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RESEARCH ARTICLE

Self-regulation and frontal EEG alpha activity during infancy and early childhood: A multilevel meta-analysis

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Abstract

Integrating behavioral and neurophysiological measures has created new and advanced ways to understand the development of self-regulation. Electroencephalography (EEG) has been used to examine how self-regulatory processes are related to frontal alpha power during infancy and early childhood. However, findings across previous studies have been inconsistent. To address this issue, the current meta-analysis synthesized all prior literature examining associations between individual differences in self-regulation and frontal EEG alpha power (baseline and/or task). In total, 23 studies consisting of 1275 participants between 1 month and 6 years of age were included, which yielded 149 effect sizes. Findings of the three-level meta-analytic model demonstrated a non-significant overall association between self-regulation and frontal alpha power. Yet, significant moderating effects were found for self-regulation construct (emotion regulation, effortful control, executive function), self-regulation measurement (behavioral task, computer assessment, lab observation, questionnaire), and children's mean age. Self-regulation was only significantly correlated with frontal alpha power when studies focused on the executive functioning construct. Moreover, the use of behavioral tasks or questionnaires and a higher mean age of the children resulted in small but significant effect size estimates. Higher frontal alpha power values were related to higher order top-down mechanisms of self-regulation, indicating that these mechanisms might become stronger when the frontal cortex is sufficiently developed. The findings of the current meta-analysis highlight the importance of longitudinal analyses and multimethod approaches in future work to reach a more comprehensive understanding of the role of frontal EEG alpha activity in the etiology of individual differences in early self-regulation.

KEYWORDS
alpha rhythm, early childhood, EEG, frontal cortex, meta-analysis, self-regulation

Research Highlights

- The first meta-analysis of individual differences in self-regulation and frontal EEG alpha power during infancy and early childhood demonstrated a non-significant overall association.
- Moderation analyses revealed that variations in frontal alpha power were significantly associated with executive function, but not with effortful control and emotion regulation.
- Frontal alpha power was related to variations in self-regulation when measured by behavioral tasks and questionnaires, but not via computer assessments and lab observations.
- The association between individual differences in self-regulation and frontal alpha power becomes significantly stronger with age.

1 | INTRODUCTION

Before the initial step into a kindergarten classroom, children already live in dynamic social contexts that require them to regulate their emotions, thoughts, and behaviors in accordance with the situation (i.e., self-regulation; Karoly, 1993). For example, children need to adapt their eating and sleeping patterns to family routines, including sharing food with siblings although they would like to keep this for themselves and inhibiting doing something desirable in order to get ready for bed (Brownell, 2016). The development of self-regulatory skills is crucial for positive child outcomes, such as academic achievement and social competence (Blair & Raver, 2015; Moffitt et al., 2011). Understanding and promoting the development of self-regulation during the first years of life is therefore of crucial importance (Vink et al., 2020).

Individual differences in the development of self-regulation are linked to biopsychosocial factors, including frontal cortical development and environmental experiences (Calkins et al., 2016). In the current meta-analysis, we focus on the potential role of neural indices, specifically that of the frontal EEG alpha rhythm, in variability in emerging self-regulatory skills during infancy and early childhood. In the following sections, we synthesize the existing literature, considering potential moderators of brain-behavior associations that encompass various self-regulatory theoretical constructs (i.e., emotion regulation, effortful control, executive functioning) and methods of neural and behavioral assessment.

1.1 | Frontal EEG alpha rhythm

Neuroimaging research has revealed that the frontal cortex plays a central role in the development of self-regulation (for reviews, see Bhavnani et al., 2021; Fiske & Holmboe, 2019). Interconnections between the frontal cortex and other cortical and subcortical areas, such as regions representing the reward, salience, and emotional value of a stimulus, serve to coordinate goal-directed and self-regulatory behaviors (Heatherton & Wagner, 2011; Johnson, 2000). Electroencephalography (EEG) is a widely used method to examine the potential role of neural indices in emerging self-regulatory processes, typically with a focus on recordings from frontal scalp sites (Cuevas & Bell, 2022). The EEG signal consists of multiple oscillatory rhythms, with the 6–9 Hz "alpha" rhythm being the primary frequency band investigated by most waking EEG research with infants and young children. Previous studies revealed that young children engaged in self-regulatory processes exhibit changes in frontal alpha power (oscillatory amplitude) and frontal alpha functional connectivity (statistical interdependencies across scalp sites), which reflect neural activity and communication between brain regions, respectively (e.g., Cuevas et al., 2012; Swingler et al., 2011). Furthermore, within-subjects analyses indicate that frontal alpha measures vary as a function of task demands (i.e., increases in regulatory processes) and exhibit distinct patterns of activity preceding successful as compared to unsuccessful self-regulation (e.g., Broomell & Bell, 2017; Cuevas et al., 2012).

However, research on direct links between self-regulation and frontal alpha measures have yielded mixed results. Whereas some studies found a positive association between self-regulation and frontal alpha power in young children (e.g., Bell, 2001; Perone et al., 2018), others failed to find such associations (e.g., Perone & Gartstein, 2019; Swingler et al., 2011). Moreover, even within the same study, findings revealed both positive and negative associations with measures of frontal alpha functional connectivity as a function of neural regions of interest (Swingler et al., 2011). As a result, general conclusions about the association between individual differences in self-regulation and frontal alpha activity in early childhood and potential factors that affect this association are still lacking.

One challenge for the developmental EEG literature is a lack of theory as to what specific cortical rhythms are reflecting. Rather, the focus has been primarily on the functional properties and behavioral correlates of EEG measures within specific frequency bands. The frequency range of the 6–9 Hz infant/child "alpha" band, for example, overlaps both the adult theta (4–7 Hz) and alpha (8–13 Hz) bands; in some contexts, the infant/child 6–9 Hz rhythm exhibits properties similar to the adult theta rhythm (see Cuevas & Bell, 2022, for review). In the adult literature, alpha oscillations have been proposed to serve as mechanisms of cognitive control deployed to modulate processing in other cortical and subcortical regions (Sadaghiani & Kleinschmidt, 2016). According to the inhibition timing hypothesis, higher alpha power reflects inhibitory processes, such as blocking task-irrelevant information (for a review, see Klimesch et al., 2007). In line with anticipated age-related increases in oscillatory power in mid-frequency rhythms, higher alpha power values are considered markers of brain maturation from infancy into early childhood (Bell & Fox, 1994; Marshall et al., 2002).

The first aim of the current study was to synthesize the findings of previous studies examining the association between variations in self-regulation and frontal alpha activity during infancy and early childhood. This was an attempt to organize existing literature and enhance the understanding of the alpha cortical rhythm and its links to individual differences in self-regulation. Mixed findings in the extant literature might be related to various factors, such as differences in self-regulation conceptualization and measurement, frontal EEG measurement, sample characteristics, and study characteristics. Thus, the second aim of the current study was to identify potential factors that moderate the association between self-regulation and frontal alpha activity.

1.2 | Self-regulation conceptualization and measurement

The strength of the association between self-regulation and frontal alpha activity may differ as a function of how self-regulation is conceptualized and operationalized. Self-regulation is studied from multiple disciplines, using different terms that are all subsumed under the broad concept of self-regulation (e.g., emotion regulation, effortful control, executive functioning, Nigg, 2017). According to theoretical models of temperament, early emerging biologically-based tendencies toward emotional and motor reactivity during infancy are followed by the development of alerting and orienting aspects of attention and later the ability to control behavior and attention (Posner & Rothbart, 2000; Rothbart & Derryberry, 1981).

The regulation of emotions is an important emerging capacity of infants (Rothbart et al., 2011). Emotion regulation is a broad construct that refers to any external or internal process that includes the modulation of one or more aspects of an effective response (Gross, 2014). During infancy, a considerable amount of emotion regulation occurs through the efforts of external regulators. For instance, caregivers' capacity to comfort infants when they express negative emotions provide external regulation for children who cannot yet fully regulate emotions themselves (Bernier et al., 2010; Lobo & Lunkenheimer, 2020). Following the theoretical framework of Nigg (2017), these extrinsic regulatory processes can work via both reactive bottom-up processes and top-down intrinsic processes. With age, the interaction between external and internal factors lead children to recruit their own internal resources to participate in the process of regulating emotions themselves through top-down regulatory processes (Eisenberg et al., 2004; Kopp, 1982).

According to the temperament developmental framework, the shift from more reactive bottom-up processes to more top-down regulatory processes is accompanied by the development of temperament control mechanisms, such as effortful control (Rothbart et al., 2003). Effortful control is a temperamentally-based self-regulation construct, defined as the ability to suppress a dominant response in order to perform a subdominant response (Rothbart & Derryberry, 1981). Although effortful control regulates emotional responses, it also involves the regulation of behavior and cognition (Nigg, 2017). More specifically, effortful control includes the abilities to shift and focus attention as needed, to inhibit and monitor inappropriate behavior, and to perform an action when there is a strong tendency to avoid it (Rothbart et al., 2003).

Closely related to the developing processes of emotion regulation and effortful control is executive functioning. Executive functioning has frequently been defined as a set of top-down neurocognitive processes to engage, direct, or coordinate other (bottom-up) cognitive processes (Perone et al., 2018; Zelazo, 2015). Often this is specified in three subcomponents; the ability to shift between tasks or mental sets, updating and monitoring of working memory representations, and the inhibition of dominant or prepotent responses, such as controlling impulses and delaying gratification (e.g., Miyake et al., 2000). More recently, Doebel (2020) proposed a novel view of executive function as a unitary construct, defined as control of behavior in the service of particular goals. According to Perone et al. (2021), these goal-directed behaviors emerge from multiple, interactive components, such as reciprocal interactions between goal-related (or top-down) information and knowledge. To date, there are diverse opinions regarding the conceptual differences and similarities between the various constructs of self-regulation (Bridgett et al., 2013; Zhou et al., 2012). Therefore, the current meta-analysis examined whether self-regulation construct moderates the association between individual differences in self-regulation and frontal alpha activity.

At the same time, developmental investigations of emotion regulation, effortful control, and executive function often use different kinds of behavioral assessments. The type of measurement might impact the magnitude of associations between variability in self-regulation and frontal alpha activity. For instance, to examine the early developing processes of self-regulation, lab observations are often used to assess infants' reactions to specific situations. During lab observations, children are often seated in a room with their caregiver or external stimuli and children's behaviors are coded afterwards based on video recordings. Examples include attentional capture by salient stimuli (Perry et al., 2016) or observation of infant's self-regulatory abilities when mothers were relatively unavailable to them (Dawson et al., 1999). Furthermore, frequently used parent-reported questionnaires during infancy often include more general self-regulatory factors, such as soothability (e.g., reduction in distress by parental intervention) and cuddliness (e.g., expression of enjoyment while being held by a caregiver), that represent important external regulation processes by which infants use a caregiver to regulate themselves (Gartstein & Rothbart, 2003).

In contrast, executive functions have been measured mainly through direct assessments of self-regulatory behaviors, such as performance based tasks. Many of the common tasks in young children (e.g., dimensional change card sort test: DCCS; Zelazo, 2006) are adaptations of adult measures of executive functioning (e.g., Wisconsin card sorting test; Milner, 1963), that have typically been used as neuropsychological assessments of frontal function (Müller & Kerns, 2015). Most performance based tasks involve face-to-face interaction and test administration, such as following rules of the experimenter to guide children's sorting behavior (e.g., sort by shape). These type of tasks are defined as behavioral tasks in the current meta-analysis. However, there are also some computerized assessment tools in which similar tasks are performed on a tablet or computer, such as the Minnesota Executive Function Scale (Carlson & Zelazo, 2014). It is unclear whether the experimenter observing and communicating with the child in behavioral versus computerized self-regulatory assessments might be an important factor in brain-behavior associations. To examine whether the type of measure of self-regulation conditions the association between self-regulation and frontal alpha activity, self-regulation measurement was included as a moderator in the current meta-analysis.

1.3 | Frontal EEG measurement

The strength of the association between self-regulation and frontal alpha measures may also be affected by differences in the EEG acquisition context. One common technique is obtaining a baseline (or resting-state) EEG recording when children are awake, calm, and not completing an assigned task (see Anderson & Perone, 2018, for review). A variety of procedures (e.g., video clips, live events, bubble blowing) have been used to obtain baseline EEG recordings during infancy and early childhood. In general, baseline measures are conceptualized as providing information about the functional organization of the brain as well as the array of processes that can be supported (Deco et al., 2013). Developmental analyses of baseline EEG reveal increases in oscillatory alpha power from infancy to early childhood (Marshall et al., 2002), with higher baseline alpha power values often interpreted in terms of greater brain maturation (e.g., Bell & Fox, 1992; Wolfe & Bell, 2004). More recent conceptualizations of baseline recordings propose that young children might engage cognitive and affective processes while behaviorally adapting to the open task environment (e.g., inhibiting movement, visually attend to stimuli; Anderson & Perone, 2018; Camacho et al., 2020). Thus, the baseline EEG context could capture variations in self-regulatory processes measured in other contexts for a variety of reasons.

Traditionally, to investigate how brain activity changes during self-regulatory processes, baseline EEG is compared to task-related EEG. During task-related EEG, children perform a cognitive (or affective) task while brain activity is being recorded (Bell & Cuevas, 2012). Previous studies in young children revealed that higher levels of self-regulation are associated with increases in EEG alpha power from baseline to task at the frontal regions (Bell, 2001; Watson & Bell, 2013). However, contradictory findings have been found for EEG alpha power measured solely during a task, where lower frontal alpha power values were related to sustained attention in infants (Xie et al., 2018). In order to investigate whether the acquisition EEG context moderates the association between self-regulation and frontal alpha activity, the frontal EEG context was included as a moderator in the current meta-analysis.

EEG power is frequently grouped together into small clusters over regions of interest, including frontal pole (Fp1, Fp2), medial frontal (F3, F4), and lateral frontal (F7, F8) regions. Most of the developmental self-regulation EEG literature has focused on medial frontal scalp locations (e.g., Degnan et al., 2011; Lo et al., 2013). However, frontal pole and lateral frontal scalp locations are also often reported. Due to differences in detected activity of groups of neurons (Scrivener & Reader, 2022), it might be that the reported effect sizes differ systematically by the location of the frontal region electrode sites. Therefore, we sought to explore whether frontal scalp location moderates the association between self-regulation and frontal alpha activity.

1.4 | Children's age

The strength of the association between self-regulation and frontal alpha activity might also differ as a function age. The frontal cortex and its interconnections exhibit a protracted period of development within the first postnatal years marked with rapid changes in brain, behavior, and cognitive processes (Diamond, 2002). Neural oscillatory rhythms in the alpha range exhibit ontogenetic changes in peak frequency as well as increases in alpha EEG power (Marshall et al., 2002; Perone et al., 2018). At the same time, externally-regulated behaviors assemble into more advanced, cognitive forms of self-regulation (Kochanska et al., 2001; Kopp, 1982). Whereas at young ages children's capacity to self-regulate depends heavily on external regulation from their environment, at later ages, the frontal cortex likely plays a more central role in higher-order, cognitive forms of self-regulation (Blair & Ursache, 2011). Thus, we hypothesized that the association between self-regulation and frontal alpha activity would increase as a function of age.

2 | THE CURRENT META-ANALYSIS

In sum, there is a lack of a general conclusion about the association between individual differences in self-regulation and frontal alpha activity, especially during infancy and early childhood. The current meta-analysis extends previous work by synthesizing the results of previous studies, leading to higher statistical power and a more accurate estimation of the association between self-regulation and frontal alpha activity. Moreover, the current state of the field shows wide methodological variations, and the diversity in measurements of self-regulation and frontal brain electrical activity often raises confusion regarding which approach to use for what particular purpose (Anderson & Perone, 2018; McCoy, 2019). Integrating all available empirical information could lend insight into possible moderators as explanations for different findings, moving the field toward a set of best practices. Such a synthesis will also identify gaps in the literature, highlighting valuable areas of future inquiry. The goal of the current meta-analysis wa therefore to examine (1) whether individual differences in self-regulation are associated with frontal EEG alpha activity during infancy and early childhood, and (2) whether mixed findings in previous studies are related to differences in self-regulation conceptualization and measurement, frontal EEG measurement, children's age, and study characteristics.

3 | METHOD

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) checklist (Moher et al., 2009) was used as a guideline for the setup of the meta-analysis. The aims and plans of the meta-analysis were preregistered at PROSPERO (registration number: CRD42020158229) to enable transparency.

3.1 | Study selection

3.1.1 | Literature search

Relevant articles were gathered through a systematic search of articles available by April 19th, 2021 in the electronic databases *PubMed*, *PsychINFO*, *Web of Science* and *Medline*. Searches were limited to articles published (or available through online advance access) in English. Studies were identified by keywords containing variables concerning brain activity (i.e., power, functional connectivity), electroencephalogram (EEG), early childhood (i.e., child, baby, infant, toddler, pre-school) and self-regulation (i.e., emotion regulation, effortful control, executive functioning, compliance). Supplementary approaches to identifying other relevant studies included an additional search through the reference lists of the identified articles, relevant reviews and meta-analyses, and requesting researchers known for their work on EEG and child development. Furthermore, a call for relevant data was posted in the International Congress of Infant Studies and the Cognitive Development Society email list. Unpublished work, review articles, book chapters, dissertations, and conference abstracts were not included, as findings in these forums are often subsequently published in peer-reviewed journals. Moreover, concerns have been raised about the quality of unpublished studies, as they have not gone through peer review (Cook et al., 1993). Previous research has shown that meta-analyses that included unpublished studies were just as likely to find evidence for publication bias as those that did not (Ferguson & Brannick, 2012). After removing duplicates, the literature search resulted in 988 unique hits. Through the additional search through other sources, an additional seven articles were found (Figure 1).

3.1.2 | Inclusion criteria

The identified articles were screened on the titles, keywords, and abstracts for eligibility by the first author. If a study appeared to be relevant, or if the relevance of the study was uncertain, then full texts were screened. Of the 988 identified articles, 10% were randomly selected to be double-screened by the second author and the results of the two authors were compared. The interrater reliability yielded a high Kappa of .89. Disagreements were resolved through discussion, until consensus was reached.

Studies were eligible for the meta-analysis if they met all of the following selection criteria: studies had to (1) provide data on the association between self-regulation and frontal EEG activity, (2) examine continuous brain activity via EEG power or functional connectivity analyses[1], (3) report measures of the alpha frequency band, (4) include samples of infants and children between birth and 6 years of age, (5) include a community sample, (6) contain sufficient information for the calculation of effect sizes, or sufficient information had to be available after contacting the authors, and (7) be published in an English language peer-reviewed journal. Clinical samples may yield other effects from what would be expected in a community sample, both in self-regulation and frontal alpha activity (e.g., Manian & Bornstein, 2009; Marshall et al., 2008). Hence, studies using a partly clinical sample were only included when data of the non-clinical part of the sample were available. Studies could be either cross-sectional or longitudinal and there were no restrictions on publication date or country of origin.

After the application of the inclusion and exclusion criteria, 23 articles appeared eligible for inclusion in the meta-analysis focusing on frontal alpha power. Only five frontal alpha functional connectivity articles were eligible, including studies with overlapping samples (e.g., Cuevas et al., 2012; Whedon et al., 2016). A very small number of studies may result in underestimated standard errors and an increase in the number of type 1 errors in testing the overall effect size and the moderator effects (Van den Noortgate & Onghena, 2003; Viechtbauer, 2005). Since conclusions based on this limited number of studies could be misleading, studies focusing on functional connectivity analyses were excluded and the multilevel meta-analysis only included 23 frontal alpha power studies.

3.2 | Moderators and effect size coding procedure

Following Lipsey and Wilson (2001), each study was coded by the first author with a detailed coding scheme where moderators were organized in self-regulation conceptualization and measurement, frontal EEG measurement, children's age, and study characteristics. A subset of 25% of the studies was double coded by the second author and responses of the two coders were compared. The intercoder reliabilities were high, with Kappa = .87 for the categorical variables and ICC = .99 (range .98–.99) for the continuous variables, indicating almost complete agreement (Landis & Koch, 1977). Inconsistent responses were resolved by in-depth reading and discussion, until consensus was reached.

3.2.1 | Self-regulation conceptualization and measurement

The self-regulation construct was coded as belonging to one of the following three categories: emotion regulation, effortful control, or

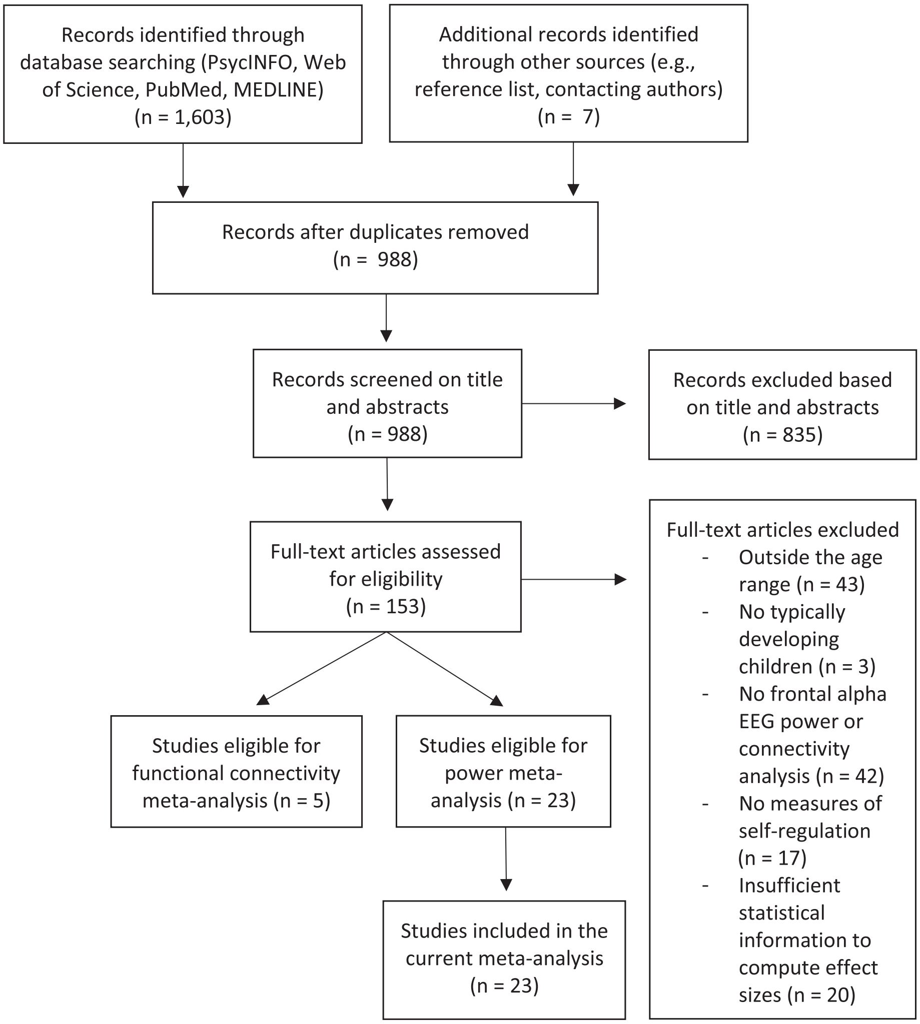

FIGURE 1 The preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram used to identify studies for detailed analysis of the association between frontal EEG activity and self-regulation

executive function[2]. As *emotion regulation* measures of any process that influences the onset, offset, magnitude, duration, intensity, or quality of one or more aspects of emotion response were coded (Gross, 2014). As *effortful control* measures of the temperament-based outcomes were coded, such as the deliberate control of behavior and attention, which may be motivation- or emotion driven behavioral responses (Rothbart & Derryberry, 1981). Self-regulation measures that examined aspects of shifting between tasks or mental sets, updating and monitoring of working memory representations, or the inhibition of dominant or prepotent responses were coded as *executive functions* (Miyake et al., 2000). Finally, in some studies the construct of self-regulation was unclear or the behaviors were conceptualized as self-regulation as a broad construct (e.g., observation of infant's behaviors used to gain mother's attention; Dawson et al., 1999). These measures were coded as *global self-regulation*. In addition, assessment type (behavioral task, computer assessment, lab observation, questionnaire) was coded as a categorical variable.

3.2.2 | Frontal EEG measurement

Two characteristics of the frontal EEG measurement were coded for each sample: frontal EEG context and the frontal scalp location. Frontal EEG context was coded as one of three categories: during baseline, during task, or during both baseline and task (i.e., difference scores). The frontal scalp location was coded as belonging to one of the following three categories: frontal pole, medial frontal, or lateral frontal.

3.2.3 | Children's age

The mean age of the children at the start of the study was coded both as a continuous and as categorical variable: young infants (0–1 years), older infants (1–3 years) and pre-school age children (3–6 years). Effect sizes of studies with repeated measurement moments were coded separately for each moment and the age during the start of the first measurement was coded as a continuous variable.

3.2.4 | Study characteristics

Coded study characteristics related to the publication of the study included the year of publication and the impact factor. Both variables were coded as a continuous variable. In addition, the design of the study was coded as a dummy variable, including whether the effect sizes were based on cross-sectional or longitudinal data.

3.2.5 | Effect size calculation

To examine the magnitude of the association between self-regulation and frontal alpha power, Pearson's bivariate correlation coefficients (*r*) were obtained for all included studies, which represents the association between two continuous variables (Lipsey & Wilson, 2001). The *r* values were coded such that a positive *r* value indicates that a high level of self-regulation is associated with a high level of frontal alpha power. If additional information for calculating the effect sizes was needed, the author(s) of the study were emailed in order to request the additional statistical information. In total, we contacted the authors of $n = 35$ articles, including studies overlapping in datasets. Of those, 40% provided (some of) the correlations, 49% replied, but no longer had access to the data or were unable to run the requested analyses, and 11% did not reply to our email or reminder. In the latter cases, if other relevant information for calculating *r* values was available, the effect sizes were converted into *r* values using the effect size calculations proposed by Lenhard and Lenhard (2016). When a study did not report an exact effect size, but only indicated that the association was non-significant, an effect size of zero was assigned. This is a commonly used, conservative strategy (Lipsey & Wilson, 2001). When within a single study separate effects sizes were reported for each hemisphere, these were averaged prior to the analysis to provide one effect size for each frontal region. Studies including overlapping samples from the same longitudinal dataset were coded as effect sizes coming from the same sample (e.g., Kraybill & Bell, 2013; Watson & Bell, 2013).

Prior to conducting the meta-analyses, Fisher's *r*-to-*z* transformation (Fisher, 1921) was used to convert the effect sizes from each association into a *z* score to correct for skewness in the sampling distribution of *r* (Lipsey & Wilson, 2001). This *z* score is assumed to approach normality, which is necessary for the accurate determination of mean effect size estimates and for unbiased tests of statistical significance.

3.3 | Data-analysis

The overall association between self-regulation and frontal alpha power was calculated using a three-level meta-analytic model (Assink & Wibbelink, 2016; Cheung, 2014). The multilevel meta-analysis was conducted using the metafor package in R (version 3.6.1; Viechtbauer, 2015) as described by Assink and Wibbelink (2016). Given that there is overlap in information when multiple effect sizes from the same study are included, an important requirement in traditional single-level meta-analytic approaches is that there is no dependency between effect sizes (e.g., Rosenthal, 1984). However, the three-level approach makes it possible to deal with dependency of effect sizes by allowing the examination of differences in outcomes within studies (i.e., within-study heterogeneity) as well as differences between studies (i.e., between-study heterogeneity). In this way, all relevant findings can be included without the need to aggregate effect sizes per study. By performing the analyses using all relevant effect sizes, all information can be preserved and maximum statistical power can be achieved (van den Noortgate & Onghena, 2003). Three levels of variance were included in the model: the sampling variance of each effect size (level 1), the within-study variance of effect sizes in the same study (level 2) and the between-study variance of effect sizes from different studies (level 3).

If there was evidence for heterogeneity in effect sizes, moderator analyses were conducted to test variables that might explain within-or between-study heterogeneity (Borenstein et al., 2010). All model parameters were estimated using the restricted maximum likelihood estimation method. Before moderator analyses were conducted, continuous variables (mean age and publication year) were centered around their means and dummy variables were created for all categorical variables (self-regulation construct, self-regulation measure, frontal scalp location, EEG context). Publication bias was also assessed using visual inspection of the funnel plot trim-and-fill procedure (Duval & Tweedie, 2000) and Egger's regression test (Egger et al., 1997). If there was absence of publication bias, effect sizes were assumed to be distributed symmetrically with respect to the true effect size, with effect sizes from large studies more closely approximating the true effect size than those from small studies (Sterne et al., 2005).

4 | RESULTS

4.1 | Descriptive statistics

Table 1 shows the characteristics of the studies included in the meta-analysis. There were 23 studies representing 22 independent samples, including 1275 children (importantly, not every study represented an independent sample: some studies included multiple samples, whereas other studies had overlapping samples). All studies were performed in the USA, except for one study that was performed in Taiwan (Lo et al., 2013). The publication year ranged from 1999 to 2020. A total of 149 effect sizes were coded. Of the effect sizes, most studies defined alpha power as 6–9 Hz, with the exception of two studies in which the boundaries of the frequency bands were defined based on individual alpha peak frequency (Perone & Gartstein, 2019; Perone et al., 2018) and one study that focused on the adult alpha 8–12 Hz (Lo et al., 2013). Most effect sizes were based on behavioral task measures (51%). Other measures included parent-reported questionnaires (34.2%), lab observations (12.1%), and computer assessments (2.7%). Of the effect sizes, 90.6% were cross-sectional and 9.4% were longitudinal. Of the longitudinal data, the average time between the measures was 27.07 months (*SD* = 15.39; range 2–44 months). An overview of the measures and constructs of self-regulation used for the different developmental

TABLE 1 Characteristics of the included studies used in the meta-analysis

	Study	N (total) sample	Mean age (months)	Overlap sample	Number of effect sizes	Study design	EEG context	Frontal location	SR measure	SR type of measure	SR construct EF	EC	ER	SR
1	Bell (2001)	62	8.30	NO	3	Cross-sectional	Baseline and task	Fp1/Fp2, F3/F4, F7/F8	Looking A-not-B	Behavioral task	X			
2	Blankenship et al. (2018)	41	54	NO	1	Cross-sectional	Task	F3/F4	DCCS	Behavioral task	X			
3	Broomell et al. (2020)	410	5.40	YES	4	Longitudinal	Baseline	F3/F4	Visual search DCCS Simon says	Behavioral task	X			
4	Cuevas et al. (2012a)	410	5.40	YES	6	Longitudinal	Baseline and task	Fp1/Fp2, F3/F4, F7/F8	Looking A-not-B	Behavioral task	X			
5	Cuevas et al. (2012b)	64	49	YES	2	Cross-sectional	Baseline and task	F3/F4	EF composite (mommy/me, forward digit span)	Behavioral task	X			
									CBQ inhibitory control	Questionnaire		X		
6	Cuevas et al. (2016)	148	48	YES	6	Cross-sectional	Baseline and task	Fp1/Fp2, F3/F4, F7/F8	Day-Night	Behavioral task	X			
7	Dawson et al. (1999)	63	14	NO	5	Cross-sectional	Baseline and task	F3/F4	ACCTI soothability ACCTI attention	Questionnaire		X	X	
									Sustained attention Positive/Negative bids for attention	Lab observation		X		X
8	Degnan et al. (2011)	291	36	NO	3	Longitudinal	Baseline	F3/F4	CBQ EC CCTI ER CCTI attention	Questionnaire		X	X	
9	Hardin et al. (2020)	33	3.50	NO	8	Cross-sectional	Baseline	F3/F4, F7/F8	IBQ-R cuddliness IBQ-R low pleasure IBQ-R orienting IBQ-R soothability	Questionnaire		X	X	X
10	Jones et al. (2004)	78	1.16	NO	6	Longitudinal	Baseline	F3/F4	IBQ orienting IBQ soothability	Questionnaire		X	X	
11	Kraybill and Bell (2013)	56	10.33	YES	1	Longitudinal	Baseline	F3/F4, F7/F8	EF composite (Yes/No, Pig/Bull, DCCS)	Behavioral task	X			
12	Lo et al. (2013)	26	66	NO	1	Cross-sectional	Baseline and task	F3/F4	Stop-Signal	Computer assessment	X			
13	Mize and Jones (2012)	29	12.90	NO	12	Cross-sectional	Baseline	F3/F4, F7/F8	CCTI attention CCTI soothability IBQ-R cuddliness IBQ-R low pleasure IBQ-R orienting IBQ-R soothability	Questionnaire		X	X	X

(Continues)

TABLE 1 (Continued)

	Study	N (total) sample	Mean age (months)	Overlap sample	Number of effect sizes	Study design	EEG context	Frontal location	SR measure	SR type of measure	SR construct EF	EC	ER	SR
14	Mize et al. (2014)	38	8.92	NO	8	Cross-sectional	Baseline	F3/F4, F7/F8	IBQ-R cuddliness IBQ-R low pleasure IBQ-R orienting IBQ-R soothability	Questionnaire		X	X	X
15	Morasch and Bell (2011)	81	25	YES	6	Cross-sectional	Baseline and task	Fp1/Fp2, F3/F4, F7/F8	Looking A not B	Behavioral task	X			
									ECBQ inhibitory control	Questionnaire		X		
16	Perone and Gartstein (2019)	53	8.43	NO	8	Cross-sectional	Baseline	Fp1/Fp2, F3/F4	IBQ-R cuddliness IBQ-R low pleasure IBQ-R orienting IBQ-R soothability	Questionnaire		X	X	X
17	Perone et al. (2018b)	44 45 48	39 51 63	NO	3	Cross-sectional	Baseline	F3/F4	Minnesota EF Scale (MEFS)	Computer assessment	X			
18	Perry et al. (2016)	388	5	YES	4	Longitudinal	Baseline and task	F3/F4	Frustrating puzzle task Looking time glove puppet	Lab observation		X	X	
19	Swingler et al. (2017)	388	5	YES	3	Longitudinal	Baseline and task	F3/F4	Looking time glove puppet	Lab observation		X		
20	Swingler et al. (2011)	104	50	NO	3	Cross-sectional	Baseline and task	Fp1/Fp2, F3/F4, F7/F8	EF composite (WM, PTP, SCA, STS, SSS, GNG)	Behavioral task	X			
21	Watson and Bell (2013)	68	37	YES	3	Cross-sectional	Baseline and task	F3/F4	Less is More Hand Game Day-Night	Behavioral task	X			
22	Wolfe and Bell (2007)	11 17 18	42 48 54	NO	45	Cross-sectional	Baseline	Fp1/Fp2, F3/F4, F7/F8	Tongue task Simon Says Day-Night Yes/No	Behavioral task	X			
23	Xie et al. (2018)	18 17 16 17	6 8 10 12	NO	8	Cross-sectional	Task	Fp1/Fp2, F3/F4	Looking behavior Sesame street	Lab observation		X		

Note: N (total) sample = number of children at start of study, mean age (months) = mean age at the start of the study, overlap sample = overlap with sample of other studies. Moderator information: EEG context = acquisition EEG context, Fp1/Fp2 = frontal pole, F3/F4 = medial frontal, F7/F8 = lateral frontal, EF = executive functioning, EC = effortful control, ER = emotion regulation, SR = specified as self-regulation, DCCS = dimensional change card sort, (A)CCTI = (Adapted) Colorado Child Temperament Inventory, IBQ = Infant Behavior Questionnaire, ECBQ = Early Childhood Behavior Questionnaire, CBQ = Child Behavior Questionnaire, WM = Working Memory Span, PTP = Pick the Picture, SCA = Spatial Conflict Arrows, STS = Something's the Same, SSS = Silly Sounds Stroop, GNG = Animal Go No-Go.

TABLE 2 Overview of measures and conceptualizations of self-regulation used for the different developmental periods

Mean age	Number of effect sizes	Type of measurement (%)				Self-regulation construct (%)			
		Behavioral task	Parent report	Lab observation	Computer task	EF	EC	ER	SR
0–1 years	57	24%	53%	23%	0%	25%	33%	21%	21%
1–2 years	19	0%	74%	26%	0%	0%	42%	26%	32%
2–3 years	9	33%	67%	0%	0%	33%	56%	11%	0%
3–4 years	19	95%	0%	0%	5%	100%	0%	0%	0%
4–5 years	43	96%	2%	0%	2%	98%	2%	0%	0%
5–6 years	2	0%	0%	0%	100%	100%	0%	0%	0%

Note: EF = executive functioning; EC = effortful control; ER = emotion regulation; SR = specified as self-regulation.

periods is presented in Table 2. This overview shows that mean age was correlated with both self-regulation construct (r = .661) and type of measurement (r = .592).

4.2 | Overall mean effect size

No significant overall association was found between individual differences in measures of self-regulation and frontal alpha power in infants and pre-school age children (r = .023; 95% CI –.032–.077; p = .414). To account for the possible influence of outliers (i.e., extreme effect sizes), the analysis was repeated after removal of five outliers. This yielded a somewhat larger but still non-significant overall association between self-regulation and frontal alpha power (r = .033; 95% CI –.021 to .086; p = .166).

Subsequently, two separate one-tailed log-likelihood-ratio-tests were performed to examine whether the variance between effect sizes extracted from the same study (Level 2) and the variance between studies (Level 3) were significant. The likelihood ratio test comparing models with and without within-study variance (level 2) showed the variance between the effect sizes within studies was significant (p = .001), indicating a heterogeneous effect size distribution. The likelihood ratio test comparing models with and without between-study variance (level 3) showed that significant variance was present at the between-study level as well (p = .004). In order to determine variables that can explain the variance at level 2 or level 3, moderator analyses were conducted.

4.3 | Moderator analyses

An omnibus test was performed to determine whether a (potential) moderating effect of one or more variables included in the model was significant. Table 3 shows the results of the moderator analyses.

4.3.1 | Self-regulation conceptualization and measurement

Two characteristics related to the conceptualization and measurement of self-regulation were assessed as moderators: self-regulation construct and type of measurement. The results of the univariate moderator analyses revealed a significant effect of self-regulation construct, F(3, 145) = 10.313, p < .001. The association between self-regulation and frontal alpha power was only significant when effect sizes were based on executive functioning (r = .103; 95% CI .069–.137), and not when based on effortful control (r = –.019; 95% CI –.067–.030), emotion regulation (r = –.043; 95% CI –.104–.019), or when the construct was only specified as global self-regulation (r = –.053; 95% CI –.136–.029).

Furthermore, there was a significant difference in effect size depending on the type of self-regulation measurement, F(3, 145) = 11.276, p < .001. Self-regulation was only significantly associated with frontal alpha power when assessed by a behavioral task or a questionnaire. The average correlation for effect sizes using behavioral self-regulation tasks was r = .107 (95% CI .072–.142), whereas r = .003 (95% CI –.171–.176) for computer assessments and r = .000 (95% CI –.055–.054) for lab observations. In contrast, the significant association between self-regulation questionnaires and frontal alpha power was negative, r = –.054 (95% CI –.099 to –.009).

4.3.2 | Frontal EEG measurement

Two characteristics related to the measurement of frontal alpha activity were assessed as moderators: frontal EEG context (e.g., baseline, task) and frontal scalp location. Neither EEG context, F(2, 146) = 0.927, p = .398 or scalp location, F(2, 146) = 0.544, p = .582, were significantly related to the association between self-regulation and frontal alpha power.

4.3.3 | Children's age

There was a significant moderating effect of the mean age of the children, F(1, 147) = 8.458, p = .004. The regression coefficient was .002; t(147) = 2.908, p = .004, indicating that the association between self-regulation and frontal alpha power becomes stronger with increased age. Accordingly, there was a significant difference in effect size depending on the age group of the children, F(2, 146) = 6.090, p = .003. The average correlation for effect sizes for young infants (0–1 years) was r = –.016 (95% CI –.071–.040), r = –.044 (95% CI –.135–.047) for older infants (1–3 years), and r = .088 (95% CI .029–.147) for pre-school age children (3–6 years).

TABLE 3 Results for the moderator analyses on the relation between self-regulation and frontal EEG alpha power

Moderator	N ES	β0 (95% CI)	t0	β1 (95% CI)	t1	F(df1, df2)	P
Self-regulation construct						F(3, 145) = 10.313	< .001***
Executive functioning (RC)	80	.103 (.069 to .137)	5.961***				
Effortful control	33	−.019 (−.067 to .030)	−0.763	−.122 (−.181 to −.063)	−4.070***		
Emotion regulation	18	−.043 (−.104 to .019)	−1.362	−.146 (−.217 to −.075)	−4.078***		
Specified as self-regulation	18	−.053 (−.136 to .029)	−1.271	−.156 (−.246 to −.067)	−3.458**		
Measurement Type						F(3, 145) = 11.276	<.001***
Behavioral task (RC)	76	.107 (.072 to .142)	6.068***				
Computer assessment	4	.003 (−.171 to .176)	0.029	−.105 (−.282 to .072)	−.1.172		
Lab observation	18	.000 (−.055 to .054)	−0.018	−.108 (−.173 to −.043)	−3.293**		
Questionnaire	51	−.054 (−.099 to −.009)	−2.370*	−.161 (−.218 to −.104)	−5.601***		
EEG context						F(2, 146) = 0.927	.398
During baseline only (RC)	105	.022 (−.038 to .081)	0.726				
During task only	12	.078 (−.035 to .191)	1.358	.056 (−.056 to .168)	0.993		
During baseline and task	32	.003 (−.072 to .077)	0.077	−.019 (−.084 to .046)	−0.579		
Frontal scalp location						F(2, 146) = 0.544	.582
Medial frontal (RC)	80	.019 (−.038 to .076)	0.653				
Frontal pole	31	.036 (−.043 to .115)	0.896	.033 (−.039 to .105)	0.908		
Lateral frontal	37	−.005 (−.081 to .072)	−0.119	−.011 (−.080 to .059)	−0.299		
Children's age							
Mean age (continuous)	149	.002 (.001 to .004)	2.908**	.027 (−.017 to .007)	1.221	F(1, 147) = 8.458	.004**
Age group						F(2.146) = 6.090	.003**
Pre-schoolers 3–6 (RC)	67	.088 (.029 to .147)	2.962**				
Older infants 1–3	23	−.044 (−.135 to .047)	−0.959	−.132 (−.233 to −.032)	−2.598*		
Young infants birth-1	59	−.016 (−.071 to .040)	−0.559	−.104 (−.168 to −.040)	−3.196**		
Study characteristics							
Publication year (continuous)	149	−.002 (−.009 to .005)	−0.477	.023 (−.031 to .077)	0.851	F(1, 147) = 0.227	.634
Impact factor (continuous)	149	.031 (−.008 to .069)	1.562	.016 (−.037 to .070)	0.600	F(1, 147) = 2.439	.121
Design						F(1, 147) = 0.200	.655
Cross-sectional (RC)	135	.025 (−.031 to .080)	0.872				
Longitudinal	14	.009 (−.072 to .090)	0.223	−.015 (−.083 to .053)	−0.447		

Note: *N* ES = number of effect sizes, B0 = mean effect size correlation, CI = confidence interval, B1 = estimated regression coefficient, *t*-values = difference in mean *r* with zero, *F*-value = omnibus test of regression coefficients, *p*-value of omnibus test, RC = reference category. *$p < .05$; **$p < .01$; ***$p < .001$.

4.3.4 | Study characteristics

Three study characteristics were assessed as moderators: publication year, impact factor, and study design. None of these were significant moderators, indicating that the strength of the association between self-regulation and frontal alpha power was independent of the publication year, $F(1, 147) = 0.227$, $p = .634$, the impact factor, $F(1, 147) = 2.439$, $p = .121$, and whether the study was cross-sectional or longitudinal, $F(1, 147) = 0.200$, $p = .655$.

4.4 | Publication bias

To statistically check the influence of publication bias, a funnel plot (Figure 2) using Fisher's z transformations was inspected and Egger's regression test was applied (Egger et al., 1997). Results of the regression test for funnel plot asymmetry showed that there was no significant asymmetry ($z = -1.8052$, $p = .071$), suggesting that no significant publication bias was detected for the results found above.

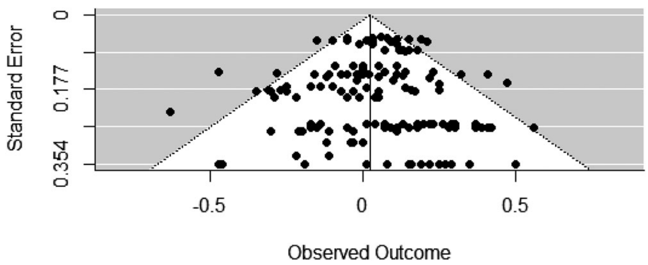

FIGURE 2 Funnel plot of publication bias

5 | DISCUSSION

The current study provides the first meta-analytic synthesis of the literature on the relations between individual differences in self-regulation and frontal EEG alpha power during infancy and early childhood. After combining all information from relevant studies and requesting additional non-reported findings, leading to 149 effect sizes from 23 studies that consisted of 1275 participants, the findings of the current meta-analysis demonstrated a non-significant overall association between self-regulation and variability in frontal EEG alpha power. However, self-regulation construct, measurement type, and children's mean age emerged as significant moderators. These findings have important implications for understanding the etiology of individual differences in emerging self-regulatory skills as well as for the study of the neural underpinnings of self-regulation development early in life.

5.1 | Moderating effect of self-regulation characteristics

Both self-regulation construct and measurement type were significant moderators of brain-behavior associations. First, executive functioning was the only self-regulation construct significantly correlated with frontal alpha power. Importantly, most EEG studies of executive function in the current meta-analysis used performance-based behavioral assessments, such as DCCS and Stroop-like tasks. In contrast, EEG investigations of emotion regulation and effortful control that met inclusion criteria typically used lab observations (e.g., attentional capture by salient stimuli) or parent-reported questionnaires (e.g., IBQ). It might be that, at least during early childhood, lab observations and parent-reported questionnaires also include measures of external regulation (e.g., soothability), or more reactive (bottom-up) processes, whereas executive functioning tasks are more likely to capture top-down activity of the frontal cortex. Many of the common executive functioning behavioral tasks in young children are adaptations of adult frontal lobe neuropsychological assessments (Müller & Kerns, 2015). Accordingly, the association between self-regulation and frontal alpha power was significantly higher when self-regulation was assessed using performance-based behavioral assessments.

The current meta-analysis also revealed that apart from the A-not-B looking task (Bell, 2001), studies using other behavioral tasks to examine self-regulation in relation to frontal alpha power in children under 3 years of age are still rare. Given the need to understand and follow instructions, many of the common performance-based tasks in early childhood are suitable for children 3 years and older, such as Stroop-like (Stroop, 1935) and gift delay tasks (Mischel et al., 1972). Importantly, studies of emotion regulation and effortful control in the current meta-analysis mainly focused on infants. It is therefore unclear whether the magnitude of the effects for effortful control and emotion regulation would also be higher if analogous behavioral tasks were utilized to assess these constructs. Thus, more multi-method research including different types of self-regulation measurements and the use of performance-based behavioral tasks with younger children is needed to further examine how the measurement type conditions the association between self-regulation and frontal alpha power.

Furthermore, surprisingly, a small but significant reverse moderating effect was found for parent-reported questionnaires, indicating that less frontal alpha power was associated with higher levels of self-regulation. One possible explanation for the different findings for questionnaires might be that, in the current meta-analysis, almost all studies using questionnaires to assess self-regulation focused on children under 3 years of age. In infants, some factors of the questionnaires (e.g., soothability and cuddliness) seem to capture processes of self-regulation that are more likely to rely on external regulation, rather than children's own self-regulation capacity. Moreover, findings of previous research using parent-report measures revealed that, at least during infancy, the variability in each self-regulation factor was linked with a different multi-rhythm neural signature. For instance, 6- to 12-month-olds' attention abilities were associated with lower levels of frontal theta activity and higher levels of frontal beta and gamma activity, whereas cuddliness was related to higher theta and lower beta activity at posterior sites (Perone & Gartstein, 2019). Even when looking at the alpha frequency band solely, previous research found that different aspects of self-regulatory skills (e.g., sustained attention, adaptive control, selective attention) were related to distinct alpha modulating effects (e.g., increases vs. decreases in alpha power; see Sadaghiani & Kleinschmidt, 2016, for review). Thus, further inquiry into the use of parent-reported questionnaires to identify brain-behavior relations is needed to promote the understanding of how the different measures of self-regulation and variations in frontal alpha power are connected.

5.2 | Moderating effect of frontal EEG characteristics

Frontal alpha EEG characteristics (acquisition context, frontal scalp location) were not significant moderators in the present meta-analysis. Differences in the EEG context (i.e., baseline, task, baseline-to-task) did not impact the association between individual differences in self-regulation and frontal alpha power. This finding is in line with the notion that baseline measures still require young children to behaviorally adapt to the open task environment, such as inhibiting physical movement and visually attend to a stimulus on the screen, that may engage self-regulatory processes. Depending on the complexity of the resting-state procedure, this may lead to increased frontal activation during baseline (Anderson & Perone, 2018; Camacho et al., 2020). At the same time, baseline alpha measures may reflect general indices of brain maturation (e.g., Bell & Fox, 1992; Wolfe & Bell, 2004); therefore, there are multiple factors that could contribute to similar effect sizes across EEG contexts. Moreover, the frontal scalp location (i.e., frontal pole, medial frontal, lateral frontal) did not affect the association between variations in frontal EEG alpha power and self-regulation, indicating that the reported effect sizes do not differ systematically by the location of the frontal region electrode sites.

5.3 | Moderating effect of children's age

The mean age of the children significantly moderated the association between self-regulation and frontal EEG alpha power, with stronger effects found in older children compared to younger children. These findings are in line with previous research that indicate that young infants gradually develop self-regulation with increasing age (Blair & Ursache, 2011; Karoly, 1993). During the early postnatal period, bottom-up mechanisms that involve responses that are mostly automatic assemble into the more higher order top-down mechanisms of self-regulation (Nigg, 2017). Given what is known about the timetable for maturation of the frontal cortex, it may be that individual differences in higher order self-regulatory behaviors are not apparent in variations in frontal alpha power until the point at which the frontal cortex would be sufficiently developed to be involved in higher order self-regulatory processes (Blair & Raver, 2015). As a result, the association between self-regulation and frontal alpha power might appear stronger at older ages. Accordingly, a significant moderating effect was found for the age group of the children; the association between self-regulation and frontal alpha power only became significant after 3 years of age. However, at the same time, almost all of the effect sizes for children 3 years and older were based on behavioral measures of executive function. Self-regulation tasks often require verbal comprehension and the need to flexibly shift the focus of attention, both of which are particularly difficult for young infants (Garon et al., 2008). As a result, self-regulation in infants is typically measured by observational measures or questionnaires, that potentially capture more factors of external regulation compared to performance based executive functioning tasks. Therefore, it is unclear whether this effect is solely a function of age, self-regulation construct, or measurement type.

5.4 | Strengths, limitations, and future directions

The current meta-analysis provides the first integrative developmental analysis of individual differences in self-regulation and frontal alpha power, pointing to gaps in the literature and valuable areas for future directions. However, our findings should be considered in light of limitations of the extant literature and the present analysis. One reason for the non-significant overall association between self-regulation and frontal alpha power may be that successful self-regulation relies on interconnections between the frontal cortex and other cortical and subcortical regions (Heatherton & Wagner, 2011). EEG functional connectivity measures allow for investigating how these brain regions communicate; however, too few relevant developmental studies of frontal alpha functional connectivity were available to examine this measure in the current meta-analysis. This implies a need for further research in this area.

In addition, from a more holistic standpoint, self-regulatory processes and frontal cortical activity are supported by multiple co-occurring neural oscillatory rhythms. Identifying potential "neural oscillatory phenotypes" for individual differences in self-regulation might be challenging based on examinations of frontal alpha power in isolation from other neural oscillations. Moreover, previous research revealed that the theta/beta power ratio, rather than theta and beta activity independently, was most relevant to executive functioning in early childhood (Perone et al., 2018). In addition to relative power ratios, cross-frequency coupling of interaction between neural oscillations and their temporal coordinating properties demonstrates that the hierarchical organization of brain rhythms is represented at multiple correlated scales (Buzsáki & Watson, 2012). More multi-frequency band EEG research is therefore needed to further investigate the associations between self-regulation and frontal alpha power, in which relative power ratio and cross-frequency coupling mechanisms are taken into consideration.

Furthermore, most studies included in the current analysis were cross-sectional. The present meta-analysis, however, demonstrates that children's age moderates the association between self-regulation and frontal alpha power. In order to truly show ontogenetic effects, more longitudinal investigations of self-regulation and frontal alpha power across multiple points are needed to examine indices of developmental change. For instance, recent evidence from growth curve modeling reveals that, although initial levels of resting-state frontal alpha power were not associated with subsequent executive function, changes in frontal alpha power from 10 months to 4 years of age were associated with variations in executive functions during early childhood (Whedon et al., 2020). Thus, measures of developmental change, whether behavioral or neural, are potentially informative indices of individual differences in self-regulation not captured by the current meta-analysis.

In the broader literature, the role of frontal alpha activity in emerging self-regulatory processes has come from a variety of approaches, including within-subjects analyses revealing changes in frontal alpha power as a function of self-regulatory processing, task demands, and task performance (see Bell & Cuevas, 2016, for review). The present meta-analysis, however, only considered effect sizes from investigations of between-subjects analyses of children's relative levels of frontal alpha power and self-regulation. Thus, the findings represent only one aspect of frontal EEG alpha activity's potential role in self-regulatory processes, and are unable to attest to whether similar magnitude of effects and moderators generalize to frontal alpha findings from other approaches.

A challenge with the existing literature is that many studies contributing to the combined effect size had small sample sizes, leading to low statistical power. Power issues and replicability are a cause of concern within neuroimaging research (Button et al., 2013). Although the meta-analytic synthesis of all available studies and the three-level approach to include all relevant effect sizes leads to maximum statistical power (Assink & Wibbelink, 2016), the inclusion of small sample sizes still decreases the possibility of detecting true effects. Furthermore, most studies were conducted in the United States and mainly included White children from higher socioeconomic status families. Multiple studies also originated from the same population (e.g., Perry et al., 2016; Swingler et al., 2017). More heterogenous and larger samples are therefore needed to allow for greater generalizability (and contextualization) of results (Bhavnani et al., 2021; Miller-Cotto et al., 2022).

Finally, due to the high correlations between self-regulation construct, measurement type, and the mean age of the children, we were unable to test a multiple moderator model. The current meta-analysis revealed that studies with 3- to 6-year-olds primarily included behavioral tasks to assess executive functioning, whereas studies with younger children mainly used questionnaires and observations to assess effortful control and emotion regulation. As a result of these intercorrelations, it remains unclear which of the moderating effects are most relevant and deserve the most attention (Hox, 2010). Advances in multimethod approaches, including the development of measures of executive functioning suitable for infants, are needed to investigate nuances in associations between frontal alpha power and self-regulation. One promising measure is the novel Early Executive Functions Questionnaire designed to bridge the gap between existing self-regulatory measures in infants and more complex executive functioning skills in preschoolers (Hendry & Holmboe, 2021).

6 | CONCLUSIONS

The current study provides the first meta-analytic synthesis of research examining self-regulation and variability in frontal EEG alpha power in children between 1 month and 6 years of age. The findings demonstrated that the overall association between individual differences in self-regulation and frontal alpha power was not significant. However, the construct executive functioning, the assessment of self-regulation using behavioral tasks or questionnaires, and a higher mean age of the children resulted in small but significant associations between self-regulation and frontal alpha power, where higher frontal alpha power values were related to higher order top-down mechanisms of self-regulation. These findings are in line with the assumption that increases in alpha power might be a marker of brain maturation from infancy to early childhood (for reviews, see Bell & Fox, 1994; Marshall et al., 2002). Following the inhibition timing hypothesis, task-related increases in alpha activity may reflect the ability to efficiently suppress distracting information and could therefore be a marker of task-related engagement (Klimesch, 2012). However, important future directions for the field will require developmental theoretical frameworks of oscillatory rhythms and systematic research to come to a clear description of what the alpha rhythm is thought to reflect.

Moreover, the findings of the current meta-analysis indicate that top-down mechanisms of self-regulation, such as executive functioning, might become stronger, capturing between-subject variability, when the frontal cortex is sufficiently developed to exert top-down control for successful self-regulatory skills (Blair & Ursache, 2011). Yet, the current meta-analysis highlights the need for longitudinal analyses and advances in multimethod approaches to reach a more comprehensive understanding of the association between individual differences in neural oscillatory rhythms (beyond frontal alpha power) and self-regulation during the first years of life, including their development over time.

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CONFLICT OF INTEREST

There are no conflicts of interest by any of the authors.

ETHICAL STATEMENT

This article does not contain any studies with human participants performed by any of the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Marissa Hofstee (m.hofstee@uu.nl), upon request.

ENDNOTES

[1] EEG asymmetry scores were not included because lateralized neural responses were beyond the scope of the present meta-analysis. Frontal EEG asymmetry in relation to child internalizing and externalizing behaviors within this age range has been the focus of another meta-analysis (Peltola et al., 2014), with no significant effects. We had no hypotheses involving hemisphere, and used values averaged across hemisphere, consistent with the corresponding developmental literature.

[2] Based on the theoretical frameworks that were used throughout the current study (e.g., Nigg, 2017; Rothbart & Derryberry, 1981), there would have been a fourth category of self-regulation: compliance. However, there were no relevant studies that could be included in the meta-analysis based on the inclusion and exclusion criteria.

NOTE

Studies included in the meta-analyses are marked with an *

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