOVAs for each task per ROI pair are described, for a full overview see Supplementary Table 3.

For the Incongruent condition of the Stroop task, the RM ANOVAs demonstrated significant large main effects of TIME for all five connectivity pairs: FM-FLr ($F(2.397,160.592) = 35.244$, $p < .001$, $\eta_p^2 = .345$), FM-FLl ($F(2.761,184.979) = 39.995$, $p < .001$, $\eta_p^2 = .374$), FM-parietal

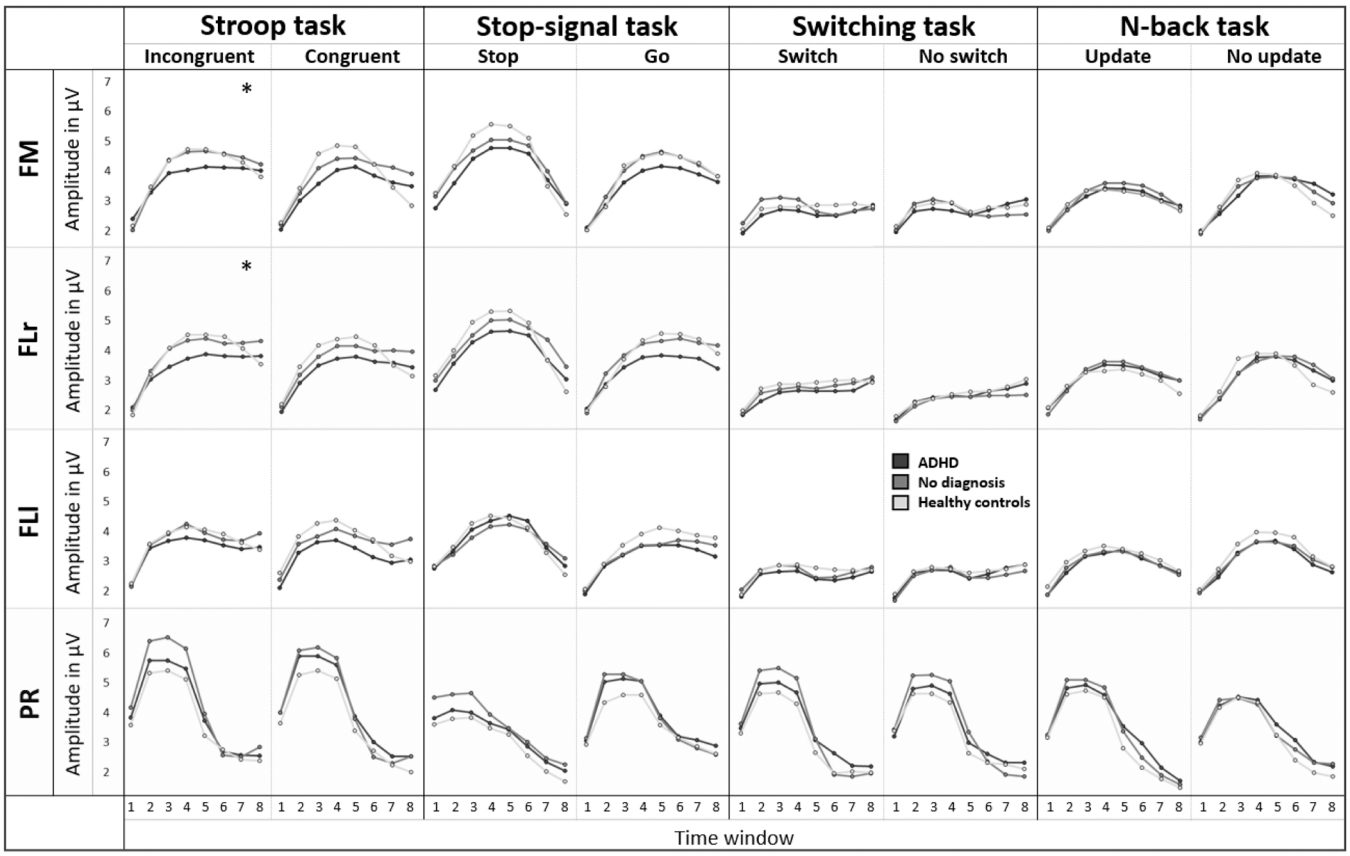

Fig. 2. Mean power in the frontal midline (FM) region, frontolateral right (FLr) and left (FLl) region, and parietal region across eight (overlapping) 200 ms sliding time windows (i.e., -100 to 800 ms after stimulus onset) for the correct responses on the Stroop, Stop-signal, Switching, and N-back task for the ADHD group, No diagnosis group, and controls. *Note: * Significant interaction TIME x GROUP (p ≤.05).*

region (F(3.070,205.676) = 71.888, p <.001, η_p^2 =.518), parietal region-FLr (F(2.774,185.850) = 72.485, p <.001, η_p^2 =.520), and parietal region-FLl (F(2.728,182.752) = 71.901, p <.001, η_p^2=.518). The same effect of TIME was found for the Stop condition of the Stop-signal task (FM-FLr: F(3.078,169.263) = 13.945, p <.001, η_p^2 =.202, FM-FLl: F (3.142,172.808) = 19.097, p <.001, η_p^2 =.258, FM-parietal region: F (2.899,159.431) = 14.142, p <.001, η_p^2 =.205, parietal region-FLr: F (3.142,172.818) = 15.192, p <.001, η_p^2 =.216, and parietal region-FLl: F (2.975,163.601) = 15.814, p <.001, η_p^2 =.223. For both the Incongruent and Stop condition, there were no significant main effects of GROUP or interaction effects TIME x GROUP.

For the Switch condition of the Switching task there were again significant main effects of TIME for all ROI pairs: FM-FLr (F (3.628,203.142) = 8.527, p <.001, η_p^2 =.132), FM-FLl (F(3.490,195.434) = 16.705, p <.001, η_p^2 =.230), FM-parietal region (F(3.156,176.731) = 24.287, p <.001, η_p^2=.303), parietal region-FLr (F(3.435,192.367) = 20.835, p <.001, η_p^2 =.271), and parietal region-FLl (F(3.257,182.416) = 49.877, p <.001, η_p^2 =.471). Additionally, there was as expected a significant medium interaction effect of TIME x GROUP for FM-parietal region (F(6.312,176.731) = 2.324, p =.032, η_p^2 =.077). However, a post-hoc one-way ANOVA did not show a significant group difference in connectivity between FM and parietal region for Time window 4 (F (2,56) = 1.720, p =.188). Lastly, there were no significant main effects for GROUP.

Finally, for the Update condition of the N-back task there were also significant large main effects of TIME for all ROI pairs: FM-FLr (F (3.041,185.500) = 13.862, p <.001, η_p^2 =.185), FM-FLl (F (3.486,212.665) = 12.087, p <.001, η_p^2 =.165), FM-parietal region (F (2.684,163.706) = 21.573, p <.001, η_p^2 =.261), parietal region-FLr (F (2.900,176.874) = 18.813, p <.001, η_p^2 =.236), and parietal region-FLl (F(2.721,165.983) = 20.227, p <.001, η_p^2 =.249). There were no significant main effects for GROUP or interaction effects TIME x GROUP.

Overall, all ROI pairs showed a similar course of connectivity over time for all tasks. For the Incongruent, Switch, and Update condition, connectivity increased from the start and peaked around Time Window 3 or 4 (i.e., 100-300 or 200-400 ms), before decreasing again. Only in the Stop condition, the peak of connectivity was slightly later at Time Window 5 (i.e., 300-500). The Incongruent and Stop condition had relatively higher connectivity peaks as compared to the Switch and Update condition.

3.5. Neurocognitive associations between neurophysiological markers and behaviour

For the Incongruent condition of the Stroop task, we found significant medium correlations between the power in the FLr at Time window 4 and both RT (r(70) = -.459, p <.001) and scores on the Task monitor subscale of the BRIEF-A (r(70) = -.309, p =.009). This suggests that greater power in this ROI at this time point is related to faster RT and fewer complaints on the Task Monitor subscale. Additionally, significant correlation were found between RT and power in the FM and FLl at Time window 4 (r(70) = -.450, p <.001) and r(70) = -.390, p =.001), respectively). The Stop condition of the Stop-signal task did not show any significant correlations. For the Switch condition of the Switching task, there was a significant medium correlation between power in the FLr at Time window 4 and AC (r(59) =.418, p =.001), indicating that

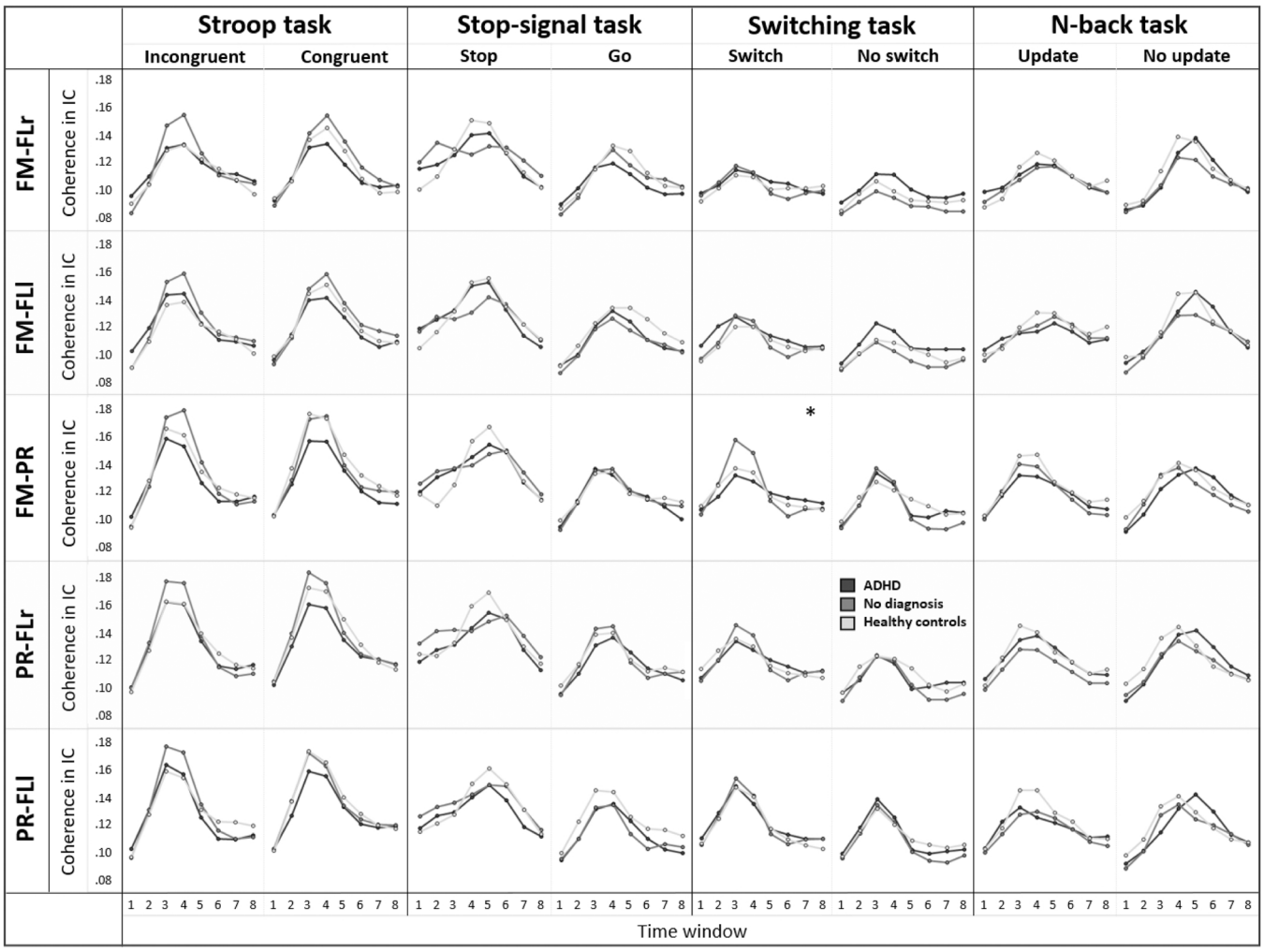

Fig. 3. Mean connectivity between midcingulate cortex (FM), frontolateral right (FLr) and left (FLl) region, and parietal region across eight (overlapping) 200 ms sliding time windows (e.g., from -100 to 800 ms after stimulus onset) for the correct responses on the conditions of the Stroop, Stop-signal, Switching, and N-back task for the ADHD group, No diagnosis group, and controls. *Note: IC = imaginary coherence. * Significant interaction TIME x GROUP ($p \leq .05$).*

greater power at this ROI and time is associated with a higher AC. However, no other significant correlations between power and connectivity in the other ROIs/ROI pairs and behavioural outcomes were found. Finally, the Update condition of the N-back task, showed significant medium correlations between five neurophysiological markers and RT. Specifically, power at Time window 4 in the FM ($r(64) = -.415$, $p = .001$), FLr ($r(64) = -.357$, $p = .004$), and FLl ($r(64) = -.433$, $p < .001$), and connectivity between FM-FLr ($r(64) = -.370$, $p = .003$) and FM-FLl ($r(64) = -.372$, $p = .002$), were all positively correlated with RT. In other words, higher power or connectivity was associated with faster RT. For an overview of all correlations, see Supplementary Table 4.

4. Discussion

The current study examined theta power and functional theta connectivity in the sensor space of the superordinate network as neurophysiological markers of the core EFs: conflict monitoring, response inhibition, set-shifting, and working memory updating. Additionally, behavioural performance on these four EFs was assessed. Three groups were formed: participants with EF complaints & ADHD diagnosis, participants with EF complaints without a diagnosis, and controls without EF complaints. This grouping allows the assessment of the sole effect of having subjective EF complaints, as well as the additional effect of an ADHD diagnosis next to experiencing EF complaints.

As expected, all four EF tasks show a dynamical increase in theta power over time in the FM, FLl, FLr, and parietal region, as well as in functional theta connectivity between these regions. This indicates that across groups, the four EFs tasks elicit power and connectivity changes in and between these regions. Strong group differences are found especially for conflict monitoring, with neural differences in power in the FM and FLr. Interestingly, these neural markers are also associated with actual behavioural performance and complaints in daily life. For set-shifting, group differences are less pronounced, and for response inhibition and working memory updating, no group differences are found at all. Below, we discuss the results for each EF in more detail.

4.1. Conflict monitoring

In conflict monitoring, as expected, the results show group differences in the theta power dynamics over time in the FLr and FM and in the behavioural outcome RT, as well as neurocognitive associations between them and with complaints in daily life. Although in the critical time window for EFs (i.e., 200 - 400 ms), only the power in the FLr is significantly lower for the participants with EF complaints & ADHD compared to controls. In general, conflict monitoring describes a situation with competing or conflicting actions that requires additional cognitive resources to be resolved. The MCC monitors and detects these situations and the DLPFC resolves potential conflict by focusing attention to important aspects of a task or inhibiting inappropriate actions via the rIFC (Egner & Hirsh, 2005; Forstmann et al., 2008; van den

Wildenberg et al., 2010). The current findings suggest that adults with EF complaints & ADHD, have less involvement of right lateral frontal brain regions, such as the DLPFC, which reduces attention to task-relevant aspects. Detection of conflict by brain areas in the FM, such as the MCC, appears to function normally in the group with ADHD, while impairments in the FM have been found in other studies (Vogt, 2019; Bush et al., 1999). In contrast to group differences in power, connectivity was similar between groups, indicating that information exchange in the network is not impaired in individuals with EF complaints with or without ADHD diagnosis.

Interestingly, greater power in the FLr at the time window critical for EFs (i.e., 200-400 ms) is associated with a faster RT, and most importantly, with fewer complaints in this EF domain in daily life (e.g., less problems with impulsiveness, being distracted, or rushing things). Additionally, greater power in the FM and FLl at this same time window are also associated with a faster RT. These neurocognitive associations fit with the observed group differences in RT; participants with EF complaints & ADHD are slower than the controls. Our results fit with other studies, showing slower responses on the Stroop task in individuals with ADHD (e.g., Snyder et al., 2015; Lampe et al., 2007; Woods et al., 2002). Generally, slower responding is assumed to reflect less efficient or disengaged processing, as RT reflects the time needed for perceptual and motor-planning computations required to prepare and execute a response (Brenner & Smeets, 2018).

In summary, individuals with EF complaints & ADHD are less able to upregulate theta power in the FLr (i.e., hypoactivation) during conflict monitoring, which is associated with less efficient conflict monitoring, and may reflect less directing of attention to relevant aspects of the task. Since our ADHD sample mainly comprises the inattentive subtype, it may be a salient feature especially in this group. The subjective experience of EF complaints alone did not influence task performance as differences between the participants with EF complaints without a diagnosis and the controls were not significant. Notably, the current results are observed despite stimulant use by 2/3 of the participants with ADHD. In general, this drug class is considered to increase activation in regions such as the FM (Bush, 2009) and rIFC (Rubia et al., 2014), and can at least in children with ADHD improve conflict monitoring (Langleben et al., 2006; Nakanishi et al., 2017). However, stimulant use does not seem to have an effect here, as power in the FLr and RT was similar for ADHD participants who used stimulants and non-users.

4.2. Response inhibition

There were no group differences in response inhibition in terms of neural measures and behavioural performance. Participants with EF complaints & ADHD thus exhibit relatively normal performance and unaffected neural functioning. Additionally, there were no associations between the neural measures and behaviour. In children, impaired response inhibition is usually found as a central feature of ADHD (Alderson et al., 2007), but in adults the results are mixed (e.g., Congdon et al., 2014). On the one hand, this finding could indicate that inhibitory control develops to a normal level in adulthood. On the other hand, the lack of significant differences in the current study could be related to other factors. First, our ADHD sample mainly included participants with the inattentive subtype, who generally seem to show better response inhibition than individuals with the combined ADHD subtype (Bluschke et al., 2016). Second, individuals with ADHD may have developed compensatory mechanisms that could mask their cognitive impairments (Planton et al., 2021). Third, stimulant use by the majority of the ADHD participants could have improved response inhibition (Aron et al., 2003; Overtoom et al., 2009). However, findings on the effects of stimulants on response inhibition are mixed (Congdon et al., 2014), which can reflect differences in the sampling and inclusion of ADHD and its subtypes in different studies. Fourth, it could be that ADHD more strongly affects the strength of pre-trial (proactive) theta band activity instead of theta during response inhibition trials (Adelhöfer et al., 2021).

One limitation to the analyses of connectivity and power in this task is the lack of statistical power. The group with controls only includes sixteen participants, although eighteen participants are required to demonstrate a medium effect. For the behavioural outcome SSRT, there are no statistical power issues.

4.3. Set-shifting

For set-shifting, the groups show very similar patterns of both power, connectivity, and behaviour. Only for connectivity between the FM and parietal region there are significant group differences in the dynamics over time, but without group differences in the time window critical for EFs (i.e., 200-400 ms). In general, connectivity between the FM and parietal region seems to reflect signalling of a detected condition that requires cognitive control (Liston et al., 2006; Niendam et al., 2012). In this study, connectivity between the FM and parietal region was not associated with any of the behavioural outcomes of set-shifting or complaints in daily life in this EF domain. In contrast, greater power in the FLr at the time window critical for EFs (i.e., 200-400 ms) was associated with a higher AC. There were, however, no behavioural differences between groups regarding set-shifting. Given the absence of both behavioural differences and associations between connectivity and set-shifting performance, it is challenging to provide context for any group differences in connectivity between the FM and the parietal region. Therefore, this isolated finding should be interpreted with caution, as it may be a false positive result.

The lack of differences in neural underpinnings and behaviour in the group with EF complaints & ADHD compared to controls contrasts earlier studies. These show adults with ADHD with specific difficulties in set-shifting (e.g., Luna-Rodriguez et al., 2018), which has been linked to functional abnormalities in regions such as the prefrontal cortex, parietal lobe, and anterior cingulate cortex (Bálint et al., 2015). The use of stimulant medication by the majority of the participants with ADHD could be an explanation for the non-deviating performance, as some studies found that they can improve set-shifting in ADHD (e.g., Ni et al., 2013). Fitting with this thought is a recent fMRI analysis demonstrating similar activation of brain areas during set-shifting in controls and ADHD patients treated with stimulant medication, as opposed to ADHD patients not treated with medication (Berberat et al., 2021). Nevertheless, the results on the effects of stimulants on cognition, including set-shifting, are mixed (Advokat, 2010). It should also be noted that studies on the effects of stimulants often assess 'set-shifting' using the Wisconsin Card Sorting Test or its equivalent, which is not a pure measure of set-shifting, as it requires both multiple EFs and non-EF abilities. The specific effects of stimulants on set-shifting and its neural basis are, therefore, still unclear in ADHD, and further research is needed in this area. Finally, compensatory mechanisms may play a role in ADHD or other neuronal aspects involved in set-shifting may be more strongly affected, for instance oscillatory synchronisation in the delta band (López et al., 2019).

4.4. Working memory updating

For working memory updating, there were no group differences in neural measures and behavioural performance. Interestingly, a faster reaction time in working memory updating was associated with greater power in the FM, FLr, and FLl and with greater connectivity between FM and both FLr and FLl. This result suggests that theta activity in the fronto-medial and lateral brain regions is closely associated with the efficiency of working memory updating. Notably, this association is not affected by the presence of EF complaints or ADHD diagnosis.

In general, individuals with ADHD seem to perform poorly on working memory tasks, although, there is no scientific consensus on exactly which process (e.g., span, recall) or mechanisms are affected (Ortega et al., 2020) and contrary results have also been shown (e.g., Zhao et al., 2020). It is possible that there are simply no differences

between the groups because the subjective experience of EF complaints has no influence on the updating of working memory. The unaffected performance of the group with EF complaints and ADHD could also be due to the cognitive effects of taking stimulants, as the majority of participants with ADHD take medication (Tamminga et al., 2021). Another reason might be the use of compensatory mechanisms, such as prolonged maintenance of theta synchronisation after the occurrence of a stimulus (Missonnier et al., 2013).

4.5. Subjective EF complaints in daily life without diagnosis

There are several explanations for possible subjective EF complaints in daily life without a clinical diagnosis. First, there could be an underlying disorder or condition that affects EFs and is not (yet) diagnosed, for example, undiagnosed ADHD is particularly common in women (Quinn, 2005). The use of compensatory strategies by individuals with ADHD can also mask their symptoms and delay a diagnosis (e.g. Canela et al., 2017). This explanation in particular is likely for some participants in the current study, as the group without a diagnosis had a similar number of attention symptoms as the ADHD group and seven participants suspected a diagnosis of ADHD. Second, individuals who do not meet the full criteria for a clinical diagnosis of, for example ADHD, may have attention and behavioural difficulties that are not at the extreme end of the continuum (McLennan, 2016). The value of a continuum of trait distributions in the population rather than using discrete categorical diagnoses is also emphasised, for example, in the Research Domain Criteria (RDoC) framework (Cuthbert, 2014). Third, psychological factors, including personality factors, depressive symptoms and perceived stress, may contribute to the experience of EF complaints (Smit et al., 2021). However, whether or not there is an underlying disorder, subjective cognitive difficulties can interfere with daily functioning in healthy people (e.g., Stenfors et al., 2013) and should be considered in research and treatment.

5. Final remarks

The main strength of the current study is the use of an integral approach; assessing multiple neurophysiological markers in the sensor space of different regions of the superordinate network for the four core EFs in participants with subjective EF complaints in daily life and controls. It is, however, important to note that presenting the results of multiple neurophysiological markers and EF tasks in the same paper does increase the risk of false positives (i.e., type I errors) due to multiple comparisons. We have taken this into account in the interpretation of the findings. Furthermore, our results apply only to scalp measures of theta (4-8 Hz) and are evaluated in a specific time window (i.e., -100 to 800 ms after stimulus onset) and ROIs (pairs), so they do not apply to other neuronal features, such as frequency coupling and further neural oscillations. Moreover, medication use was not an exclusion criterion, which has the advantage that a representative group was included and statements can be generalised, and the disadvantage that stimulant use is a confounding factor in the ADHD group. Understanding the neural basis of EFs, such as neural oscillations, has the potential to contribute to the understanding of EF deficits and offers solutions for developing new interventions that target specific neural dysfunctions.

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Declaration of interest

None.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2023.108503.

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