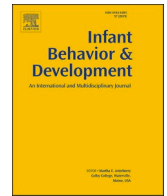




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The direct and indirect effects of parenting behaviors and functional brain network efficiency on self-regulation from infancy to early childhood: A longitudinal mediation model

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ABSTRACT

There is growing interest in the hypothesis that early parenting behaviors impact children's self-regulation by affecting children's developing brain networks. Yet, most prior research on the development of self-regulation has focused on either environmental or neurobiological factors. The aim of the current study was to expand the literature by examining direct and indirect effects of variations in parenting behaviors (support and stimulation) and efficiency of functional brain networks (small-worldness) on individual differences in child self-regulation, using a three-wave longitudinal model in a sample of 109 infants and their mothers. Results revealed that parental support predicted child self-regulation at 5 months, 10 months, and 3 years of age. This effect was not mediated by infants' small-worldness within the alpha and theta rhythm. Parental stimulation predicted higher levels of infants' alpha small-worldness, whereas parental support predicted lower levels of infants' theta small-worldness. Thus, parents may need to stimulate their infants to explore the environment autonomously in order to come to more efficient functional brain networks. The findings of the current study highlight potential influences of both extrinsic environmental factors and intrinsic neurobiological factors in relation to child self-regulation, emphasizing the role of parental support as a form of external regulation during infancy, when the brain is not yet sufficiently developed to perform self-regulation itself.

1. Introduction

Infant development is characterized by very rapid growth in physical, psychological, and social skills. One important area of rapid growth is the development of infants' emerging self-regulatory capacities, referring to the ability to control emotions, behavior, and cognition (Nigg, 2017). According to biopsychosocial frameworks (e.g., Calkins et al., 2016; Olson & Sameroff, 2009), the development of child self-regulation is linked to both extrinsic environmental factors and intrinsic neurobiological factors, such as variations in parenting behaviors (Kraybill & Bell, 2013) and maturation of functional brain networks (Cuevas & Bell, 2011). There is growing interest in the hypothesis that early parenting behaviors impact child self-regulation by affecting children's developing brain networks

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(e.g., Belsky and De Haan, 2011; Bernier et al., 2010). Yet, most prior research on the development of self-regulation has focused on either environmental or neurobiological factors. The aim of the current study was therefore to examine the direct and indirect effects of variations in parenting behaviors and functional brain networks on the development of self-regulation from infancy to early childhood, using a longitudinal mediation model.

1.1. The link between parenting and self-regulation

The social environment is of central importance to the development of child self-regulation. For instance, co-regulation (i.e., comforting behaviors) of parents provides external regulation for children who cannot yet fully regulate themselves (e.g., Bernier et al., 2010; Rothbart et al., 2011). Co-regulation gradually decreases as children's capacity for internal self-regulation increases (Kopp, 1982; Lobo & Lunkenheimer, 2020). The development of internal self-regulatory skills depends heavily on learning opportunities, provided by more and a richer exploration of the environment (Hadwin et al., 2017). Following attachment-theoretical frameworks, a flexible balance between simultaneously offering support and encouragement to explore the environment autonomously is needed to stimulate children's exploration of the environment (Ainsworth, 1979; Bowlby, 1969). As a result, both supportive and stimulating parenting behaviors appear to be important factors in the development of self-regulation (Fay-Stammach et al., 2014).

Ainsworth (1969) defined supportive parenting behaviors as parents' abilities to be aware of children's emotional cues, to interpret them accurately, and to respond in an appropriate and prompt way. Previous developmental literature focusing on young children revealed that supportive parenting behaviors were positively related to variations in child self-regulation. For instance, infants with mothers who showed more sensitive behaviors during home visits had better performance on an executive functioning task across the preschool period (Bernier et al., 2010). In addition, observed positive affect of mothers toward their children at 5 months of age was positively associated with children's sustained attention (i.e., time spent attending to a glove puppet) at 10 months of age (Swingler et al., 2017). Thus, children may feel more comfortable exploring new self-regulatory strategies in environments where parents serve as a warm and secure base (Ainsworth, 1969).

Parental stimulation refers to the encouragement of children to explore materials and providing learning opportunities that enhance positive development, such as the development of cognitive skills (Bradley et al., 2011). Previous research revealed positive associations between parental stimulation and self-regulatory skills in young children (for a review, see Fay-Stammach et al., 2014). Parental stimulation, as indexed by the Home Observation for Measurement of the Environment (HOME; Bradley et al., 2011), was associated with sustained growth in inhibitory control and cognitive flexibility across the preschool period (Clark et al., 2013). Furthermore, infants who experienced higher levels of parental stimulation, such as the presence of learning materials in the home environment, showed higher levels of self-regulation (i.e., executive attention) than infants who experienced lower levels of parental stimulation (Mezzacappa et al., 2011). These findings are in line with attachment-theoretical frameworks, suggesting that stimulating parenting behaviors enhance the exploration of the environment, providing children with greater opportunities to exercise self-regulatory skills autonomously (Matas et al., 1978; Riksen-Walraven et al., 1993).

1.2. The link between functional brain network efficiency and self-regulation

During self-regulatory processes, well-established or habitual responding must be overridden to direct behaviors guided by internal states or intentions (Strack & Deutsch, 2015). Relating these self-regulatory processes to the development of the brain, researchers often point towards complex networks of interconnected brain regions (for a review, see Vink et al., 2020). For instance, the orienting-attention brain network (including connections between frontal, parietal, and temporal brain regions) arises in infancy and enables children to orient to stimuli and to shift attention from one stimulus to another (Posner & Rothbart, 2018). Subsequently, when children are approximately two years of age, the executive network becomes more influential. The executive network functions to resolve conflict among competing responses by regulating other brain networks, such as enhancing activity in cognitive areas of the frontal brain region and inhibiting activity in emotional areas of the posterior brain region, operating through neural connections between the nodes of these distinct brain regions (Posner, 2016; Posner & Rothbart, 2007). The development of functional brain networks therefore depends on improving the efficiency of neural connections between distributed brain regions, such as the frontal cortex and regions representing the reward, salience, and emotional value of a stimulus (Heatherington & Wagner, 2011; Posner et al., 2016).

During the first postnatal year, the infant brain rapidly produces neural connections between brain regions (i.e., functional connectivity), which enables the exchange of important information and therefore promotes positive child development, such as cognitive abilities (Gao et al., 2017). More specifically, the study of Bell (2012) revealed that infants with higher levels of functional connectivity between the frontal-parietal brain regions, assessed by using electroencephalography (EEG), showed better performance on an inhibitory control task (i.e., looking A-not-B task) compared to infants with lower levels of neural connections between these regions. However, according to the theoretical model of Greenough et al. (1987), increases in functional connectivity do not always indicate more optimized communication. In order to obtain stronger and more focal activity patterns in the distinct brain areas, the overproduction of neural connections during infancy is followed by a systematic pruning of neural connections in early childhood, which eliminates redundancy in brain networks and facilitates efficient information transfer (Durstun et al., 2006; Tau & Peterson, 2010).

In line with the theoretical model of Greenough et al. (1987), lower levels of functional connectivity between the frontal-temporal brain regions in pre-school age children were related to better performance on the tongue task and mommy/me task, assumed to measure inhibitory control (Broomell et al., 2019). Thus, although providing relevant information about specific functions of brain regions, measures of local functional connectivity do not always directly assess the efficiency of neural connections underlying the

functional brain networks, especially during the periods of blooming and pruning of neural connections in early childhood. For that reason, there is growing interest in measuring the efficiency of functional brain networks, which reflects a rich repertoire of underlying local patterns of functional connectivity (Rubinov & Sporns, 2010).

Small-worldness is one of the most frequently analyzed topological properties of functional brain network efficiency (Bassett & Bullmore, 2006). Small-worldness represents the brain network as a graph with nodes and edges, respectively reflecting distributed brain regions and the functional connectivity between these regions (Bullmore & Sporns, 2009). Although literature on the direct relation between functional connectivity and small-worldness in (early) childhood is still lacking, the first study that examined this relationship in adults revealed a negative association between these two measures (Päeske et al., 2020). Whereas local functional connectivity measures the strength of connections between nodes (e.g., EEG electrodes), small-worldness quantifies the complex relations between these interconnected nodes and other clusters of interconnected nodes, demonstrating the topological organization of functional brain networks (Bassett & Bullmore, 2006). More specifically, small-world networks are generally characterized by a high clustering coefficient (dense interconnections between neighboring nodes) in combination with few edges between clusters of nodes, also referred to as short path lengths. Short path lengths (i.e., less functional connectivity between distinct clusters) might enable the rapid combination of specialized information from distributed brain regions (Muldoon et al., 2016).

Similar to functional connectivity, small-worldness can be calculated in multiple cortical rhythms (Bassett & Bullmore, 2006). The alpha and theta rhythms have been most commonly related to self-regulatory processes (Hofstee et al., 2022; Klimesch, 1999). In general, the alpha rhythm is thought to reflect inhibitory processes, such as blocking task-irrelevant information (for a review, see Klimesch et al., 2007). On the other hand, the theta rhythm is assumed to reflect engagement of different brain networks in control of behavior (Liu et al., 2014; Orekhova et al., 2006). Yet, there is a lack of theory as to what specific developmental changes in cortical rhythms are thought to reflect in early childhood.

Even though measures of functional brain network efficiency within the alpha and theta rhythm might overcome some of the interpretative complexities related to the rapidly developing neural connections in infants and preschool age children, only few studies investigated measures of functional brain network efficiency within this developmental period. Results of the study of Fekete et al. (2014) revealed that functional brain networks (assessed by fNIRS) exhibited reduced levels of the small-world index in toddlers with lower levels of parent-reported self-regulation (assessed by the CBQ). These findings indicate that small-worldness is positively related to variations in child self-regulation. In contrast, the EEG study of Xie et al. (2019) revealed that lower levels of alpha small-worldness (i.e., increase in path length and decrease in clustering coefficient) were related to higher levels of infants' self-regulation (i.e., sustained attention). However, given the inhibitory role of the alpha rhythm, Xie et al. (2019) explain this as the possible release of task-relevant brain areas from inhibition (Klimesch et al., 2007). More research is therefore needed to examine whether and how small-worldness in the alpha and theta rhythm might be interpreted as functional brain network efficiency in relation to variations in child self-regulation.

1.3. The link between parenting and functional brain network efficiency

The process of overproduction and subsequent pruning of neural connections suggests that functional brain network efficiency is not entirely predetermined. Instead, according to the theoretical model of Greenough et al. (1987), experience-dependent pruning allows for a topological refinement of neural connections, thereby adapting to the infants' environment. Neuroimaging research revealed that neural connections that are actively stimulated by the environment are strengthened and maintained, whereas neural connections that are rarely activated are eliminated (for a review, see Huttenlocher, 2009). In this way, the environment influences how functional brain networks are being fine-tuned and become more efficient, providing foundations for the development of more complex behaviors, such as self-regulation (Knickmeyer et al., 2008).

Parents can play an important role in the process of modifying and refining neural connections between brain regions (for a review, see Belsky and de Haan, 2011). For instance, previously institutionalized children, who had been randomly assigned to a foster care intervention at 2 years of age, showed lower levels of alpha functional connectivity between the frontal-temporal regions than children who had been randomized to remain in institutional care (Marshall et al., 2008). These results indicate that more nurturing environments are associated with lower levels of functional connectivity. However, little attention has been directed toward the association between variations in normative parenting behaviors and functional connectivity. One of the few available studies focused on the relations between the quality of parent-child interactions and individual differences in infants' functional connectivity between the frontal-posterior regions (Perone & Gartstein, 2019). Results revealed that observed parental support (i.e., responsiveness) during a two-minute free play session was related to lower levels of infants' frontal functional connectivity within the alpha rhythm and lower levels of functional connectivity between the frontal-posterior regions within the theta rhythm.

The finding that parental support is related to lower levels of functional connectivity in infants might be indicative of more optimized functional brain network efficiency as a result of synaptic pruning. Yet, studies to support these claims in early childhood are still lacking. Concerning older children, the MRI study of Richmond et al. (2019) did not find support for an association between positive parenting behaviors, such as warmth and structured communication, and variations in small-worldness in eight-year-olds. However, in the MRI study of Li et al. (2021) the positive association between parental warmth and behavioural outcomes (i.e., extraversion) was mediated by higher levels of small-worldness in 8- to 15-year old children. Thus, increased small-worldness might be a mechanism that links parenting behaviors to behavioral outcomes in older children and adolescents. However, more longitudinal research is needed to investigate the direct and indirect relations between parenting behaviors, small-worldness, and self-regulation during infancy and early childhood.

1.4. The current study

Taken together, besides the direct effects of parenting behaviors and functional brain network efficiency on variations in child self-regulation, it might be that there is also an indirect effect of parenting behaviors on child self-regulation through the efficiency of infants' developing brain networks (Belsky and de Haan, 2011; Rothbart et al., 2011). Yet, studies to support this hypothesis in early childhood are, to our knowledge, still lacking. Gaining insight into biopsychosocial factors underlying the early development of self-regulation is needed for an integrated approach to the study of self-regulation. In this way, early identification of risks and interventions that have the potential to alter the development of child self-regulation at the earliest, most modifiable stage can be improved (Vink et al., 2020). Thus, the aim of the current study was to examine the direct and indirect effects of variations in parenting behaviors (support and stimulation) and efficiency of functional brain networks (small-worldness) within the alpha and theta rhythms on individual differences in child self-regulation.

First, a positive association between parenting behaviors (support and stimulation) and child self-regulation was expected (hypothesis 1). Second, it was expected that higher levels of small-worldness would be positively related to child self-regulation (hypothesis 2). Third, it was expected that parental support and parental stimulation would be positively associated with infants' small-worldness (hypothesis 3). Lastly, a mediation effect of parenting on child self-regulation through infants' small-worldness was expected (hypothesis 4). Given that both the alpha and theta rhythms have been related to cognitive development (Hofstee et al., 2022; Klimesch, 1999) and parenting behaviors (e.g., Perone & Gartstein, 2019), it was expected that these effects would be present in both the alpha and the theta rhythm.

2. Method

2.1. Participants

Data for the current study were collected as part of the YOUth cohort study (Youth of Utrecht), a large-scale ongoing longitudinal study following children from 20 to 24 weeks gestational age until the age of 16 years, conducted in the Netherlands. More detailed information about the study design can be found in Onland-Moret et al. (2020). The YOUth cohort study comprises two independent cohorts: YOUth Baby & Child and YOUth Child & Adolescent. In the current study, data were derived from three waves of the YOUth Baby and Child cohort (T1 = 5 months, T2 = 10 months, T3 = 3 years). YOUth has an accelerated and flexible longitudinal design, including broad age ranges (Onland-Moret et al., 2020). The sample for the current study consisted of 109 children (55% girls) that participated at the third wave and had complete EEG data at T1 and T2. For more information on attrition and data loss concerning EEG data in the YOUth project see an earlier study by van der Velde and Junge (2020). The participant characteristics and demographics are presented in Table 1. Mean age of the children was 4.86 months ($SD = 0.73$) at T1, 9.93 months ($SD = 0.81$) at T2, and 34.20 months ($SD = 6.51$) at T3. All infants were born full-term (38–42 weeks), had normal birth weight, and did not have developmental delays or abnormalities in visual or auditory processing. Mothers of the infants were predominantly higher educated (49.5% reported having at least a bachelor's or master's degree in scientific education) and 63.3% reported that their monthly gross household income was above €4000. Mean age of the mothers was $M = 33.01$ years ($SD = 3.58$) at T1, $M = 33.43$ years ($SD = 3.55$) years at T2, and $M = 35.45$ years ($SD = 3.56$) at T3.

Table 1
Participant demographics.

	N (percentage)
Highest level of education mother	
Primary education	0 (0%)
Pre-vocational education	2 (1.8%)
Higher general continued education	4 (3.7%)
Preparatory scientific education	2 (1.8%)
Middle-level applied education	12 (11%)
Higher professional education	31 (28.5%)
Scientific education	54 (49.5%)
Doctoral Degree	1 (0.9%)
Not reported	3 (2.8%)
Monthly gross household income	
< €1250	1 (0.9%)
€1250 - €2000	2 (1.8%)
€2000 - €3000	10 (9.2%)
€3000 - €4000	19 (17.5%)
> €4000	69 (63.3%)
Not reported	8 (7.3%)
Genetic relation	
Biological mother	107 (98.2%)
Non-biological mother	2 (1.8%)

2.2. Procedure

Children and at least one of their parents were invited into the research laboratory of YOUth at Utrecht University in the Netherlands (Onland-Moret et al., 2020). During the lab visit, children and one of their parents participated in a variety of measurements. A full overview of the collected data during the lab visit can be found at the website: www.uu.nl/en/research/youth-cohort-study. In addition, both parents received several online questionnaires at each measurement wave. The questionnaires on parenting behaviors and the development of the child were filled in by the primary caregiver, which were all mothers in the current sample. For the current study, only the EEG recording and the parent-reported questionnaires were used. The data were collected by a team of trained and experienced researchers and research assistants. Ethical approval for the YOUth cohort study was provided by the Medical Research Ethics Committee of the University Medical Center Utrecht and informed consent was obtained from both parents at each measurement wave. Parents were compensated €30 for each lab visit.

2.3. Measures

2.3.1. Parenting behaviors

Self-reported parenting behaviors were assessed using the Comprehensive Early Childhood Parenting Questionnaire (CECPAQ; Verhoeven et al., 2017). The CECPAQ measures a range of parenting behaviour across five domains (support, structure, stimulation, harsh discipline, and positive discipline) rated on a 6-point Likert scale ranging from *never* (1) to *always* (6). However, due to an error within the online questionnaire, a 5-point Likert scale ranging from *never* (1) to *often* (5) for parental support was presented to participants. *Parental support* (e.g., “I notice when my child is sad or doesn’t feel good”) was determined by averaging the scores on the Sensitivity ($N = 4$ items), Responsiveness ($N = 5$ items), and Affection ($N = 4$ items) subscales. *Parental stimulation* (e.g., “I tell my child stories or read books to him/her”) was determined by averaging the scores on the Activities ($N = 3$ items), Exposure ($N = 5$ items), and Toys ($N = 5$ items) subscales. Both parenting behavior scales had satisfactory internal consistency ($\alpha = .85$ for support and $\alpha = .70$ for stimulation).

2.3.2. Electroencephalogram (EEG)

EEG recording. During the EEG recording, infants were seated in a quiet and dimly lit room on their parents’ lap or in a car seat positioned at eye level 65 cm from the computer screen. The EEG coherence task consisted of two, 1-minute long, videos repeated three times. One video consisted of singing women, while the other consisted of moving toys without human interference. In between videos, short breaks were taken (5 in total) after which the new video was started. EEG was recorded using a cap with 32 electrodes (ActiveTwo system, BioSemi) positioned according to the international 10/20 system. During recording, EEG was sampled at a rate of 2048 Hz. Recordings were made from 16 left and right scalp sites: frontal pole (Fp1 and Fp2), medial frontal (F3 and F4), lateral frontal (F7 and F8), central (C3 and C4), temporal (T7 and T8), medial parietal (P3 and P4), lateral parietal (P7 and P8), and occipital (O1 and O2). The common Mode Sense (CMS) and driven Right Leg (DRL) electrode were used to provide an active ground.

EEG analysis. EEG data was analyzed in Matlab, using functions of the FieldTrip toolbox (Oostenveld et al., 2011). The original 2048 Hz data was down sampled to 512 Hz, using chip interpolation and band-pass filtered at 0.1–70 Hz with a two-way Butterworth filter. Artifacts were removed from the continuous EEG. That is, if trials contained too high amplitudes (> 250 μV); contained jumps (detected with *ft_jump_removal.m*); were excessively non-normal (kurtosis > 7); contained flatlining electrodes (inverse of variance > 0.1); or contained excessive noise (variance > 1500). Channels were removed if more than 40% of the signal in a channel contained artifacts. If more than two bad channels were found, the subject was removed completely from further analysis. The cleaned data for each subject was bandpass filtered into 6 bands: delta (0.1–3 Hz), theta (3–6 Hz), infant alpha (6–9 Hz), adult alpha (9–12 Hz), beta (12–25 Hz), and gamma (25–45 Hz).

In the current study, we focused on the infant alpha and theta rhythm, as these rhythms are thought to reflect cognitive performance in the developmental EEG literature (Hofstee et al., 2022; Klimesch, 1999). Previous research revealed that the alpha and theta rhythm networks can be reliably measured in infants (van der Velde et al., 2019). The resulting data was cut into 5s epochs. Twenty random epochs were picked per subject per session. For each epoch, connectivity between pairs of electrodes ($32 * 31/2 = 496$) was calculated using the phase lag index (PLI), relying on the same principle of phase locking or phase synchrony (Tass et al., 1998). The PLI was chosen over the debiased weighted PLI (Vinck et al., 2011), as previous work has shown that the PLI is slightly more reliable in infants (van der Velde et al., 2019).

As an indicator of global network efficiency in infants, the small-world propensity (SWP) was used (Muldoon et al., 2016). This recently developed measure for small-worldness is generally more applicable to weighted brain networks than previous measures of small-worldness (Watts & Strogatz, 1998), due to the incorporation of weighted estimates for clustering coefficient and path length. Additionally, the SWP is density-independent, whereas with previous definitions of small-worldness a negative relationship between network density and small-worldness was observed (small worldness decreased as network density increased). This allows us to use the entire brain network, side-stepping the need for arbitrary thresholds. To calculate the SWP, the deviation of the observed network’s clustering coefficient and path length from both lattice and random networks constructed with the same number of nodes and degree distribution is used:

$$SWP = 1 - \sqrt{\frac{\Delta_C^2 + \Delta_L^2}{2}}$$

where

$$\Delta_C = \frac{C_{latt} - C_{obs}}{C_{latt} - C_{rand}}$$

and

$$\Delta_L = \frac{L_{obs} - L_{rand}}{L_{latt} - L_{rand}}$$

Both Δ_C and Δ_L have been bound between 0 and 1 and therefore SWP is also a value between 0 and 1. Networks with a value closer to 1 will have more small-world characteristics (Muldoon et al., 2016). Bassett & Bullmore (2017) suggest a threshold of SWP > .4 for the network to be considered small-world, but stress that this measure should be seen as continuous, with increasing SWP indicating an increasingly small-world network. The SWP was calculated for each epoch in every subject and the median value was used as efficiency value for a subject.

Functional connectivity within the frontal-parietal regions was computed as the average and normalized PLI between pairs of frontal (Fp1, Fp2, AF3, AF4, F3, F4, F7, F8) and posterior (P3, P4, PO3, PO4, P7, P8, O1, O2) sites and functional connectivity between the frontal-temporal regions were computed as the average PLI between pairs of frontal (Fp1, Fp2, AF3, AF4, F3, F4, F7, F8) and temporal (T7, T8, FC5, FC6, C3, C4, CP5, CP6) sites. The resulting PLI could range from 0 (low connectivity) to 1 (high connectivity). Given the high correlations between local functional connectivity strength and global network strength, the functional connectivity values were normalized to enhance the focus on relative network strength.

2.3.3. Self-regulation

Parent-reported measures of child self-regulation were the Dutch versions of the Infant Behavior Questionnaire – revised - short form (IBQ-R-SF; Putnam et al., 2014), Early Childhood Behavior Questionnaire – short form (ECBQ-SF; Putnam et al., 2006) and Children’s Behavior Questionnaire – very short form (CBQ-SF; Putnam & Rothbart, 2006), depending on the age of the child (IBQ-R-SF for children at T1 and T2, ECBQ-SF for children < 3 years at T3 and CBQ-SF for children 3 years of age and older at T3). The IBQ-R-SF, ECBQ-SF and the CBQ-SF are developmentally equivalent measures that have been shown to have longitudinal stability (Putnam et al., 2008). Mothers were asked to rate the behaviors of their children on a 7-point scale ranging from *never/extremely untrue* (1) to *always/extremely true* (7). An example item of the IBQ is: “When singing or talking to your baby, how often did your baby soothe immediately?” An example item of the CBQ is “Can easily stop doing something when told no”. Parent-reported child self-regulation at T1 and T2 was determined by averaging the scores on the Duration of Orienting ($N = 6$ items), Low Intensity Pleasure ($N = 7$ items), Cuddliness ($N = 6$ items), and Soothability ($N = 7$ items) subscales of the IBQ-R-SF (Putnam et al., 2014). Parent-reported child self-regulation at T3 was determined by averaging the scores on the Attention Focusing ($N = 6$ items), Attention Shifting ($N = 8$ items), Cuddliness ($N = 6$ items), Inhibitory Control ($N = 6$ items), and Low-Intensity Pleasure ($N = 6$ items) subscales of the ECBQ-SF (Putnam et al., 2006), or the Attention Focusing ($N = 6$ items), Inhibitory Control ($N = 6$ items), Perceptual Sensitivity ($N = 6$ items), and Low Intensity Pleasure ($N = 8$ items) subscales of the CBQ-SF (Putnam & Rothbart, 2006). The items used to create the self-regulation score had good internal consistency ($\alpha = .81$ for IBQ-R-SF at wave 1, $\alpha = .85$ for IBQ-R-SF at wave 2, $\alpha = .84$ for ECBQ-SF, and $\alpha = .88$ for CBQ-SF at wave 3).

2.4. Data analysis

The first step in the data analysis included the calculation of Pearson correlations between all variables in IBM SPSS Statistics (version 28).¹ Subsequently, changes in the mean scores of small-worldness and self-regulation over time were investigated using a paired samples t-test. To test the longitudinal mediation model, path analyses were conducted using MPlus 8.4 (Muthén & Muthén, 2007) in which parental support and stimulation at T1 were hypothesized to predict children’s small-worldness at T2 which, in turn, predicts children’s self-regulation at T3. Given that there were high variations in the standard deviations of the variables, standardized scores were created by converting all scores into the same scale (z -scores). Insights from Cole and Maxwell (2003) suggest that causation cannot be inferred without controlling for potential confounds, such as prior levels of the dependent variables. Thus, within the longitudinal model, we controlled for the prior level of small-worldness at T1 and for the prior level of self-regulation at T1 and T2 (see Fig. 1). In addition, given the broad age range within the third wave of the YOUth cohort study, we added mean age of the children at T3 as a control variable. Within the longitudinal mediation model, parental support and parental stimulation were allowed to correlate with each other, as well as the small-world propensity within the alpha and theta rhythms. Throughout the analyses, missing data (4.6% for parenting behaviors at T1, 2.8% for self-regulation at T1, 8.3% for self-regulation at T2 and 0.9% for self-regulation at T3) were handled using maximum likelihood estimation (MLE; Muthén & Muthén, 2007). Goodness-of-fit statistics were used to evaluate the model fit, for which the following cutoffs were used: $\chi^2/df < 3$, Comparative Fit Index (CFI) > .95, Root Mean Square Error of Approximation (RMSEA) < .06, and Standardized Root Mean Square Residual (SRMR) < .08 (Schreiber et al., 2006). Indirect

¹ To provide a more general overview of individual differences in functional connectivity, interconnections between the frontal-parietal and frontal-temporal regions were additionally explored. Correlations with regard to the frontal-parietal and frontal-temporal regions can be found in the supplementary file.

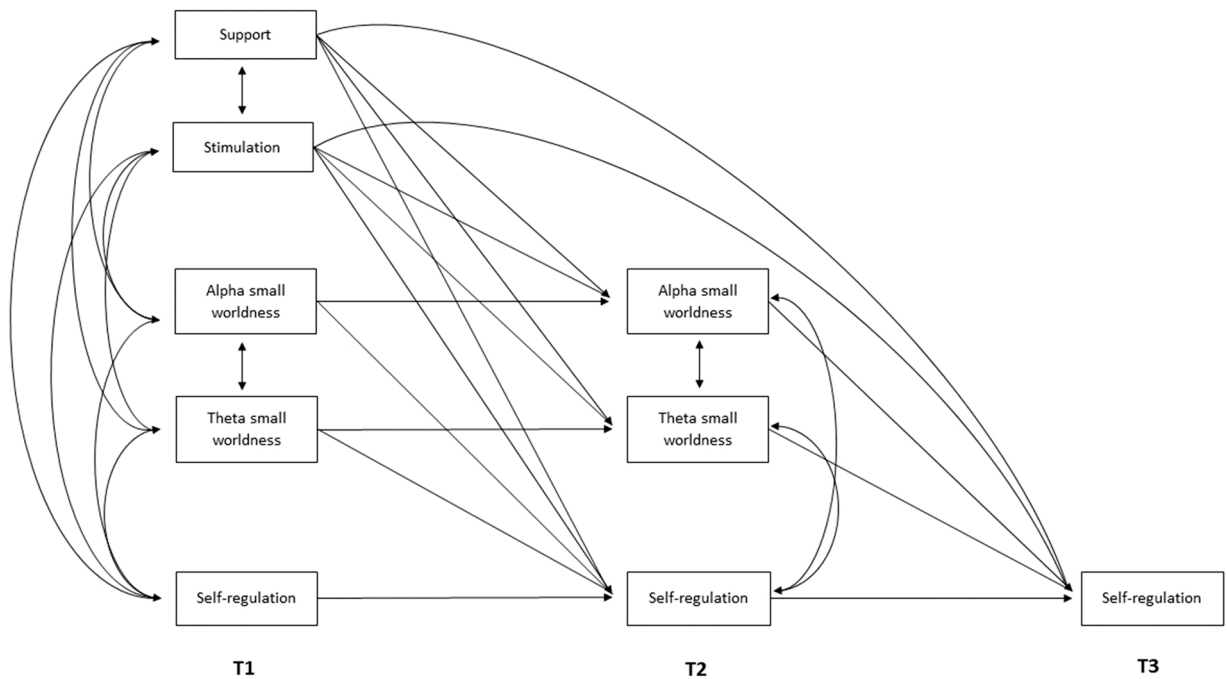


Fig. 1. The hypothesized longitudinal mediation model of the direct and indirect effects of parental support and stimulation and small-worldness within the alpha and theta rhythm on self-regulation from infancy into early childhood.

effects were tested using 10,000 bootstrap samples. The bias-corrected (BC) bootstrap is a recommended nonparametric resampling procedure that is advocated for testing indirect effects in mediation models (Shrout & Bolger, 2002).

3. Results

3.1. Descriptive statistics and correlations

The means, standard deviations, and correlations of the study variables are presented in Table 2. On average, mothers in the sample reported high levels of support and stimulation. Self-regulation decreased over time,² with a significant difference between the first and last wave, $t(104) = 4.87, p < .001$. Infants of the current study showed characteristics of a small-world network topology.³ Levels of small-worldness increased over time, with a significant difference between T1 and T2 within the alpha rhythm, $t(108) = -6.60, p < .001$ and a significant difference between T1 and T2 within the theta rhythm, $t(108) = -6.22, p < .001$. Parental support at T1 was significantly associated with higher levels of child self-regulation at all measurement waves and lower levels of theta small-worldness at T2. No significant associations emerged between parental support and small-worldness within the alpha rhythm. Parental stimulation was not significantly associated with child self-regulation and also no significant associations emerged between parental stimulation and infants' small-worldness. In addition, small-worldness within the alpha rhythm and self-regulation were not significantly correlated. However, within the theta rhythm, lower levels of small-worldness at T2 were related to higher levels of self-regulation at T1 and T2, whereas small-worldness at T1 was positively associated with self-regulation at T3.

3.2. Testing the longitudinal mediation model

In the hypothesized model, direct and indirect effects of parental support and stimulation and children's small-worldness and self-regulation were estimated, controlling for prior levels of small-worldness and self-regulation (see Fig. 1). All fit indices indicated that the hypothesized model had a good fit to the data, $\chi^2/df = 1.36$, CFI = .954, RMSEA = .058, SRMR = .048. The parameter estimates, their standardized errors, and the lower and upper bounds of the confidence interval are presented in Table 3. For an overview of the significant paths in the model, see Fig. 2.

² In addition to the descriptive statistics, mean age of the children was added as a control variable at T3. Mean age at T3 was significantly related to children's self-regulation at T3 ($\beta = .39, SE = .10, p < .001$), indicating that older children in the third wave had higher levels of self-regulation than younger children in this wave.

³ More information about the characteristics of the small-world network topology in infants of the current study can be found in the supplementary file.

Table 2
Descriptive statistics and Pearson correlations for the study variables.

	<i>M</i>	<i>SD</i>	1	2	3	4	5	6	7	8
1. Parental support T1	4.58	.36	–							
2. Parental stimulation T1	4.38	.59	.33**	–						
3. Small-worldness alpha T1	.48	.05	.02	.09	–					
4. Small-worldness alpha T2	.52	.04	.00	.18	.25**	–				
5. Small-worldness theta T1	.50	.04	-.01	-.02	.71**	.07	–			
6. Small-worldness theta T2	.53	.04	-.22*	-.04	-.15	.44**	-.17	–		
7. Self-regulation T1	5.51	.57	.47**	.18	.00	-.18	.05	-.25*	–	
8. Self-regulation T2	5.23	.54	.40**	.10	.12	-.18	.17	-.40**	.50**	–
9. Self-regulation T3	5.13	.62	.31**	.07	.06	-.05	.20*	-.17	.16	.34**

Note. Means and standard deviations were based on a scale ranging from 1 to 5 for parental support and on a scale ranging from 1 to 6 for parental stimulation. * $p < .05$. ** $p < .01$

Table 3
Parameter estimates for the longitudinal mediation model.

	β	<i>SE</i>	<i>p</i>	95% <i>CI</i>	
				Lower bound	Upper bound
Direct effects on self-regulation T2					
Parental support T1	.24	.12	.039	.00	.45
Parental stimulation T1	-.05	.10	.606	-.23	.15
Alpha small-worldness T1	.02	.13	.852	-.21	.31
Theta small-worldness T1	.12	.13	.330	-.15	.35
Direct effects on self-regulation T3					
Parental support T1	.21	.10	.027	.02	.39
Parental stimulation T1	.01	.11	.942	-.20	.22
Alpha small-worldness T2	.03	.10	.770	-.16	.23
Theta small-worldness T2	-.11	.10	.253	-.30	.08
Direct effects on alpha small-worldness T2					
Parental support T1	-.06	.10	.547	-.25	.14
Parental stimulation T1	.18	.08	.035	.00	.34
Direct effects on theta small-worldness T2					
Parental support T1	-.24	.11	.031	-.44	-.01
Parental stimulation T1	.05	.10	.638	-.14	.23
Indirect effects on self-regulation T3					
Parental support T1 through alpha small-worldness T2	.00	.01	.885	-.05	.01
Parental support T1 through theta small-worldness T2	.03	.03	.346	-.01	.11
Parental stimulation T1 through alpha small-worldness T2	.01	.02	.797	-.03	.06
Parental stimulation T1 through theta small-worldness T2	-.01	.02	.749	-.06	.01
Associations with self-regulation T1					
Parental support T1	.47	.08	< .001	.29	.62
Parental stimulation T1	.18	.10	.081	-.03	.37
Alpha small-worldness T1	.00	.10	.995	-.19	.19
Theta small-worldness T1	.06	.09	.534	-.12	.25
Associations with self-regulation T2					
Alpha small-worldness T2	-.16	.12	.190	-.39	.08
Theta small-worldness T2	-.29	.11	.009	-.48	-.05
Associations with alpha small-worldness T1					
Parental support T1	.03	.09	.757	-.15	.21
Parental stimulation T1	.09	.11	.404	-.12	.31
Associations with theta small-worldness T1					
Parental support T1	-.01	.08	.940	-.17	.16
Parental stimulation T1	-.01	.11	.904	-.21	.20

Note. All values are standardized estimates. Direct and indirect effects on self-regulation and small-worldness include values controlled for the previous levels of self-regulation and small-worldness. Estimates presented in bold refer to statistically significant estimates.

Parenting and self-regulation. Model results revealed that parental support was positively associated with child self-regulation at T1 ($\beta = .47$, $SE = .08$, $p < .001$) and it significantly predicted higher levels of child self-regulation at T2 ($\beta = .24$, $SE = .12$, $p = .039$) and at T3 ($\beta = .21$, $SE = .10$, $p = .027$), while controlling for the previous levels of self-regulation. In contrast to parental support, parental stimulation did not significantly predict children's self-regulation at any wave.

Functional brain network efficiency and self-regulation. Alpha small-worldness was not related to variations in child self-regulation at any wave. Lower levels of theta small-worldness at T2 were significantly associated with higher levels of child self-regulation at T2 ($\beta = -.29$, $SE = .11$, $p = .009$). However, theta small-worldness at T2 did not significantly predict variations in children's self-regulation at T3.

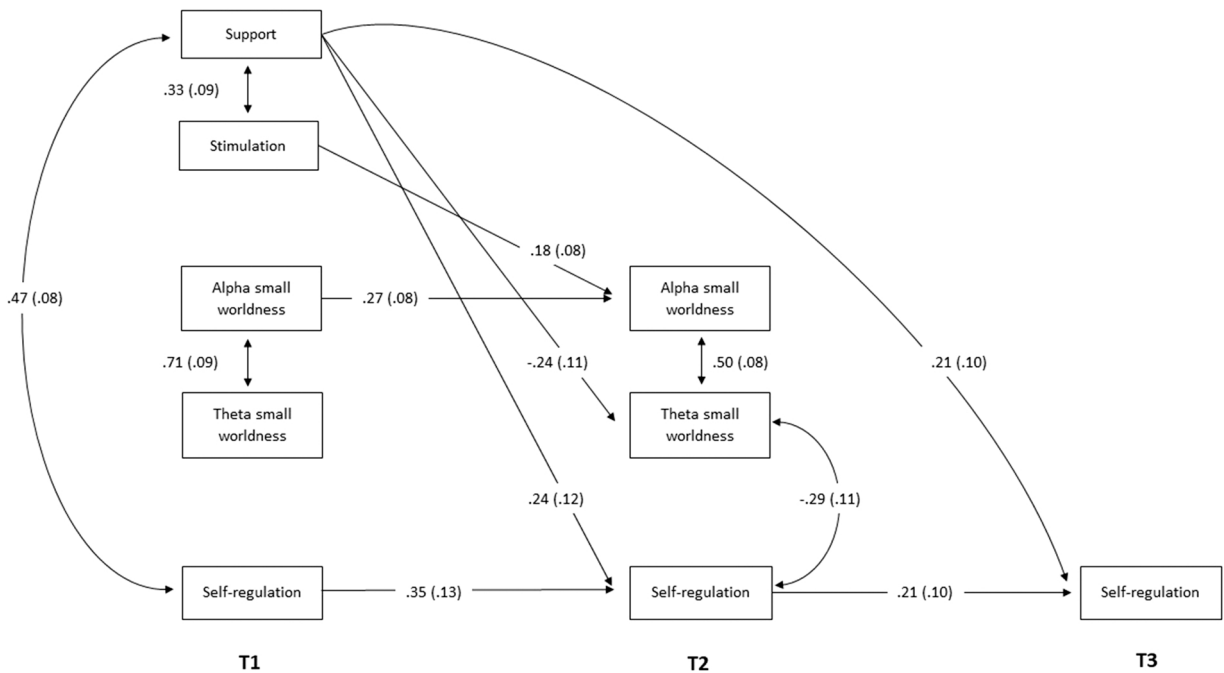


Fig. 2. Standardized model results of the direct and indirect effects. Only significant paths are shown ($p < .05$).

Parenting and functional brain network efficiency. Parental support did not significantly predict alpha small-worldness at T2. However, parental stimulation significantly predicted higher levels of alpha small-worldness at T2 ($\beta = .18$, $SE = .08$, $p = .035$), controlling for small-worldness at T1. There were no significant associations between parenting behaviors and alpha small-worldness at T1. Parental support significantly predicted lower levels of infants' theta small-worldness at T2 ($\beta = -.24$, $SE = .11$, $p = .031$), controlling for theta small-worldness at T1. Parental stimulation did not significantly predict infants' theta small-worldness at T2. Accordingly, infants' small-worldness in both the alpha and theta rhythm at T2 did not mediate the relationship between parenting behaviors at T1 and children's self-regulation at T3.

4. Discussion

The aim of the current study was to expand the literature by examining direct and indirect effects of parenting behaviors (support and stimulation) and the efficiency of functional brain networks (small-worldness) within the alpha and theta rhythms on variations in child self-regulation, using a longitudinal mediation model. The main findings demonstrated that parental support predicted child self-regulation at 5 months, 10 months, and 3 years of age. The effect of parental support on child self-regulation at 3 years of age was not mediated by infants' small-worldness within the alpha and theta rhythm. However, parental support was related to lower levels of infants' small-worldness within the theta rhythm, whereas parental stimulation was related to higher levels of infants' small-worldness within the alpha rhythm. In addition, theta small-worldness was negatively related to individual differences in self-regulation in infants at 10 months of age. These results highlight potential influences of biopsychosocial factors on the development of self-regulation, emphasizing the importance of addressing both extrinsic environmental factors and intrinsic neurobiological factors in relation to variations in child self-regulation. However, these results also illustrate the complex character of the relations between parenting behaviors, efficiency of functional brain networks, and self-regulation during infancy and early childhood. In the following sections, we further discuss the findings of the current study and we give possible explanations for the relations found.

4.1. Developmental changes

First, the development of small-worldness and self-regulation over time was investigated. Consistent with previous work examining the development of small-worldness in infancy (van der Velde et al., 2019), the findings revealed that small-worldness within both the alpha and theta rhythm increased from 5 months of age to 10 months of age. This finding is potentially indicative of an increase in efficiency of infants' functional brain networks (Bassett & Bullmore, 2006). Second, in contrast to developmental literature (e.g., Kopp, 1982; Lobo & Lunkenheimer, 2020), self-regulation slightly decreased over time from infancy to early childhood. However, within the third wave, older children showed higher levels of self-regulation compared to younger children. Although an increase in self-regulation during infancy would be expected as well, the study of Gartstein and Rothbart (2003) also revealed decreases in measures of parent-reported self-regulation during infancy. In addition, previous research revealed a lack of longitudinal measurement invariance when using parent reports to examine self-regulation development in toddlers and preschoolers (Geeraerts et al., 2021).

Therefore, a possible explanation for the decrease in infants' self-regulation might be found within the parent reports.

Although the self-regulation questionnaires used in this study are assumed to be conceptual equal (Putnam et al., 2008), there do appear to be differences between items related to external and internal self-regulation. For instance, Gartstein and Rothbart (2003) describe that many items of the IBQ seem to capture caregiver involvement in infants' regulatory functions (i.e., external regulation), such as soothability. As children grow older, they generally become less dependent on external regulation (Kopp, 1982; Lobo & Lunkenheimer, 2020). Furthermore, increases in mobility might make children less likely to enjoy being held closely by a caregiver (Gartstein & Rothbart, 2003). In contrast, at 3 years of age, items of the (E)CBQ appear more likely to capture factors of internal self-regulation (e.g., inhibitory control and attention focusing) that might rely more on internal child characteristics instead of external regulation. Thus, the decrease in self-regulation from infancy to early childhood, but the increase in self-regulation at 3 years of age, might be a result of the developmental shift from external to internal self-regulation (Kopp, 1982; Lobo & Lunkenheimer, 2020). These conceptual differences in self-regulation can hinder interpretations regarding developmental changes in self-regulation from infancy into early childhood.

4.2. The link between parenting and self-regulation

The social environment is an important context through which co-regulation is built and it plays a crucial role in the developmental shift from external to internal self-regulation (Lobo & Lunkenheimer, 2020). In line with our hypothesis and previous literature (e.g., Bernier et al., 2010; Swinger et al., 2017), parental support predicted higher levels of self-regulation from infancy into early childhood, while controlling for the previous levels of self-regulation. This is consistent with our theoretical framework, assuming that children may feel more comfortable exploring new self-regulatory strategies in environments in which parenting behaviors serve as a warm and secure base (Ainsworth, 1979; Matas et al., 1978). It was surprising to find that parental stimulation was not related to variations in child self-regulation, as stimulating parenting behaviors have been linked to self-regulatory behaviors in previous literature (for a review, see Fay-Stammach et al., 2014). However, within the review of Fay-Stammach et al. (2014), positive associations between parental stimulation and individual differences in child self-regulation were found in studies using observational measures (HOME; Bradley et al., 2011) to assess parental stimulation in the home environment (e.g., Clark et al., 2013; Mezzacappa et al., 2011). In contrast, parental stimulation was not related to individual differences in child self-regulation when parental stimulation was assessed by self-reports (Blankson et al., 2011). This might be a result of the more general items of parental stimulation, such as items of the CECPAQ used in the current study, that focus on stimulating motor and language development, rather than children's self-regulatory behaviors (Verhoeven et al., 2017). Future studies could use other complementary methods to investigate variations in parenting behaviors, such as observational tools, to better quantify aspects of parental stimulation related to children's self-regulatory behaviors.

4.3. The link between functional brain networks and self-regulation

In line with the notion that increases in small-worldness are indicative of increased functional brain network efficiency (Muldoon et al., 2016), previous research revealed that small-worldness was positively related to variations in child self-regulation (Fekete et al., 2014). Unexpectedly, we found the opposite pattern of results: Alpha small-worldness was not related to individual differences in child self-regulation at any wave and lower levels of theta small-worldness were related to higher levels of child self-regulation at 10 months of age. Given that the first year of life is a critical period in the maturation of functional brain networks, during which the over-production of neural connections is followed by synaptic pruning (Gao et al., 2017), it might be that the small-world network needs to flexibly adapt to the reorganization of neural connections in infancy. This is supported by the first study to examine the relationship between functional connectivity and small-worldness in adults, showing that increased functional connectivity is compensated with decreased small-worldness and vice versa (Päeske et al., 2020). In addition, results of the study of Xie et al. (2019) revealed a presence of a small-world topology in infants 6 and 8 months of age, but not in infants 10 and 12 months of age. These differences in small-world network topology suggest that functional brain networks of infants continuously reorganize with a rewiring of neural connections (Gao et al., 2017; Gilmore et al., 2018). More research is needed to examine whether and how small-worldness is a measure of brain network efficiency in the different developmental periods.

Furthermore, although the same parent reports were used in both studies to assess variations in child self-regulation, the current study revealed significant relations between individual differences in small-worldness and self-regulation in infants at 10 months of age, whereas the study of Fekete et al. (2014) focused on pre-school age children. Given that the parent reports in the current study, that were used to assess variations in self-regulation during infancy, seem to have captured some factors of external self-regulation, it might be that infants with lower levels of small-worldness rely more on external regulation of their parents, such as soothing techniques. This could explain their higher scores on the parent reports of self-regulation during infancy. This notion is further supported by our finding that higher levels of theta small-worldness in infants 5 months of age did relate to higher levels of self-regulation in children 3 years of age; a developmental phase in which the parent reports appear more likely to capture factors of internal self-regulation. These findings highlight the possible conceptual differences between the parent reports during infancy (IBQ) and during early childhood (ECBQ and CBQ).

4.4. The link between parenting and functional brain networks

Considering that higher levels of small-worldness are indicative of more optimized brain network efficiency, we expected that both

parental support and parental stimulation would predict higher levels of infants' small-worldness. In line with our hypothesis, parental stimulation indeed predicted higher levels of small-worldness within the alpha rhythm at 10 months of age, while controlling for alpha small-worldness at 5 months of age. However, in contrast, parental support predicted lower levels of small-worldness within the theta rhythm at 10 months of age, while controlling for the prior levels of theta small-worldness. Given the co-regulatory role of supportive parenting behaviors, it might be that parental support is a form of external regulation, that does not necessarily lead to more optimized functional brain networks in infants. Parental support is defined as the ability to attend and respond to children in ways that are contingent to children's signals and needs (Ainsworth, 1969). For instance, young infants still need their parents in order to calm down and recover from distress (e.g., Bernier et al., 2010; Rothbart et al., 2011). Although these parenting behaviors are needed to externally regulate infants' emotions, thoughts, and behaviors, it might be that infants who rely too much on support from their parents might not yet develop efficient brain networks within the first year of life.

In order to stimulate positive child development, parents may also need to encourage their children to explore the environment themselves, without the need for co-regulation (Ainsworth, 1979; Bowlby, 1969). As parental stimulation provides greater opportunities for infants to exercise self-regulatory skills autonomously and efficient communication between distinct brain regions is needed to perform these more complex behaviors, this might result in more efficient brain networks in infants at 10 months of age (Heatheron & Wagner, 2011; Posner et al., 2016). Thus, besides providing a warm and secure environment for infants, parents might need to stimulate the development of efficient brain networks by stimulating their children to explore the environment autonomously.

Beside the conceptual differences between parental support and parental stimulation, the different findings with regard to the two parenting behaviors may be related to frequency-dependent changes as well. As the alpha rhythm is thought to reflect inhibitory processes (Klimesch et al., 2007) and the theta rhythm is thought to reflect cognitive control (Liu et al., 2014; Orekhova et al., 2006), these frequency bands might be differently related to parental support and stimulation. This is supported by results of the study of Perone and Gartstein (2019), that revealed that the significant relation between parental support and infants' functional connectivity between specific brain regions was depended on the type of cortical rhythm (i.e., frontal region within the alpha rhythm and frontal-posterior regions within the theta rhythm). However, within the developmental EEG literature there is a lack of theory as to what specific cortical rhythms are measuring. For example, in some contexts, the infant alpha rhythm exhibits properties similar to the adult theta rhythm (see Cuevas & Bell, 2022, for review). More multi-frequency band EEG research is therefore needed to further investigate the relations between parenting behaviors and functional brain networks in young children.

4.5. The mediating role of functional brain network efficiency

Although self-regulation was significantly related to parental support and theta small-worldness, and significant associations between parenting behaviors and theta small-worldness were found, the hypothesized mediational pathway of small-worldness was not significant. These findings indicate that parenting behaviors and functional brain networks each uniquely contribute to variations in child self-regulation. Given the complex nature of interactions between extrinsic environmental factors and intrinsic neurobiological factors, it might be that parenting behaviors and infants' functional brain networks work together, as well as individually, to influence emerging self-regulatory capacities (Calkins et al., 2016; Olson & Sameroff, 2009). Importantly, findings of the current study were most prominent within the theta rhythm, although most previous literature focuses on relations with the infant alpha rhythm (for a meta-analysis, see Hofstee et al., 2022). This is in agreement with earlier work from van der Velde et al. (2021), that revealed that functional connectivity within the theta rhythm was related to variations in social development in infants, in contrast to the alpha rhythm. Thus, future research could investigate the theta rhythm in addition to the alpha rhythm, to reach a more comprehensive understanding of the differences between the alpha and the theta rhythm in relation to child development.

4.6. Strengths, limitations, and future directions

The current study provides the first longitudinal analysis of interactions between variations in parenting behaviors and efficiency of functional brain networks in relation to individual differences in self-regulation in infants and preschool age children. Moreover, as a result of the large scale YOUth cohort study, the current study included a larger sample size compared to most neuroimaging research (Button et al., 2013). Although providing relevant information about the direct and indirect effects of biopsychosocial factors on self-regulation over time in a relatively large sample of children, the current study comes with some limitations.

One reason for the non-supported hypotheses may be that only data from the primary caregivers was included, that happened to be solely mothers within this population. However, fathers also generally play a significant role in the development of child self-regulation and the findings relating to mothers' behaviors may not generalize to fathers' behaviors (Cassano et al., 2014). Attention to the potential role of fathers' behaviors or even behaviors of nonparental caregivers is essential to gain a more complete picture of the relation between extrinsic environmental factors and variations in child self-regulation. Moreover, mothers within the current study mostly had a higher SES and there was little variation in positive and negative parenting behaviors, which limits generalizability of results. Future studies should try to include more heterogeneous and larger samples to allow for greater generalizability of results and a clearer insight into the relations with variations in parenting behaviors (Bhavnani et al., 2021).

Furthermore, only the effects of variations in parenting and functional brain networks on individual differences in child self-regulation were investigated, without regard to reciprocal processes. The transactional model of development emphasizes multidirectional perspectives, where individual behaviors reciprocally changes both extrinsic environmental factors and intrinsic neurobiological (Sameroff, 2010). Yet, examining the bi-directional nature of the biopsychosocial factors of self-regulation was beyond the scope of the current study. Future research is necessary to study whether bi-directional relationships exist between the biopsychosocial

factors of self-regulation during infancy and early childhood.

Finally, although the larger sample size is a strength of the current study, power could still be an issue if more variables were included within the longitudinal mediation model. Brain function contains different dimensions that can be measured by a variety of indicators. In the current study, we focused on the global network characteristic small-worldness as a mediator. However, small-worldness is only one property of the complex brain network at a certain threshold and does not completely characterize the network efficiency. Future studies could include more network characteristics in their analysis to gain more insight into the relations of individual differences in parenting and self-regulation with variations in functional brain network efficiency.

5. Conclusions

Findings of the current study demonstrate the complex nature of interactions between extrinsic environmental factors and intrinsic neurobiological factors. They also indicate that parenting behaviors and functional brain networks may be uniquely related to variations in emerging self-regulatory capacities in young children. More specifically, parents may need to stimulate their infants to explore the environment autonomously, to come to more efficient functional brain networks as children grow older. Until that time, parental support might fill in the role of external regulation in infants, when the brain is not sufficiently developed to perform self-regulation itself. Thus, a flexible balance between supportive and stimulating parenting behaviors might be most effective in the development of both children's functional brain networks and children's self-regulatory behaviors. However, much more research is needed to further investigate whether and how small-worldness is a measure of the efficiency of functional brain networks in the different developmental periods and how this is related to variations in parenting behaviors and self-regulatory skills during infancy and early childhood.

CRedit authorship contribution statement

Marissa Hofstee: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Bauke van der Velde:** Conceptualization, Software, Formal analysis, Writing – review & editing. **Jorg Huijding:** Supervision, Conceptualization, Methodology, Writing – review & editing. **Joyce Endendijk:** Conceptualization, Methodology, Writing – review & editing. **Chantal Kemner:** Funding acquisition, Writing – review & editing. **Maja Deković:** Supervision, Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

Author note

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.infbeh.2022.101769](https://doi.org/10.1016/j.infbeh.2022.101769).

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