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Event-related brain oscillations in attention-deficit/hyperactivity disorder (ADHD): A systematic review and meta-analysis

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ABSTRACT

Previous studies have associated attention-deficit/hyperactivity disorder (ADHD) with several alterations in electroencephalographic (EEG) activity. Time-frequency analyses capturing event-related power modulations are becoming an increasingly popular approach, but a systematic synthesis of the time-frequency literature in ADHD is currently lacking. We conducted the first systematic review and meta-analysis of time-frequency studies of children and adults with ADHD in comparison to neurotypical controls. Searches via Medline, Embase, and Web of Science, as well as reference lists, identified 28 eligible articles published until March 2021. Of these, 13 articles with relevant data were included in a multi-level meta-analysis. Most studies examined power modulations of alpha, theta and/or beta frequencies ($N = 21/28$), and focused on children ($N = 17/28$). Meta-analyses showed significantly weaker theta increases (Cohen's $d = -0.25$, $p = 0.039$; $N_{ADHD} = 346$, $N_{CONTROL} = 327$), alpha decreases ($d = 0.44$, $p < 0.001$; $N_{ADHD} = 564$, $N_{CONTROL} = 450$), and beta increases (Cohen's $d = -0.33$, $p < 0.001$; $N_{ADHD} = 222$, $N_{CONTROL} = 263$) in individuals with ADHD relative to controls. These patterns indicate broad brain-oscillatory alterations in individuals with ADHD with small (theta) and small-to-moderate (alpha and beta) effect sizes. These group differences were partly consistent when repeating analyses by age group (<18 and 18+ years) and task type (cognitive control, working memory, and simple attention tasks). Overall, our findings identify widespread event-related brain-oscillatory alterations in individuals with ADHD during a range of neurocognitive functions. Future research requires larger samples, a broader range of frequency bands (including delta and gamma) during a wider type of cognitive-affective processes, and should clarify whether atypical event-related power profiles are ADHD-specific or shared with other neuropsychiatric conditions.

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a highly heritable neurodevelopmental disorder that affects 5–7% of children and adolescents, and 2–4% of adults worldwide (Polanczyk et al., 2014; Simon et al., 2009). ADHD is associated with wide-ranging alterations in cognitive and brain functions, encompassing both higher-level executive functions and more basic, self-regulatory and reward processes (Cortese et al., 2012; Franke et al., 2018; Willcutt et al., 2005). These impairments have been generally reported across studies of children and adults (Franke et al., 2018; Hervey et al., 2004; Mostert et al., 2015; Willcutt et al., 2005), although meta-analyses have also found that ADHD-related impairments may decline or differ over the life course (Cortese et al., 2012; Kaiser et al., 2020). The identification of objective measures of atypical cognitive and brain functioning is an area of active research in ADHD, with the aim to understand its etiology, inform clinical applications (e.g., biomarkers), and identify new treatment targets (e.g., for brain stimulation), consistent with precision medicine and personalized treatment approaches (Bzdok and Meyer-Lindenberg, 2018; Loo et al., 2020).

Electroencephalography (EEG) has been a key methodology to gain insights into the neurocognitive mechanisms of ADHD for over 80 years (Jasper et al., 1938). The majority of EEG studies have focused on two main analytic approaches, namely quantitative EEG (QEEG) analysis of spectral power, mostly during resting states, and event-related potentials (ERPs) in response to certain task events (Arns et al., 2013; Clarke

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et al., 2020; Johnstone et al., 2013; Kaiser et al., 2020; Lenartowicz and Loo, 2014). The most consistent findings on these EEG features indicate that children and adults with ADHD show increased power at low frequencies (delta, theta) (Arns et al., 2013; Kitsune et al., 2015; Lenartowicz and Loo, 2014; Loo et al., 2013; Rudo-Hutt, 2015) and reduced amplitudes of ERPs associated with attentional allocation (P3 in response to cue or target stimuli), response inhibition (P3 in response to non-targets), response preparation (contingent negative variation, CNV), and error processing (error-related positivity, Pe) during cognitive tasks (Kaiser et al., 2020).

In the past two decades, a growing number of studies of ADHD samples have taken advantage of advances in EEG signal processing, called time-frequency analyses, that combine the strengths of QEEG and ERP approaches and provide richer information on sub-second changes of brain activity at different frequencies (available in QEEG, but not ERP studies) and stages of stimulus processing (available in ERP, but not QEEG studies) (Herrmann et al., 2014; Loo et al., 2015; Makeig et al., 2004). Specifically, time-frequency analyses quantify event-related increases in power, also sometime called event-related synchronization (ERS), as well as decreases in power, or event-related desynchronization (ERD), relative to pre-stimulus power (Loo et al., 2015; Mazaheri and Picton, 2005). Mean event-related power changes across trials are often summarized in so-called event-related spectral perturbations (ERSP) (Makeig, 1993; Makeig et al., 2004). A typical feature of an ERSP is a power increase in the theta band (4–7 Hz) upon presentation of a salient stimulus (e.g., target), maximal over fronto-central (Bickel et al., 2012; Bozhilova et al., 2020) and/or parietal (Jacobs et al., 2006; Vainieri et al., 2020) sites, followed by a broad posterior alpha power decrease (8–13 Hz) (Fig. 1). This theta increase is postulated to reflect initial stimulus processing and attention allocation, whereas the alpha decrease has been associated with inhibition of task-irrelevant processes in support of visual attention and coordinated activity between visual and executive functioning systems (Bickel et al., 2012; Klimesch, 2012; Lenartowicz et al., 2018; Mazaheri and Picton, 2005). The power decrease can also extend to the beta range (14–30 Hz), where a beta decrease is thought to reflect attentional processes related to preparation and execution of motor responses (Pfurtscheller, 1981; Spitzer and Haegens, 2017), and may be followed by an increase in beta after

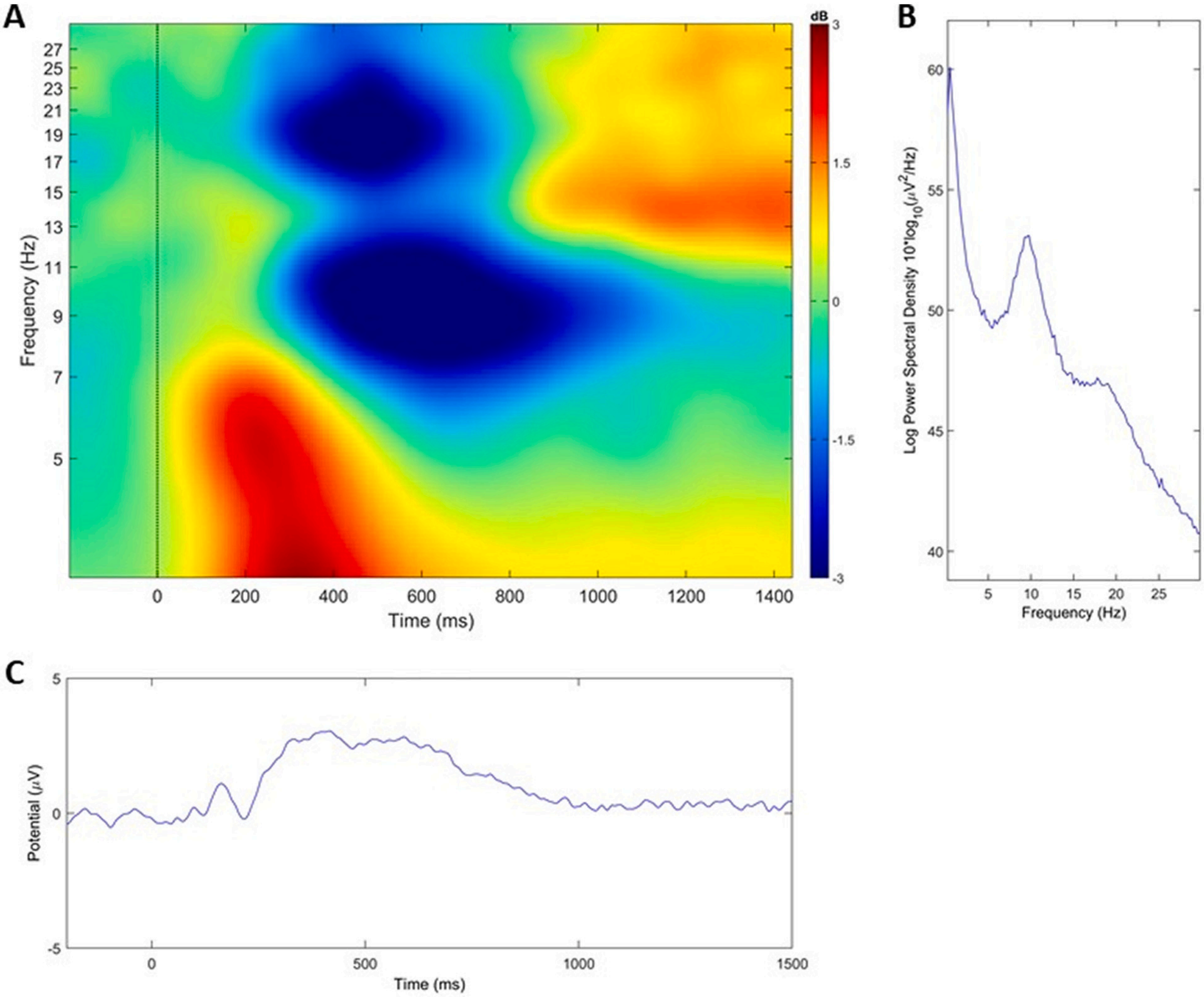


Fig. 1. Example of EEG features from data on 20 healthy adults during a simple reaction-time task. A: Time-frequency plot showing a broad increase in theta power (~100–700 ms, 3–7 Hz), in red, broad decreases in alpha (~300–1000 ms, 8–13 Hz) and beta power (~200–700 ms, 14–30 Hz), in blue, and an increase in beta power (”beta rebound”, >900 ms), in red. The color scale represents changes in power relative to a pre-stimulus (“baseline”) period, in decibel (dB). B: Log power spectral density between 0 and 30 Hz collapsed across time, commonly analyzed in discrete frequency bands (delta, theta, alpha, beta) in quantitative EEG analyses. C: Grand average event-related potential (ERP), where individual peaks (e.g., P3 around 200–700 ms) are commonly analyzed. Note that, whereas plot B only provides information about frequency and plot C only about time, plot A combines information about frequency and time, thereby showing EEG features that are not captured by either plots B or C (e.g., alpha/beta power decreases). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

movement completion (known as “beta rebound”) (Neuper and Pfurtscheller, 2001). Additional power increases have also been reported during the maintenance phase of working memory (WM) tasks, where a theta increase is commonly interpreted as a mechanism to facilitate WM storage (Lenartowicz et al., 2019; Missonnier et al., 2013; Onton et al., 2005).

Studies of children and adults with ADHD have reported differences from neurotypical controls, such as weaker alpha decreases (Bozhilova et al., 2020; Deiber et al., 2020; Hasler et al., 2016; Lenartowicz et al., 2014, 2019; Mazaheri et al., 2014; Michelini et al., 2018b), weaker beta decreases and increases (Bozhilova et al., 2020; Hasler et al., 2016), and weaker theta increases (Lenartowicz et al., 2014; Vainieri et al., 2020) in a variety of tasks. However, these differences in have not been reported consistently across all studies, possibly owing to the small sample sizes (<20 participants per group) or to the high heterogeneity that characterizes ADHD, both in terms of clinical presentations and of associated underpinnings (Lenartowicz and Loo, 2014; Nigg et al., 2020). Since no article to date has provided a systematic synthesis and meta-analysis of the time-frequency literature in ADHD, we currently lack a clear understanding of the extent to which time-frequency approaches can reliably capture neurocognitive impairments in ADHD.

The current systematic review and meta-analysis therefore sought to provide a qualitative and quantitative synthesis of available time-frequency studies in samples of children and adults with ADHD in comparison to neurotypical controls. We restricted our focus to time-frequency studies of event-related power during task performance because a comprehensive synthesis of progress in this area is currently lacking, despite the aforementioned advantages of these studies for uncovering the neural bases of ADHD (for recent reviews and meta-analyses of resting-state power and ERPs in ADHD see: Clarke et al., 2020; Kaiser et al., 2020; Rudo-Hutt, 2015). Our main aim was to review and quantify the magnitude of the difference between ADHD and control groups in event-related power across different frequency bands. We hypothesized that significant group differences would emerge in the theta, alpha and beta bands, but we did not solely restrict our literature search to these rhythms, to review potential differences in delta and gamma frequencies. Furthermore, we examined whether atypical event-related oscillations are markers of ADHD across both childhood and adulthood. Finally, since a variety of tasks have been used to study event-related dynamics in ADHD, we evaluated whether certain paradigms are especially sensitive to ADHD-related impairments in time-frequency measures.

2. Materials and methods

2.1. Literature search strategy and selection criteria

The literature search was performed following the PRISMA guidelines (Page et al., 2021) using the databases Medline (PubMed), Ovid (Embase), and Web of Science. Key words included ADHD, EEG, and frequency (or similar words; see Supplementary Material 1 for a full list). The first literature search was conducted in May 2020, with updated searches in July 2020 and March 2021.

Eligible studies were identified based on the following criteria:

(a) Inclusion of ADHD and neurotypical control groups of children, adolescents and/or adults.
(b) Individuals with ADHD identified based on a formal diagnostic process (e.g., diagnostic interview based on criteria from the Diagnostic and Statistical Manual of Mental Disorders, DSM, or International Classification of Diseases, ICD).
(c) Recording of EEG activity while participants performed a task (i.e., not during rest).
(d) Examination of EEG power in response to task events, such as event-related increases or decreases.
(e) No case studies or review articles.
(f) Peer-reviewed articles.
(g) Written in English.

Articles were imported to the open-source software Rayyan (Ouzzani et al., 2016), where duplicate articles were excluded. To minimize risk of bias in the included studies, the first and second authors independently screened titles and abstracts of all studies for eligibility, and marked studies as “exclude”, “maybe”, or “include”. All studies marked as “include” or “maybe” by either author were carried forward to the full-text screening, performed independently by the same two authors. Reference lists of the eligible studies and of excluded review articles were also screened independently by both authors to find additional relevant studies that had been missed during the database searches. Any discrepancy between the inclusion decision by the two authors were resolved in discussion with the last author.

A total of 1304 nonduplicated, potentially relevant articles were identified from database searches. Of these, 93 articles were selected for full paper retrieval and further screening based on eligibility criteria. Two additional articles were identified from the reference lists of these articles or review articles as potentially eligible. Finally, 28 studies meeting all eligibility criteria were selected for inclusion (marked with an asterisk in the reference list). Fig. 2 provides an overview of the search process and of the number of articles removed at each stage.

2.2. Data extraction

A coding spreadsheet was used to record relevant descriptive statistics, effects sizes, and study characteristics (Table 1 and Table S1). Information was extracted and coded by the second author and checked by the first author.

All 28 articles were included in a qualitative synthesis of the literature, and articles with sufficient data or relevant statistics (e.g., mean, standard deviation, effect size) were also included in a quantitative synthesis (meta-analysis). Statistics could not be retrieved for seven articles using bootstrapping or permutation-based statistical approaches, which would have required the authors of original studies to calculate effect sizes for all tested data points, frequency bins, and/or electrode locations, unlike studies testing a limited number of hypotheses. The authors of all other articles with insufficient quantitative information were contacted for missing data, with up to two reminders for each article. Relevant data were received for five studies. This resulted in 13 studies included in the meta-analysis.

2.3. Meta-analysis

Meta-analyses were run for each frequency band using three-level meta-analysis models based on random-effects assumptions (Cheung, 2014), run with the metaSEM package (Cheung, 2019) in R version 4.0.3 (R Core Team, 2018). These models allowed us to address dependencies between effects sizes when more than one effect per study was available (e.g., more than one electrode location or task condition). Specifically, all effect sizes compatible with investigated time-frequency measures in the theta, alpha, and beta bands (i.e., for all relevant measures, scalp/source regions, and time points) were extracted or calculated from descriptive statistics as reported in individual studies. Then, using available effect sizes from individual studies, we computed the standardized mean difference (Cohen's d) between individuals with and without ADHD for each time-frequency measure (Cohen, 1988). Following the criteria formulated by Cohen (1988), $d = 0.2$, $d = 0.5$, and $d = 0.8$ were interpreted as small, moderate, and large effects, respectively. A negative Cohen's d may indicate either a stronger decrease or a weaker increase in the ADHD vs. control group, whereas positive Cohen's d may indicate either a weaker decrease or a stronger increase in the ADHD vs. control group. Given these opposite patterns, for frequency bands where both decreases (i.e., defined as effects where the mean in the control group was negative) and increases (i.e., effects

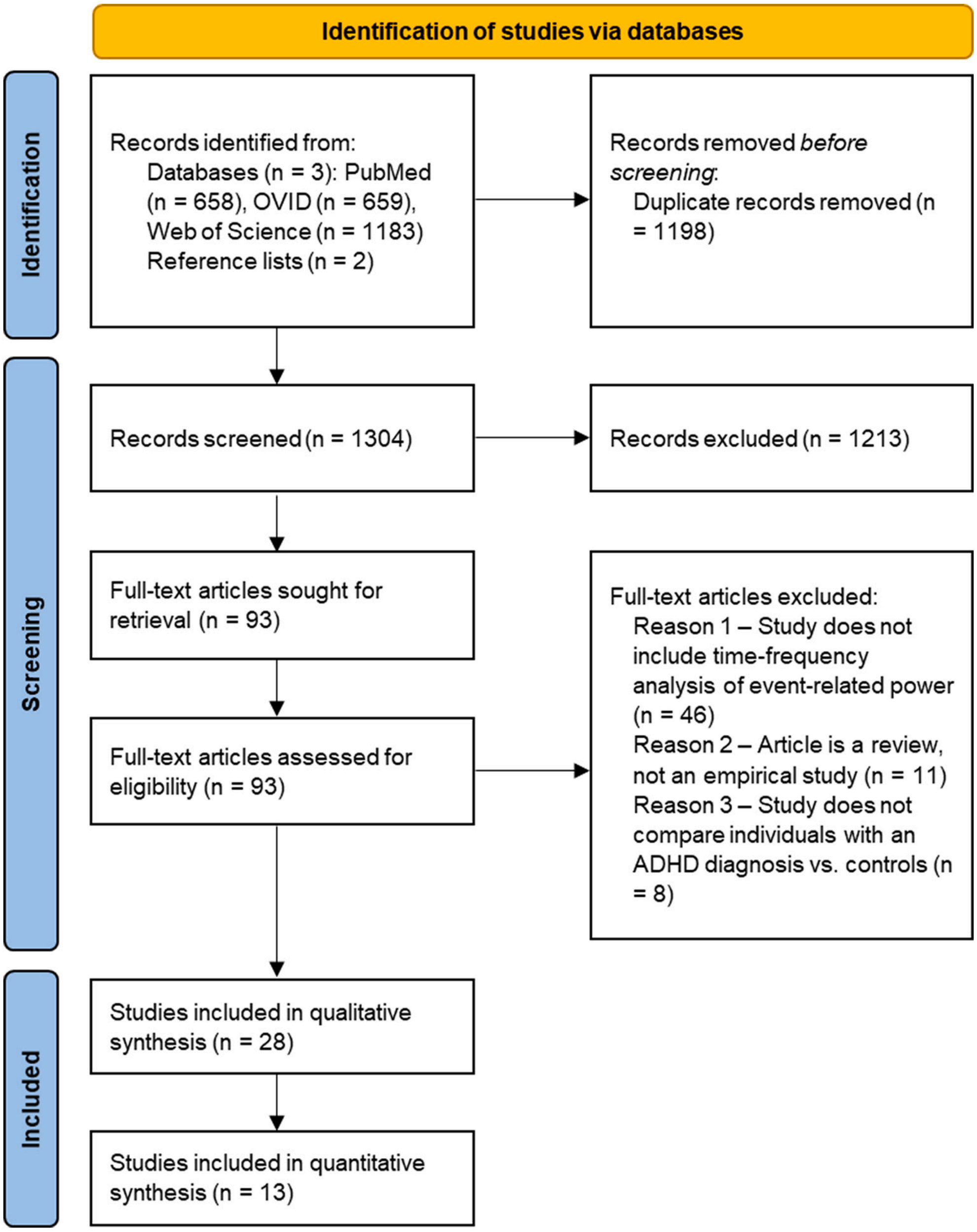


Fig. 2. Flow diagram displaying the screening, selection and review process according to the PRISMA 2020 guidelines (Page et al., 2021).

where the mean in the control group was positive) were reported, we calculated overall effect sizes as well as effect sizes for increases and decreases separately. For one study that reported the 95% confidence interval of the effects and sample size, but did not report the exact effects sizes (McAuliffe et al., 2020), we approximated the effect size by assuming normally distributed data to derive the variance and the mean difference. We also tested the homogeneity of the population effects sizes by computing the chi-square statistic Q (Cochrane's Q-test) (Hedges and Olkin, 2014). A significant Q-test denotes heterogeneity across studies, meaning that the observed variability in outcomes goes beyond what can be expected due to measurement or sampling error alone (Fletcher, 2007; Higgins and Thompson, 2002).

Further subgroup analyses explored whether differences between ADHD and control groups emerge consistently across development, by repeating analyses on studies of children (<18 years) and adults (18+ years) separately. Similarly, studies were divided in three subgroups to examine whether task type influenced results: (a) cognitive control: response-control tasks (e.g., go/no-go, flanker tasks), probing cognitive control processes (e.g., response inhibition, performance monitoring); (b) WM: tasks with encoding/retrieval and maintenance phases (e.g., n-back, delayed-match-to-sample tasks); and (c) simple attention: stimulus-response tasks (e.g., simple reaction-time tasks), probing attention orienting and vigilance. These subgroups are consistent with the taxonomy proposed by the Research Domain Criteria (RDoC), a major framework for studying ADHD and other neuropsychiatric disorders, which includes Cognitive Control, Working Memory, and Attention constructs among Cognitive Systems (Cuthbert, 2014; NIMH Workgroup on Tasks and Measures for RDoC, 2016).

Finally, sensitivity analyses were conducted to test for the robustness of the calculated standardized mean differences after excluding certain studies with minor differences from other studies included in the meta-analyses. Firstly, we re-ran the meta-analysis of theta power excluding two studies that examined response-locked (error-related) theta power (Groom et al., 2010; Keute et al., 2019), unlike other studies of theta power included in the meta-analysis, which focused on stimulus-locked power instead. Secondly, we re-ran the meta-analysis of alpha and beta

Table 1

Study characteristics of key relevance to the qualitative synthesis and meta-analysis.

Study	N ADHD	N Control	Child (1)/ Adult (2)	Task Type	Task Name	In Meta-analysis (yes = 1, no = 0)	Measured Theta (yes = 1, no = 0)	Measured Alpha (yes = 1, no = 0)	Measured Beta (yes = 1, no = 0)	Measured Gamma (yes = 1, no = 0)	Reason for exclusion in sensitivity meta-analyses	Key Findings (ADHD vs. Control)
Baijot et al. (2017)	7	7	1	Cognitive control	Cued Go/No-Go task	0	1	1	1	1		Stronger cue-related occipital beta decrease; weaker go-related central alpha decrease; weaker central theta and alpha increase
Bozhilova et al. (2020)	69	29	2	Cognitive control	Sustained Attention to Response Task	1	1	1	1	0		Weaker no-go-related parieto-occipital alpha and beta decrease; weaker go-related fronto-central theta increase
Deiber et al. (2020)	25	22	2	Cognitive control	Go/No-Go task	1	0	1	0	0		Weaker go and no-go-related parieto-occipital alpha decrease
Ellis et al. (2017)	25	25	1	Cognitive control	Go/No-Go task	1	0	1	0	0	Lateralization measure	Higher frontal alpha asymmetry during incorrect no-go trials
Gomarus et al. (2009)	15	15	1	Working memory	Selective memory search task	0	1	1	0	0		No difference in frontal and occipital theta increase and alpha decrease during storage and search conditions
Groom et al. (2010)	23	19	1	Cognitive control	Go/No-Go task	1	1	0	0	0	Response-locked	Weaker error-related fronto-central theta increase
Guo et al. (2019)	21	24	1	Simple attention	Cued visuospatial covert attention task	0	0	1	0	0		Atypical parieto-occipital alpha lateralization during human eye gaze
Guo et al. (2020)	22	24	1	Simple attention	Modified Posner's cueing paradigm	0	1	0	0	0		Stronger midfrontal theta increase; atypical theta lateralization during cue stimuli
Hasler et al. (2016)	21	20	2	Cognitive control	Attention networks task	1	0	1	1	0		Weaker parieto-occipital alpha and beta decrease in no-cue trials; weaker central and parieto-occipital cue-related alpha and beta decrease; weaker target-related central alpha decrease; weaker target-related beta decrease and increase across scalp regions
Karch et al. (2012)	24	30	2	Cognitive control	Adapted Go/No-Go task	0	0	0	0	1		Stronger fronto-central gamma increase during voluntary selection
Keute et al. (2019)	26	14	1	Other	Subliminal motor priming task	1	1	0	0	0	Response-locked	Weaker response-locked frontal theta increase during correct and incorrect trials
Khoshnoud et al. (2018)	15	19	1	Working memory	Time interval reproduction task	0	1	1	0	0		Weaker occipital theta decrease during early window of encoding and retrieval; weaker frontal alpha decrease during retrieval; weaker occipital theta increase during later window of encoding and retrieval
Lenartowicz et al. (2014)	36	42	1	Working memory	Sternberg delayed match-to-sample task	1	1	1	0	0		Weaker occipital alpha decrease during encoding; stronger occipital alpha increase and frontal theta increase during maintenance
Lenartowicz et al. (2019)	85	34	1	Working memory	Sternberg delayed match-to-sample task	1	1	1	0	0		Weaker occipital alpha decrease during encoding and retrieval; stronger occipital alpha increase during maintenance; no difference in fronto-central theta increase during maintenance
Leroy et al. (2018)	14	14	2	Simple attention	Visual oddball task with passive/	0	1	1	1	0		Weaker parieto-occipital alpha-beta increase before stimulus onset, weaker

(*continued on next page*)

Table 1 (*continued*)

Study	N ADHD	N Control	Child (1)/ Adult (2)	Task Type	Task Name	In Meta-analysis (yes = 1, no = 0)	Measured Theta (yes = 1, no = 0)	Measured Alpha (yes = 1, no = 0)	Measured Beta (yes = 1, no = 0)	Measured Gamma (yes = 1, no = 0)	Reason for exclusion in sensitivity meta-analyses	Key Findings (ADHD vs. Control)
					active observation							parieto-occipital beta decrease and stronger parieto-occipital gamma increase during passive condition; weaker parieto-occipital alpha increase and delta-theta increase during active condition
Liu et al. (2016)	136	41	2	Working memory	Delayed-match-to-sample task	1	0	1	0	0		Weaker parieto-occipital alpha increase during maintenance
Mazaheri et al. (2010)	14	11	1	Cognitive control	Cross-modal attentional switching task	0	1	1	0	0		Weaker cue-related parieto-occipital alpha decrease
Mazaheri et al., (2014)[a]	34	23	1	Cognitive control	Flanker task	1	1	1	1	0		Weaker cue-related parieto-occipital alpha decrease in inattentive subtype ADHD group; weaker cue-related central beta decrease in combined subtype ADHD group; no differences in theta increase
McAuliffe et al. (2020)	25	25	1	Other	Unilateral finger-tapping task	1	0	1	1	0	Lateralization measure; approximated effect size	Less lateralized central alpha decrease and weaker central beta decrease after finger tapping
Michelini et al., 2018b	20	20	2	Simple attention	Four choice reaction time ('Fast Task')	1	1	1	1	0		Weaker target-related parieto-occipital alpha decrease; no difference in fronto-central and parietal theta increase and in central beta decrease
Missonnier et al. (2013)	15	15	2	Working memory	n-back task	0	1	1	0	0		Weaker target-related frontal theta increase across task conditions (passive, oddball, 1-back, 2-back); weaker frontal alpha decrease and stronger frontal alpha increase during active conditions
Sánchez-González and García-Zapirain (2017)	43	23	1	Simple attention	Observation executing tasks	0	0	1	0	0		Differences in frontal, central and parietal mu power [unknown if increase/decrease and in which direction]
Sarraf Razavi et al. (2017)	19	19	1	Other	Emotion recognition task	0	0	0	0	1		Weaker occipital gamma increase during emotional face recognition
Vainieri et al. (2020)	87	169	1–2[b]	Simple attention	Four choice reaction time ('Fast Task')	1	1	1	1	0		Weaker fronto-central and centro-parietal target related theta increase; no difference in occipital alpha and central beta decrease
Vollebregt et al. (2016)	17	9	1	Simple attention	Posner's cueing paradigm	0	0	1	0	0		Weaker cue-related parieto-occipital alpha decrease contralateral to cue; weaker cue-related parieto-occipital alpha increase ipsilateral to cue
Yordanova et al. (2001)	14	14	1	Simple attention	Auditory selective attention task	0	0	0	0	1		Stronger fronto-central gamma increase
Yordanova et al. (2013)	14	14	1	Simple attention	Auditory selective attention task	0	0	1	0	0		No difference in central mu power
Zammit and Muscat (2019)	15	15	1	Working memory	Delayed-match-to-sample task	0	0	0	1	0		Weaker parietal and frontal beta decrease during encoding

Abbreviations: ADHD, attention-deficit/hyperactivity disorder; N, number of subjects.

[a] Data were available for inclusion of alpha power in the meta-analysis, but not theta and beta; thus, theta and beta were only included in the qualitative synthesis.

[b] Data for children and adults were used separately in analyses examining developmental differences.

power excluding studies investigating patterns of power lateralization, rather than difference in post-stimulus power from pre-stimulus like other studies included in the meta-analysis. Specifically, we excluded one study investigating alpha power asymmetry (Ellis et al., 2017) and one study investigating alpha and beta power lateralization (McAuliffe et al., 2020). A second reason for excluding the latter study was that effect sizes were not reported and had to be approximated, as described in Section 2.3; thus exclusion of this study in sensitivity analyses also ensured that this effect size approximation did not bias the findings.

3. Results

3.1. Study characteristics

Characteristics of the 28 eligible studies can be found in Table 1 and Table S1 (Supplementary Materials). Most studies (21 in the qualitative synthesis, 11 in the meta-analysis) investigated differences between ADHD and control groups in event-related alpha power, with fewer studies reporting effects for theta power (15 in the qualitative synthesis, 7 in the meta-analysis) and beta power (9 in the qualitative synthesis, 5 in the meta-analysis). Only 5 studies, none of which provided sufficient data for inclusion in the meta-analysis, examined gamma power (Baijot et al., 2017; Karch et al., 2012; Leroy et al., 2018; Sarraf Razavi et al., 2017; Yordanova et al., 2001). None of the eligible studies tested delta power. As such, effects on gamma and delta power are not discussed further and warrant further examination in future studies.

Number of reported effects in individual studies included in meta-analyses varied between 1 (e.g., McAuliffe et al., 2020) and 414 (Hasler et al., 2016). Sample sizes varied widely (Table 1), with the largest study including 256 participants (87 with ADHD and 169 controls) (Vainieri et al., 2020) and the smallest study including 14 participants (7 per group) (Baijot et al., 2017). In most studies, participants with and without ADHD were age- and sex-matched (Table S1), whereas IQ was lower in the ADHD group in a third of the studies that reported IQ comparisons, as expected from previous literature (Frazier et al., 2004). Over half of the studies were conducted in samples from Europe, with the remaining studies conducted in the USA, China, and Iran. In most of the studies that included medicated ADHD participants, medication was discontinued for 12–48 h prior to EEG assessments. A total of 17 studies (7 in the meta-analysis) were on children, 7 studies (5 in the meta-analysis) were on adults, and 1 study (also included in the meta-analysis) included both children and adults (Table 1). With regard to task type, 7 studies (6 in the meta-analysis) examined time-frequency indices during cognitive control paradigms, 6 (3 in the meta-analysis) during WM tasks, and 8 (2 in the meta-analysis) during simple attention tasks.

A total of 645 individuals with ADHD and 521 controls were included in the meta-analysis. Of these, 346 individuals with ADHD and 327 without ADHD were included in the meta-analysis for theta, 564 with and 450 without ADHD were included in the meta-analysis for alpha, and 222 with and 263 without ADHD were included in the meta-analysis for beta.

3.2. Standardized mean differences between ADHD and control groups

3.2.1. Event-related theta power

Across studies that examined event-related theta power, the majority (8 out of 15) reported reduced power increases time-locked to stimulus onset in individuals with ADHD relative to controls, mostly measured in fronto-central scalp regions (Table 1) (Baijot et al., 2017; Bozhilova et al., 2020; Gomarus et al., 2009; Groom et al., 2010; Keute et al., 2019; Khoshnoud et al., 2018; Leroy et al., 2018; Missonnier et al., 2013; Vainieri et al., 2020). Among other studies, five found no group differences in theta increases (Gomarus et al., 2009; Lenartowicz et al., 2019; Mazaheri et al., 2010, 2014; Michelini et al., 2018b) and two reported stronger theta increases during stimulus processing (Guo et al., 2020) and WM maintenance (Lenartowicz et al., 2014) in participants with ADHD compared to controls. One study reported a weaker occipital theta decrease during early stimulus processing together with a weaker theta increase during a later trial window (Khoshnoud et al., 2018). Finally, one study, in addition to finding a weaker fronto-central theta increase, also reported an atypical pattern of theta lateralization in the ADHD group (Guo et al., 2020).

Multi-level meta-analysis of studies with sufficient data or descriptive statistics showed a significant mean estimated effect size of $d = -0.25$ (Table 2), reflecting a small difference between ADHD and control groups (Cohen, 1988). This difference indicates a weaker theta increase in the ADHD group compared to the control group, as none of the effects included in the meta-analysis reflected a theta decrease. The Q statistic was significant (Table 2), indicating that the distribution of effect sizes was heterogeneous. Fig. 3 displays the forest plot for event-related theta power.

3.2.2. Event-related alpha power

The majority of studies of event-related alpha power (12 out of 21) reported a weaker parieto-occipital decrease following stimulus presentation in participants with ADHD compared to controls (Table 1) (Baijot et al., 2017; Bozhilova et al., 2020; Deiber et al., 2020; Hasler et al., 2016; Khoshnoud et al., 2018; Lenartowicz et al., 2014, 2019; Mazaheri et al., 2010, 2014; McAuliffe et al., 2020; Michelini et al., 2018b; Missonnier et al., 2013). Only two studies of alpha decrease did not find group differences (Gomarus et al., 2009; Vainieri et al., 2020). Results were more mixed across studies measuring alpha power increases. Three studies of WM tasks reported a greater increase in alpha power in ADHD participants during stimulus processing at frontal regions (Missonnier et al., 2013) and during maintenance at occipital regions (Lenartowicz et al., 2014, 2019), two studies showed reduced alpha increases (Leroy et al., 2018; Liu et al., 2016), and one study of central alpha (mu rhythm) showing no group differences (Yordanova et al., 2013). Furthermore, four studies reported atypical lateralization patterns of alpha power (Ellis et al., 2017; Guo et al., 2019; McAuliffe et al., 2020;Vollebregt et al., 2016).

Meta-analysis showed a significant overall mean estimated effect size of $d = 0.37$ for alpha power (Table 2), indicating a small-to-moderate difference between the ADHD and control groups (Cohen, 1988). When separating decreases and increases, effect sizes were $d = 0.44$ and $d = -0.06$, respectively, but only the former effect was statistically significant. These results indicate that modulations of alpha power, particularly power decreases over parieto-occipital regions, are attenuated in individuals with ADHD relative to controls. The Q statistic was significant in overall analyses, but not when examining increases and decreases separately, indicating that heterogeneity in overall effects is likely explained by mixing alpha increases and decreases. Fig. 4 displays the forest plot for event-related alpha power.

3.2.3. Event-related beta power

Similar to alpha, the majority of studies examining event-related beta power (5 out of 9) reported a weaker decrease in participants with ADHD relative to controls, especially over parieto-occipital scalp regions (Table 1) (Bozhilova et al., 2020; Hasler et al., 2016; Mazaheri et al., 2014; McAuliffe et al., 2020; Zammit and Muscat, 2019). Exceptions were studies reporting stronger beta decreases during processing of cues not requiring a response (Baijot et al., 2017; Leroy et al., 2018), reduced beta increases before target onset (Leroy et al., 2018) and in response to targets (Hasler et al., 2016), and non-significant group differences (Michelini et al., 2018b; Vainieri et al., 2020).

Beta power showed a significant overall mean estimated effect size of $d = 0.06$ (Table 2), suggesting a very small difference between individuals with and without ADHD (Cohen, 1988). Effects sizes for decreases and increases separately were $d = 0.14$ and $d = -0.33$, respectively, with the former not reaching statistical significance ($p = 0.06$; Table 2). This indicates that individuals with ADHD display a

Table 2

Summary of meta-analysis results, including overall effects, effects separating increases and decreases, effects by age group and task type, and effects in sensitivity analyses excluding certain studies.

	Theta							Alpha							Beta						
	k	d	95% CI	p (d)	Q	df	p (Q)	k	d	95% CI	p (d)	Q	df	p (Q)	k	d	95% CI	p (d)	Q	df	p (Q)
Overall effect	22	−0.25	−0.49; −0.01	**0.039**	42.22	21	**0.004**	442	0.37	0.18; 0.55	**<0.001**	529.20	441	**0.002**	429	0.06	0.02; 0.09	**<0.001**	704.64	428	**<0.001**
Power decrease	N/A	N/A	N/A	N/A	N/A	N/A	N/A	333	0.44	0.27; 0.61	**<0.001**	301.40	332	0.885	309	0.14	−0.01; 0.29	0.058	347.31	308	0.061
Power increase	22	−0.25	−0.49; −0.01	**0.039**	42.22	21	**0.004**	109	−0.06	−0.34; 0.23	0.686	76.49	108	0.991	120	−0.33	−0.36; −0.28	**<0.001**	109.43	119	0.724
Age																					
Child (<18 years) - overall effect	14	−0.21	−0.56; 0.13	0.228	34.82	13	**<0.001**	17	0.45	0.19; 0.71	**<0.001**	40.74	16	**<0.001**	3	−0.11	−0.28; 0.06	0.206	0.26	2	0.880
Adult (18+ years) - overall effect	12	−0.41	−0.59; −0.24	**<0.001**	14.21	11	0.221	429	0.22	−0.001; 0.45	0.054	488.19	428	**0.023**	428	0.06	0.02; 0.10	**0.002**	704.60	427	**<0.001**
Child (<18 years) - power decrease	N/A	N/A	N/A	N/A	N/A	N/A	N/A	13	0.46	0.20; 0.73	**<0.001**	39.49	12	**<0.001**	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Adult (18+ years) - power decrease	N/A	N/A	N/A	N/A	N/A	N/A	N/A	324	0.32	0.11; 0.52	**0.003**	275.59	323	**0.974**	308	0.15	0.01; 0.30	**0.049**	346.82	307	0.058
Child (<18 years) - power increase	14	−0.21	−0.56; 0.13	0.228	34.82	13	**<0.001**	4	0.32	0.05; 0.60	**0.023**	0.89	3	0.827	3	−0.11	−0.28; 0.06	0.206	0.26	2	0.880
Adult (18+ years) - power increase	12	−0.41	−0.59; −0.24	**<0.001**	14.21	11	0.221	105	−0.20	−0.26; −0.14	**<0.001**	62.63	104	1.000	120	−0.33	−0.38; −0.28	**<0.001**	109.43	119	0.724
Task type																					
Cognitive control - overall effect	12	−0.41	−0.59; −0.24	**<0.001**	14.21	11	0.221	427	0.36	0.15; 0.57	**<0.001**	481.65	426	0.032	422	0.06	0.02; 0.097	**0.001**	694.96	421	**<0.001**
Working memory - overall effect	2	0.28	−0.02; 0.59	0.071	1.60	1	0.206	6	0.37	−0.14; 0.88	0.154	21.93	5	**<0.001**	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Simple attention - overall effect	8	−0.43	−0.69; −0.17	**0.001**	8.03	7	0.330	8	0.20	−0.15; 0.54	0.261	9.79	7	0.201	6	−0.06	−0.17; 0.06	0.325	7.60	5	0.180
Cognitive control - power decrease	N/A	N/A	N/A	N/A	N/A	N/A	N/A	319	0.38	0.19; 0.58	**<0.001**	263.23	318	0.989	302	0.22	0.18; 0.25	**<0.001**	328.50	301	0.132
Working memory - power decrease	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Simple attention - power decrease	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8	0.20	−0.15; 0.54	0.261	9.79	7	0.201	6	−0.06	−0.17; 0.06	0.325	7.60	5	0.180
Cognitive control - power increase	12	−0.41	−0.59; −0.24	**<0.001**	14.21	11	0.221	108	0.03	−0.34; 0.39	0.889	76.15	107	0.989	120	−0.33	−0.38; −0.28	**<0.001**	109.43	119	0.724
Working memory - power increase	2	0.28	−0.02; 0.59	0.071	1.60	1	0.206	6	0.37	−0.14; 0.88	0.154	21.93	5	**<0.001**	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Simple attention - power increase	8	−0.43	−0.69; −0.17	**0.001**	8.03	7	0.330	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Sensitivity analyses																					
Overall effect	14	−0.15	−0.46; 0.16	0.343	35.93	13	**<0.001**	435	0.36	0.14; 0.58	**0.001**	519.84	434	**0.003**	428	0.06	0.02; 0.10	**0.002**	704.60	427	**<0.001**
Power decrease	N/A	N/A	N/A	N/A	N/A	N/A	N/A	330	0.43	0.24; 0.63	**<0.001**	296.59	329	0.900	308	0.15	0.01; 0.30	**0.049**	346.82	307	0.058
Power increase	14	−0.15	−0.46; 0.16	0.343	35.93	13	**<0.001**	105	−0.20	−0.26; −0.14	**0.001**	62.63	104	1.000	120	−0.33	−0.38; −0.28	**0.001**	109.43	119	0.724

Abbreviations: CI, confidence interval; d, Cohen's d effect size; df, degrees of freedom from Q-test; k, number of effects included in analysis; N/A, not available due to lack of relevant studies; p (d), *p* value of Cohen's d; p (Q), p value of Q-test; Q, Q statistic from Q-test of heterogeneity.

Note: Bold denotes significant *p* values. A negative Cohen's d indicates a stronger decrease or a weaker increase in the ADHD group compared to the control group, whereas a positive Cohen's d indicates a weaker decrease or a stronger increase in the ADHD group compared to the control group.

weaker increase in beta power, with a small-to-moderate effect size, and potentially also a weaker decrease, albeit with a very small effect size. The Q statistic was significant for the overall effect size, but it did not reach significance in the analysis separating between increases and decreases (Table 2), similar to the pattern observed for alpha. Fig. 5 displays the forest plot for event-related beta power.

3.3. *Subgroup analyses*

3.3.1. *Child and adult samples*

The majority of studies of children (<18 years) showed significant differences in event-related theta modulations (Table 1). Specifically, five studies reported weaker increases (Baijot et al., 2017; Groom et al., 2010; Keute et al., 2019; Khoshnoud et al., 2018; Vainieri et al., 2020), one study showed a stronger increase (Lenartowicz et al., 2014), one study showed a weaker decrease (Khoshnoud et al., 2018), and three studies reported no group differences (Lenartowicz et al., 2019; Mazaheri et al., 2010, 2014). In adults (18+ years), three available studies, including two of relatively large samples, showed significantly attenuated theta increases in ADHD participants compared to controls (Bozhilova et al., 2020; Leroy et al., 2018; Vainieri et al., 2020), with only one study reporting no significant differences (Michelini et al., 2018b).

Studies of children examining event-related alpha modulations consistently showed differences between ADHD and control groups (Table 1), particularly in the form of weaker alpha decreases (Baijot et al., 2017; Khoshnoud et al., 2018; Lenartowicz et al., 2014, 2019; Mazaheri et al., 2010, 2014). Other reported findings in children were increased alpha increases during WM maintenance (Lenartowicz et al., 2014, 2019), atypical alpha lateralization (Ellis et al., 2017; McAuliffe et al., 2020; Vollebregt et al., 2016), and no difference in parieto-occipital alpha decreases (Vainieri et al., 2020) and central alpha (Yordanova et al., 2013). Adult ADHD studies similarly showed consistently weaker modulations of alpha power, either lower decreases (Bozhilova et al., 2020; Deiber et al., 2020; Hasler et al., 2016; Michelini et al., 2018b; Missonnier et al., 2013) or lower increases (Leroy et al., 2018; Liu et al., 2016), except for one study showing no group differences (Vainieri et al., 2020).

With regard to beta power, children with ADHD showed significantly weaker beta decreases compared to control children in three studies (Mazaheri et al., 2014; McAuliffe et al., 2020; Zammit and Muscat, 2019), a significantly stronger decrease in one study (Baijot et al., 2017), and no differences in the study with the largest sample (Vainieri et al., 2020) (Table 1). In studies of adults, beta decreases was weaker in two studies (Bozhilova et al., 2020; Hasler et al., 2016), including one with a relatively large sample (Table 1), stronger in one study (Leroy et al., 2018), and did not show a group difference in two studies (Michelini et al., 2018b; Vainieri et al., 2020).

Meta-analyses of studies of children and adults with available data or descriptive statistics showed non-significant group differences in event-related theta and beta power in children and alpha power in adults, unlike results of main analyses (Table 2).

3.3.2. *Task type*

Among studies of cognitive control tasks (Table 1), three studies examining theta power reported weaker theta increases in individuals with ADHD compared to controls (Baijot et al., 2017; Bozhilova et al., 2020; Groom et al., 2010), whereas two did not find group differences (Mazaheri et al., 2010, 2014). Three of the studies examining theta during working memory tasks found significant differences – specifically, a stronger theta increase during maintenance (Lenartowicz et al., 2014), a weaker theta decrease (Khoshnoud et al., 2018) and a weaker theta increase during stimulus-processing (Khoshnoud et al., 2018; Missonnier et al., 2013). Other available studies did not find significant effects (Gomarus et al., 2009; Lenartowicz et al., 2019). Of the studies investigating theta power during simple attention tasks, two reported significant reduction in theta increases in individuals with ADHD (Leroy et al., 2018; Vainieri et al., 2020), whereas the remaining studies found stronger theta increases and atypical theta lateralization (Guo et al., 2020), as well as non-significant group differences (Michelini et al., 2018b).

All studies that included alpha power measures during cognitive control tasks found significant differences between ADHD and control groups (Table 1), which in six studies reflected a weaker alpha decrease in individuals with ADHD (Baijot et al., 2017; Bozhilova et al., 2020; Deiber et al., 2020; Hasler et al., 2016; Mazaheri et al., 2010, 2014) and in one study an atypical lateralization pattern (frontal alpha asymmetry) (Ellis et al., 2017). With regard to WM studies, the majority of studies found a weaker alpha decrease in ADHD groups, especially during WM encoding (Khoshnoud et al., 2018; Lenartowicz et al., 2014, 2019; Missonnier et al., 2013). However, stronger increases (e.g., during WM maintenance) (Lenartowicz et al., 2014, 2019; Missonnier et al., 2013) and no group differences (Gomarus et al., 2009) were also reported. In simple attention paradigms, results appeared less consistent, with one study showing a significantly weaker decrease in individuals with ADHD relative to controls (Michelini et al., 2018b), two studies showing atypical lateralization in alpha power (Guo et al., 2019; Vollebregt et al., 2016), and two studies reporting no group differences (Vainieri et al., 2020; Yordanova et al., 2013).

For beta power during cognitive control tasks, three studies reported a significant reduction in beta decreases in ADHD compared to control groups (Bozhilova et al., 2020; Hasler et al., 2016; Mazaheri et al., 2014), but stronger beta decreases (Baijot et al., 2017) and increases (Hasler et al., 2016) in ADHD have also been reported. The only study that examined event-related beta power during a working memory task found weaker beta decreases in individuals with ADHD compared to controls (Zammit and Muscat, 2019). Similar to studies of alpha power during simple attention tasks, results for beta showed a mixed pattern, with one study reporting both stronger increases and weaker decreases

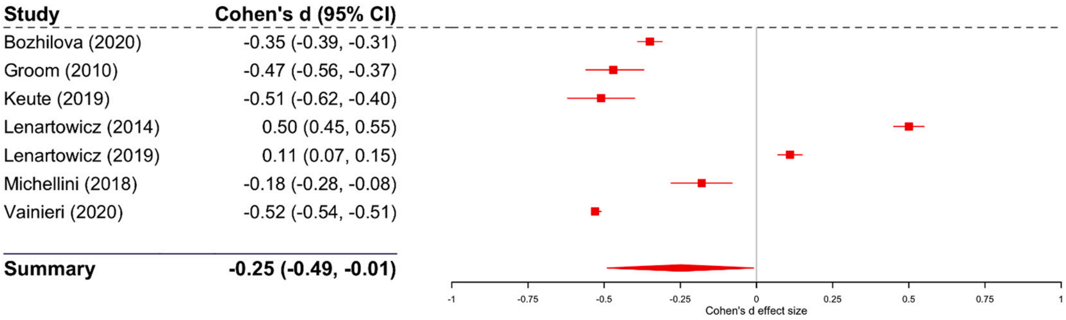
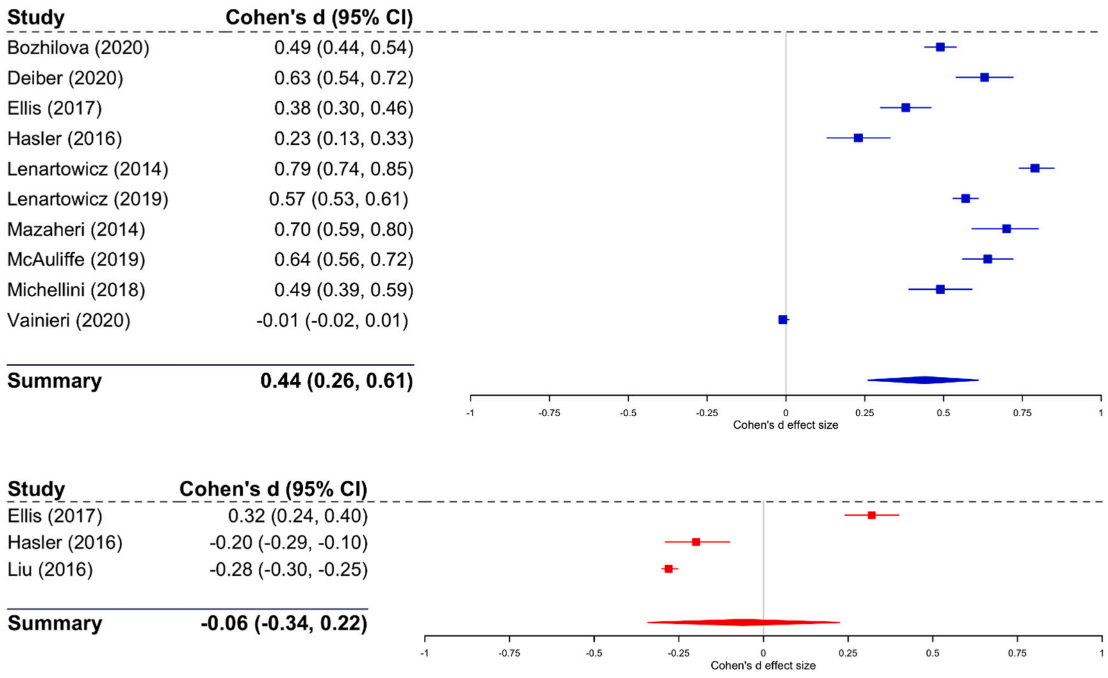


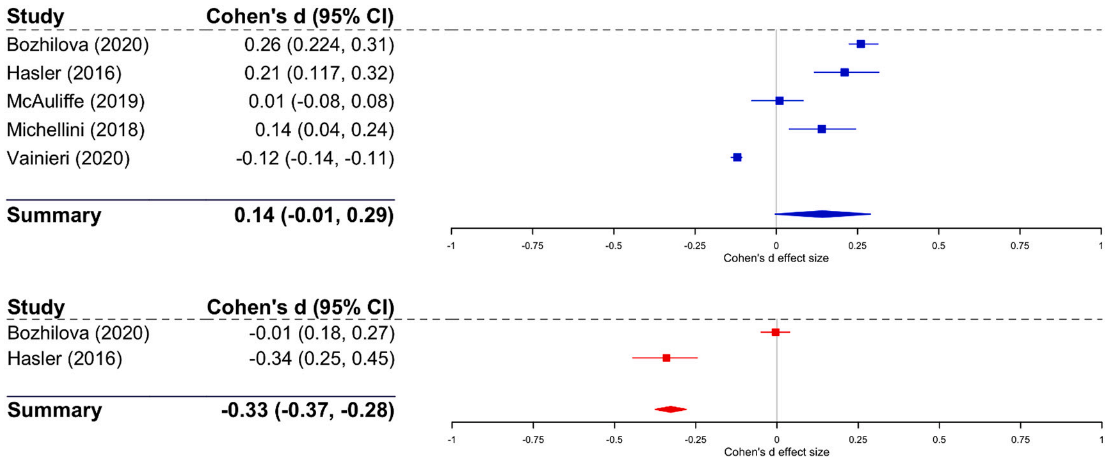
Fig. 3. Forest plot for studies reporting event-related theta power increases. Note: for studies providing more than one effect size, the mean effect was plotted. The 95% confidence interval (CI) around the effect size represents the average precision of the effect within each study. Theta power decreases were not analyzed as all studies included in the meta-analysis investigated power increases.



Study	Cohen's d (95% CI)
Bozhilova (2020)	0.49 (0.44, 0.54)
Deiber (2020)	0.63 (0.54, 0.72)
Ellis (2017)	0.38 (0.30, 0.46)
Hasler (2016)	0.23 (0.13, 0.33)
Lenartowicz (2014)	0.79 (0.74, 0.85)
Lenartowicz (2019)	0.57 (0.53, 0.61)
Mazaheri (2014)	0.70 (0.59, 0.80)
McAuliffe (2019)	0.64 (0.56, 0.72)
Michellini (2018)	0.49 (0.39, 0.59)
Vainieri (2020)	-0.01 (-0.02, 0.01)
Summary	**0.44 (0.26, 0.61)**

Study	Cohen's d (95% CI)
Ellis (2017)	0.32 (0.24, 0.40)
Hasler (2016)	-0.20 (-0.29, -0.10)
Liu (2016)	-0.28 (-0.30, -0.25)
Summary	**-0.06 (-0.34, 0.22)**

Fig. 4. Forest plot for studies reporting event-related alpha power decreases (top) and increases (bottom). Note: for studies providing more than one effect size, the mean effect was plotted. Since Mazaheri et al. (2014) included combined type and inattentive type ADHD groups of equal size, the effects of alpha decrease for these groups were also averaged. The 95% confidence interval (CI) around the effect size represents the average precision of the effect within each study.



Study	Cohen's d (95% CI)
Bozhilova (2020)	0.26 (0.224, 0.31)
Hasler (2016)	0.21 (0.117, 0.32)
McAuliffe (2019)	0.01 (-0.08, 0.08)
Michellini (2018)	0.14 (0.04, 0.24)
Vainieri (2020)	-0.12 (-0.14, -0.11)
Summary	**0.14 (-0.01, 0.29)**

Study	Cohen's d (95% CI)
Bozhilova (2020)	-0.01 (0.18, 0.27)
Hasler (2016)	-0.34 (0.25, 0.45)
Summary	**-0.33 (-0.37, -0.28)**

Fig. 5. Forest plot for studies reporting event-related beta power decreases (top) and increases (bottom). Note: for studies measuring more than one effect size, the mean effect was plotted. The 95% confidence interval (CI) around the effect size represents the average precision of the effect within each study.

(Leroy et al., 2018) and two studies showing no group differences (Michelini et al., 2018b; Vainieri et al., 2020).

Results of meta-analysis by task type showed significant effects across frequency bands for studies using cognitive control tasks, including for beta power decrease, which did not reach statistical significance in main analyses ($p = 0.06$; Table 2). Group differences in theta and alpha power increases were not significant in WM studies, and alpha and beta decreases were not significant in simple attention tasks, unlike in main analyses (Table 2).

3.4. Sensitivity analyses

Differences in theta power increases showed a smaller effect and were no longer significant when removing studies of response-locked theta power modulations (Groom et al., 2010; Keute et al., 2019), suggesting that these studies had a key contribution to mean group differences in main analyses (Table 2). Conversely, unlike in main analyses, effect sizes for alpha increases and beta decreases were significant after removing two studies reporting atypical patterns of lateralization (Ellis et al., 2017; McAuliffe et al., 2020). These results indicate weaker alpha increases and weaker beta decreases in the ADHD group compared to the control group when these studies are removed and only studies testing group differences in post-stimulus power relative to pre-stimulus power are considered.

4. Discussion

4.1. Summary and future directions

In the current systematic review and meta-analysis, we identified significant group-level differences between ADHD and neurotypical groups on event-related modulations captured through time-frequency

EEG analyses. These findings indicate broad brain-oscillatory alterations in individuals with ADHD, generally evidenced by weaker decreases (alpha) or increases (theta and beta), during a range of stimulus-related neurocognitive functions. Effects sizes were small-to-moderate for alpha decrease and beta increase, and small for theta increase, suggesting that event-related alpha and beta power measures may be stronger indicators of neurocognitive alterations in ADHD samples.

Despite the presence of some inconsistent findings in the literature, highlighted in our qualitative synthesis, our analyses of statistical heterogeneity found that effects were statistically homogeneous across studies for alpha decreases and beta increases. This suggests that the instances of inconsistent findings in alpha and beta power may be attributed to small sample sizes used in most studies included in the meta-analysis, which can increase sampling error (Higgins and Thompson, 2002; Marek et al., 2020), rather than by actual group differences in outcomes. Significant heterogeneity was found for theta increases, however, which points to study characteristics contributing to differences in the literature. This evidence of statistical heterogeneity in theta power is consistent with the high clinical heterogeneity that characterizes ADHD, which is thought to reflect the presence of multiple subgroups with partly different neurocognitive profiles (Lenartowicz et al., 2014; Nigg et al., 2020). A promising direction for future studies will be to examine whether distinct event-related power profiles may be used to reliably identify subpopulations of individuals with ADHD with different clinical presentations. Congruently, our additional analyses examining the effect of key study characteristics on meta-analysis findings provides initial evidence of differences between studies of children and adults, especially for theta and beta power. With respect to task type, effects were significant across frequency bands in tasks probing cognitive control, but less consistent with results of main analyses for studies of WM and simple attention, suggesting that atypical event-related power in ADHD may be more reliably detected in cognitive control paradigms. Alternatively, this pattern may be explained by the inclusion of a greater number of studies using cognitive control tasks relative to studies of WM or simple attention.

Taken together, our systematic review and meta-analysis highlight the progress made in event-related EEG power research in ADHD since publication of the first study two decades ago (Yordanova et al., 2001). Our meta-analytic results clarify inconsistent findings in the available literature and show that differences between individuals with and without ADHD are particularly robust for alpha power decreases and beta power increases, in line with broad alterations in attentional and motor processes often implicated in the disorder (Castellanos and Proal, 2012; Hirjak et al., 2018; Michelini et al., 2018a). Three major areas of uncertainty remain, due to a paucity of relevant studies, which will require future research. First, whereas several studies investigated modulations of alpha power in ADHD samples, further research is needed on other frequency bands, especially in the delta and gamma range. Second, most of the available studies were conducted during cognitive tasks, mainly probing higher-level cognitive functions, thus we know very little about power modulations during socio-affective or reward processes in ADHD. Finally, the majority of studies were conducted in samples of school-age children, adolescents and young adults, but it is unclear whether atypical event-related power dynamics characterize younger children at risk for ADHD as well as older adults.

4.2. Implications for neurocognitive models of ADHD

Atypical profiles in time-frequency measures underpinning a wide range of neurocognitive functions in ADHD, albeit of modest sizes, are consistent with modern theoretical models and large-scale studies that implicate multiple neurocognitive factors and putative causal pathways in the disorder (Castellanos and Proal, 2012; Franke et al., 2018; Halperin and Schulz, 2006; Michelini et al., 2018a; Mostert et al., 2015). More generally, these findings are in line with views that “true” brain-behavior relationships in neuropsychiatric populations are likely to be small (Marek et al., 2020; Paulus and Thompson, 2019) and with research approaches emphasizing integration across multiple levels of analysis to identify the numerous mechanisms underlying mental health conditions, such as the RDoC framework (Cuthbert, 2014). A promising direction for future research is the investigation of how atypical task-based event-related power modulations in ADHD map onto other measures of brain activity and behavioral performance. For example, future studies may examine the association between time-frequency and resting-state spectral power profiles in ADHD samples, extending initial evidence of associations between resting-state and task-based EEG measures in non-clinical populations (Karamacoska et al., 2018, 2019; Tenke et al., 2015).

These small and small-to-medium average effects, rather than discouraging researchers from pursuing studies of EEG time-frequency measures in ADHD, should stimulate new research into the neural mechanisms underlying the identified alterations in event-related power. Time-frequency metrics are advantageous for studying the fast-changing neurocognitive processes implicated in ADHD, as they can capture sub-second brain dynamics of inhibition and activation time-locked to specific stimuli (Loo et al., 2015). They also show high reliability estimates and can typically be reliably computed with fewer trials than ERPs (Lenartowicz et al., 2019). When coupled with source localization techniques, like in a few studies included in our review (Ellis et al., 2017; Khoshnoud et al., 2018; Lenartowicz et al., 2014, 2019), or with concurrent functional magnetic resonance imaging (Lenartowicz et al., 2016), EEG time-frequency approaches can further characterize these dynamics with more precise spatial resolution (Loo et al., 2015). For example, a recent review has suggested three putative pathways underlying occipital alpha decreases during stimulus processing (Lenartowicz et al., 2018), one of the most consistent alterations in ADHD in the current meta-analysis: bidirectional interactions between occipital cortex and thalamus, frontoparietal interactions exerting top-down effects over occipital activities via the thalamus, or directly via the superior longitudinal fasciculus. These possible pathways define mechanistic targets for research to advance our understanding of ADHD symptoms (Lenartowicz et al., 2018).

Additionally, future research should focus on developing new tasks that are particularly sensitive to atypical event-related modulations in those with ADHD and thus maximize case-control differences. Since we found that differences between ADHD and control groups are particularly consistent during cognitive control tasks, in line with a recent review linking a range of cognitive control processes with ADHD symptoms (Michelini et al., 2021), refining these paradigms would be particularly promising.

4.3. Clinical implications

An implication of these findings is that these group-level differences may have limited utility as biomarkers for ADHD at the individual level. Future research is required to translate these significant effects into robust targets for precision medicine and personalized treatment applications in ADHD. For example, future studies should not just focus on differences in diagnostic status (ADHD vs. non-ADHD), but also on continuous clinical profiles of severity in ADHD symptoms, in order to characterize associations with specific clinical aspects of the disorder (Lenartowicz et al., 2019; Vainieri et al., 2020). Similarly, it would be important to examine whether the identified event-related power dynamics are associated with symptoms of other psychiatric disorders characterized by deficits in attention, memory, and cognitive control, in line with transdiagnostic approaches to psychopathology such as RDoC (Cuthbert, 2014; Michelini et al., 2021). For example, initial evidence indicates that mood disorders may be associated with similar alterations of event-related brain oscillations (Knyazev et al., 2016; Michelini et al., 2018b). This research may help identify atypical event-related power modulations specific to ADHD which, in the future, could be targeted through personalized treatment and used for monitoring of treatment efficacy (Leuchter et al., 2009; Loo et al., 2015).

4.4. Limitations

The following limitations should be considered. First, since our meta-analysis was conducted on a limited number of studies, results should be interpreted with caution. Although this is the first systematic review and meta-analysis of time-frequency findings in ADHD samples, future work will be required to synthesize new findings as they accumulate in this relatively young research area. Second, the Q-test has low power when studies have small sample sizes or are few in number (Higgins and Thompson, 2002). As a consequence, we cannot rule out the possibility that some heterogeneity exists for effects sizes showing a non-significant Q value. Third, due to the limited number of studies, many of which were based on small samples, our synthesis of effects by age group and task type are exploratory and provide an initial attempt to parse the heterogeneity between study findings, focused on two key study characteristics. These suggestive patterns should be followed up in future larger meta-analyses with moderator analyses formally examining these and other study characteristics (e.g., IQ, comorbidities, medication) that may influence differences between ADHD and neurotypical groups.

5. Conclusions

In this first systematic review and meta-analysis of event-related brain oscillatory patterns in ADHD samples, we provided a qualitative and quantitative synthesis of the current state of the science and indicated a number of promising directions for future research. The significant, albeit modest, differences between individuals with and without ADHD in theta, alpha, and beta oscillations point to broadly reduced modulations of power in response to task events during a variety of tasks and across samples of both children and adults. Further research is needed to link the identified EEG profiles with continuous symptom severity and with treatment effects, which may pave the way toward future translational applications of event-related brain-oscillatory measures in individuals with ADHD.

Declaration of competing interest

None.

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Appendix A. Supplementary data

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[1] * denotes studies included in the systematic review

[2] ** denotes studies included in the systematic review and meta-analysis

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