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Cortex

Special Issue "Understanding Others": Research Report

The effects of interaction quality on neural synchrony during mother-child problem solving

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ABSTRACT

Understanding others is fundamental to interpersonal coordination and successful cooperation. One mechanism posited to underlie both effective communication and behavioral coordination is interpersonal neural synchrony. Although presumably foundational for children's social development, research on neural synchrony in naturalistic caregiver-child interactions is lacking. Using dual-functional near-infrared spectroscopy (fNIRS), we examined the effects of interaction quality on neural synchrony during a problem-solving task in 42 dyads of mothers and their preschool children. In a cooperation condition, mothers and children were instructed to solve a tangram puzzle together. In an individual condition, mothers and children performed the same task alone with an opaque screen between them. Wavelet transform coherence (WTC) was used to assess the cross-correlation between the two fNIRS time series. Results revealed increased neural synchrony in bilateral prefrontal cortex and temporo-parietal areas during cooperative as compared to individual problem solving. Higher neural synchrony during cooperation correlated with higher behavioral reciprocity and neural synchrony predicted the dyad's problem-solving success beyond reciprocal behavior between mothers and children. State-like factors, such as maternal stress and child agency during the task, played a bigger role for neural synchronization than trait-like factors, such as child temperament. Our results emphasize neural synchrony as a biomarker for mother-child interaction quality. These findings further highlight the role of state-like factors in interpersonal synchronization processes linked to successful coordination with others and in the long-term might improve the understanding of others.

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1. Introduction

Mutual attunement of behavior and physiology between children and caregivers is thought to play a vital role for both attachment and the development of social and emotional competences (Atzil & Gendron, 2017; Stern, 1985). This relation appears particularly relevant when the child is distressed and thus in a state of allostasis deviation, with allostasis generally referring to the process of maintaining biobehavioral balance through adaptation (McEwen & Wingfield, 2003; Sterling, 2012). The caregiver's actions of soothing the child thus help to reestablish a state of allostasis (Atzil & Gendron, 2017; Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011). Both temporal structure and rewarding nature of these synchronous interactions provide children with information to map certain bodily states to underlying mental experiences (Meltzoff & Decety, 2003). Accordingly, by being understood and cared for, children learn how to understand and care for others (Atzil & Gendron, 2017).

Despite available investigations into behavioral and physiological synchrony, we still know little about the potential role of neural synchrony in caregiver-child exchanges. Early findings from social neuroscience research suggest that neural synchrony facilitates the coordination of behavior and predicts cooperative task performance in adult-infant and parent-child interactions (Leong et al., 2017; Miller et al., 2019; Reindl, Gerloff, Scharke, & Konrad, 2018), corroborating findings from previous research in adults (Baker et al., 2016; Liu et al., 2016). Social interactions in these studies were, however, highly controlled due to the use of simplified and artificial tasks and thus did not require elaborate perspective-taking or communication. Although these studies provided important initial evidence for the role of neural synchrony in early behavioral coordination, these interactions did not reflect complex coordinated exchanges that mothers and children engage in everyday life. Hence, these findings lacked the integration of neural data with more complex and naturalistic measures of social behavior (McDonald & Perdue, 2018). In addition, few studies have examined caregiver-child interactions at preschool age when the child moves beyond the dependency experienced during infancy and toddlerhood towards greater agency (Harrist & Waugh, 2002).

Here, we observed mothers and preschool children in a naturalistic problem-solving interaction, which allowed us to examine individual differences facilitating or attenuating mother-child neural synchrony. Based on attachment theory, we predicted that behavioral reciprocity and maternal sensitivity support neural synchronization processes (Vrticka, 2017). We used dual functional near-infrared spectroscopy (fNIRS) to simultaneously measure brain activity in mothers and children during a video-recorded live interaction, thus, probing the supposed links between interaction quality, collaborative success, and neural synchronization.

In recent years, the investigation of neural synchrony has been considerably facilitated through advancements in simultaneous neuroimaging of multiple brains — known as "hyperscanning" (Babiloni & Astolfi, 2014). A growing number of hyperscanning studies looked at neural synchrony in adult dyads during imitation, free verbal conversation, and cooperative versus competitive interaction (for reviews see Dumas, Lachat, Martinerie, Nadel, & George, 2011; Hasson, Ghazanfar, Galantucci, Garrod, & Keysers, 2012; Liu & Pelowski, 2014). Conversely, adult-child and more specifically parent-child neural synchronization has only recently come into the focus of developmental research (Leong et al., 2017; Miller et al., 2019; Reindl et al., 2018). Synchronization of neural oscillations is assumed to reflect mutual attunement of behavioral and physiological rhythms (Hasson et al., 2012) that are transmitted interpersonally through the environment by coupling of the sensory system of one person to the motor system of another person. According to the phase reset model, such coupling occurs because ongoing oscillations in the receiver reset their phases to the incoming oscillations from the sender (Brandt, 1997). In doing so, both the sender's and receiver's brains entrain to the rhythm of the transmitted signal, providing a neural underpinning for interpersonal exchanges and behavioral synchronization in the form of turn taking (Wilson & Wilson, 2005). More specifically, neural synchrony is suggested to facilitate internal predictions about the self and others and thus optimize behavior during interactions (Dai et al., 2018). Beyond enabling complex coordinated behaviors, such as joint action and joint decision making (Novembre, Knoblich, Dunne, & Keller, 2017), neurobehavioral synchrony is further posited to create an optimal learning environment for the child through the regulation of the infants' needs (Atzil & Gendron, 2017). Consequently, the coupling of rhythmic brain activity can emerge dyadically through language or motion, but can be also externally triggered through joint attention or music (Cirelli, Trehub, & Trainor, 2018; Leong et al., 2017; Nummenmaa, Lahnakoski, & Glerean, 2018).

To date, only three studies that investigated adult-child and parent-child neural synchrony have been published. In a dual-electroencephalography (EEG) study by Leong et al. (2017), a female presenter sang either live or prerecorded nursery rhymes to an infant in a direct gaze and an averted gaze condition. Neural synchrony between adults and infants was increased during the live interaction compared to televised singing. In addition, higher neural synchronization was observed during direct as compared to indirect gaze, revealing mutual gaze as a modulator of neural synchrony. Using dual-fNIRS, two recently published studies investigated parent-child interactions, focusing on cooperation (Miller et al., 2019; Reindl et al., 2018). Both studies examined the interaction of school-aged children with their parents during a computerized reaction time task (Cui, Bryant, & Reiss, 2012). Findings revealed increased neural synchrony in frontal and temporal areas during parent-child cooperation in comparison to individual task engagement, competition, and stranger—child interaction. Moreover, neural synchrony predicted dyadic task performance corroborating findings from previous research on the consequences of neurobehavioral synchrony in adults (Baker et al., 2016; Liu et al., 2016). These studies further indicate that neural synchrony with the caregiver is positively related to children's emotion regulation skills (Reindl et al., 2018) and differs depending on the biological sex of the child (Miller et al., 2019). Miller et al. (2019) were also the first to take individual differences into account. They found a negative association between avoidant

child-mother attachment and neural synchrony in the right prefrontal cortex during cooperation. However, this association did not survive a more stringent correction for multiple comparisons and therefore remains preliminary.

Given this preliminary evidence of neural synchronization in adult-child and parent-child interactions (Leong et al., 2017; Miller et al., 2019; Reindl et al., 2018), it appears vital to more precisely identify personality, relationship, and interactional factors modulating neural synchrony and its consequences in early social interactions. In particular, attachment theory can provide valuable insights into possible factors reflecting individual differences in interaction quality for neural synchronization (Vrticka, 2017; Vrticka & Vuilleumier, 2012). Behavioral reciprocity is generally thought to be an important aspect of interaction quality in parent-child interactions, fundamental to the development of secure attachment, and associated with cognitive, emotional, and social competences (Leclère et al., 2014). Behavioral reciprocity refers to a "dynamic and reciprocal adaptation of the temporal structure of behaviors and shared affect between interactive partners" (Harrist & Waugh, 2002). It seems as if caregivers and children perform an intricate dance, built on the familiarity of each other's behaviors (Leclère et al., 2014). More specifically, reciprocal interactions generate a rhythmicity between the two interactive partners that helps individuals to form anticipations based on the temporal regularity of behaviors, allowing them to make mutual adjustments (Keller, Novembre, & Hove, 2014; Reddy, Markova, & Wallot, 2013). On this account, it has been shown that contingent interactions between robots and preschool children can foster second language learning (Vogt, de Haas, de Jong, Baxter, & Krahmer, 2017). In addition, temporally and semantically contingent responses from mothers were related to toddlers' expressive vocabulary (McGillion et al., 2013). However, in preschool age research regarding the direct outcomes of synchronization is still lacking (Harrist & Waugh, 2002; Leclère et al., 2014).

Behavioral coordination is assumed to be influenced by both state-like and trait-like characteristics that individuals and dyads bring to the interaction (Leclère et al., 2014). For example, maternal sensitivity has been shown to affect synchrony (Thompson & Trevathan, 2009), which is also maintained to be essential to infants' attachment (Ainsworth & Bell, 1970; Beebe & Steele, 2013; Isabella & Belsky, 1991). Within this context, maternal sensitivity is described as the mother being able to perceive and understand an infant's signals, as well as to respond contingently and adequately to the infant's needs - which makes maternal sensitivity an important prerequisite for attuning to their infant (Beebe & Steele, 2013; Thompson & Trevathan, 2009). Moving into preschool age, maternal sensitivity continues to be an important predictor of a child's social and cognitive development, especially regarding theory of mind abilities (Lemelin, Tarabulsy, & Provost, 2006; Symons & Clark, 2000). Consequently, maternal sensitivity might be instrumental in establishing neural synchronization. Interestingly, meta-analyses provided evidence that maternal sensitivity, even though important, is not an exclusive condition of attachment security, suggesting that current contextual factors, like stress, could undermine sensitive caregiving behavior

and consecutively affect the parent-child relationship (Booth, Macdonald, & Youssef, 2018; Wolff & Ijzendoorn, 1997).

As children develop beyond infancy and toddlerhood, synchronous interactions are increasingly symmetric, as children improve in communication skills and social competences (Harrist & Waugh, 2002). Preschool children become more autonomous as they gain agency during social interactions (Harrist & Waugh, 2002). Both parental and teacher agency support and child agency as such have been proposed to be indicative behaviors for high interaction quality during (pre-)school age (Houen, Danby, Farrell, & Thorpe, 2016; Rocissano, Slade, & Lynch, 1987). While evidence suggests that mothers who follow the child's lead can uphold reciprocal interactions much longer than mothers who try to control the interaction, there are only few studies that consider child agency.

Given that children differ in their emotional, motor, and attentional reaction to stimulation (Putnam, Sanson, & Rothbart, 2002), personality differences might also affect their ability to synchronize with their caregivers. There is growing evidence that children prone to negative emotionality, also described as having a difficult temperament, have difficulties synchronizing with their mothers (Feldman, 2003). However, empirical evidence also suggests that children showing negative emotionality benefit most from sensitive, responsive caregiving behavior (Ellis, Boyce, Belsky, Bakermans-Kranenburg, & van Ijzendoorn, 2011; Kochanska & Kim, 2013). Indeed, negative emotionality has been shown to strengthen the relation between reciprocal interactions and positive developmental outcomes (Feldman, Greenbaum, & Yirmiya, 1999). According to Belsky (2013), children differ in their susceptibility to both adverse and beneficial rearing environments and negative emotionality is proposed to be one of the susceptibility factors. Children can benefit tremendously from optimal caregiving, but can also be much more affected by risky environments.

We used dual-fNIRS to investigate a naturalistic caregiver-child interaction during a tangram puzzle-solving task by contrasting a cooperative problem-solving condition to individual problem-solving. The problem-solving task was designed to be challenging for a preschool child in order to encourage mutual task engagement during joint problem solving, require mutual perspective-taking and communication, and activate maternal caregiving. When the mothers and children both take turns moving the puzzle pieces, we expected the dyad to attune their behavior to one another as characterized by behavioral reciprocity. We measured neural synchrony through fNIRS in temporo-parietal areas implicated in social cognitive processes such as mentalization and shared intentionality, also referred to as the sharing of psychological states (Miller et al., 2019; Saxe, 2010; Tomasello & Carpenter, 2007). Furthermore, we assessed synchrony in prefrontal areas related to executive functioning, complex decision making, and effective communication (Reindl et al., 2018; Stephens, Silbert, & Hasson, 2010; Tsujimoto, 2008). We expected higher neural synchrony in both areas to be present during joint problem solving compared to individual problem solving and to manifest itself in concordance with behavioral reciprocity.

Furthermore, we predicted higher neural synchronization to be associated with successful joint problem solving. We also expected maternal sensitivity and child agency to be related to higher synchronization, whereas we predicted maternal stress and children's difficult temperament, namely negative emotionality, to mitigate synchronization. Taken together, we suggest that during problem solving in caregiver-child dyads, neural coupling is a fundamental mechanism supporting behavioral coordination through processes of facilitated shared intentionality, affect attunement, and communication. Probing the relation between neural synchrony and interaction quality in a naturalistic context will thus advance our understanding of the neural underpinnings to caregiver-child interactions.

2. Material and methods

2.1. Participants

Data from forty-two mothers (mean age 36.26 years; $SD = 4.81$ years; $range = 28$—46 years) and their preschool children (19 boys and 23 girls; mean age 5; 08 years; $SD = 0$; 04 years; $range = 5$; 00—6; 01) were analyzed for the present study. From the initially recruited forty-six mother-child pairs, four were excluded due to either technical problems or children not complying with the given instructions. Fifty-seven percent of mothers graduated with a university degree, while the remaining mothers graduated from vocational school. Each mother-child pair was biologically related. The pairs were all caucasian and children were typically developing. Participants were recruited from a pre-existing database of volunteers and mothers gave written consent for both themselves and their children before participating in the study. Procedures were approved by the local ethics committee.

2.2. Experimental procedure

During the experiment, mother and child sat face-to-face (see Fig. 1), separated by a table. The dyads were guided through the following sequence: Task — Rest — Task — Rest — Task — Rest — Task — Verbal Conversation. For the task phase, dyads participated in a tangram puzzle-solving task during which they were asked to arrange seven geometric shapes to recreate different templates (abstract forms, objects, animals; see SI Appendix, Figure S1). The task comprised two different experimental conditions that were equally distributed. In the cooperation condition, both caregivers and children were instructed to jointly solve the templates. The specific instructions are included in SI Appendix, Section 1. In the individual condition, an opaque screen separated the mothers and children to prevent them from interacting with each other and to provide a non-competitive context. In both conditions, four puzzle templates were provided to each dyad, and participants were instructed to recreate all of them. Each task lasted 120 s and the condition order was counterbalanced. Participants were instructed to rest (eyes closed) for 80 s in between each task. After performing all task conditions, the mothers and children were instructed to engage in an additional free verbal conversation for 240 s (not reported here). The complete procedure was video recorded from three different angles.

2.3. fNIRS data acquisition

We used a NIRScout 8—16 (NIRx Medizintechnik GmbH, Germany) Optical Topography system to record oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) concentration changes for each dyad. The four 2×2 probe sets were attached to an EEG cap with 10—20 configuration. The standard electrode locations allowed us to place the probes more precisely, as the probe sets over the left and right dorsolateral prefrontal cortex

Fig. 1 — Study set-up during cooperation (left) and individual (middle) problem solving as well as the rest phase (right). Rows indicate possible sequences to counterbalance (Latin square) the order of tasks.

(dlPFC) surrounded AF3 and AF4, whereas the probes on the left and right temporo-parietal junction (TPJ) surrounded CP5 and CP6 (see Fig. 2). ROIs were based on previous work involving social mentalizing in a cooperative setting (Jiang et al., 2012; Liu et al., 2016; Miller et al., 2019; Reindl et al., 2018). In each probe set, eight sources and eight detectors were positioned, which resulted in 16 measurement channels with equal distances of 3 cm between the optodes. The absorption of near-infrared light was measured at wavelengths of 760 and 850 mm and the sampling frequency was 7.81 Hz.

2.4. fNIRS data processing

Before analyzing the fNIRS measurements, raw data were visually inspected during an initial quality check procedure. In so doing, all channels that did not show a clear heart band were removed, which resulted in 93.4% of the channels from the whole sample being included in further analyses. In addition, we had an inclusion threshold of two channels per region of interest, which all participants passed. After this initial step, data were subsequently pre-processed using MATLAB-based functions derived from Homer 2 and SPM-fNIRS. Raw optical density data were motion corrected with MARA, a smoothing procedure based on local regression using weighted linear least squares and a 2nd degree polynomial model (Scholkmann, Spichtig, Muehlemann, & Wolf, 2010), then band-passed filtered with low- and high-pass parameters of .5 and .01 (Baker et al., 2016; Miller et al., 2019). Next, the filtered data were converted to HbO and HbR values based on Beer–Lambert Law. For later statistical analyses, we only focused on HbO values, which were reported to be more

sensitive to changes in the regional cerebral blood flow (Miller et al., 2019; Reindl et al., 2018).

2.4.1. General linear model analysis
The differential patterns of individual cortical activation that occurred throughout the different conditions were assessed using a general linear model (GLM) approach. The evoked hemodynamic responses were modelled as a boxcarr function convolved with a canonical hemodynamic response (Issard & Gervain, 2018), with the onset and duration of each condition modeled in seconds. As a result, standardized beta coefficients for each condition we estimated. The sign and magnitude of each beta coefficient provide an indicator of the direction (positive/negative) and intensity of HbO change (i.e., cortical activity) that occurred during each condition.

2.4.2. Wavelet transform coherence analysis
Neural synchrony was calculated with wavelet transform coherence (WTC) (for more information see Chang & Glover, 2010; Grinsted, Moore, & Jevrejeva, 2004). WTC was used to assess cross-correlation between the fNIRS time series in each dyad and each channel as a function of frequency and time. WTC considers global coherence patterns of brain activity and offers another advantage, as it considers phase-lagged correlations in addition to in-phase correlations. This type of coherence calculation fits well with the literature (e.g., Liu et al., 2016; Baker et al., 2016) thus far, suggesting that both concurrent and sequential behavioral synchrony might be linked with neural synchronization. Based on the duration to complete one template, visual inspection, and spectral analyses, task duration was established and the frequency band of .02 Hz–.10 Hz (corresponding to 10 - 50 sec) was identified as task-related. Average neural coherence (i.e., neural synchrony) was then calculated for the two cooperation conditions, the two individual conditions, and the three resting phases in each channel, which resulted in 3 (conditions) x 16 (channels) coherence values for each dyad. For all three conditions the same length of data, namely 240 s, were included the calculation. The resting period was included to explore two different non-interactive control conditions and to allow the dyad to have a "reset time" after each task, as well as the possibility to start off on a similar footing into each task condition.

All neural synchrony values were standardized with Fisher's z-Transformation prior to statistical analyses (Baker et al., 2016). To rule out effects due to spurious correlation, we conducted a random pair analysis with 1,000 permutations. Coherence values of original dyads in each condition were tested against a distribution of randomized pair coherences in the same condition. Resulting p-values were then corrected with a false discovery rate (FDR) for multiple comparisons (Benjamini & Hochberg, 1995).

2.5. Behavioral ratings

The caregivers' and children's behavior during the cooperation condition was rated from video recordings by trained graduate students to assess interaction quality using a customized coding scheme based on the Coding System for Mother–Child Interactions (CSMCI) (Healey, Gopin, Grossman,
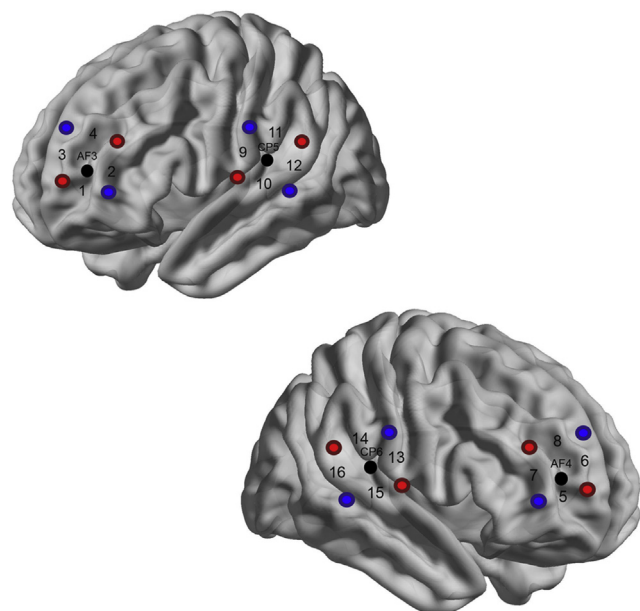

Fig. 2 – Cap Configuration. Red circles mark sources, while blue circles mark detectors. Numbers (1–16) mark measurement channels between sources and detectors. Black circles mark EEG 10–20 channel positions for orientation. The top graphic shows the left hemisphere, while the bottom graphic shows the right hemisphere.

Campbell, & Halperin, 2010). In addition, a German instrument was used to assess mother-child interactions, labeled INTAKT (an agglomeration of the German word Interaktion meaning interaction, and intakt, meaning intact - referring to an intact mother child relationship; Hirschmann, Kastner-Koller, Deimann, Aigner, & Svecz, 2011). For this study, ratings of maternal supportive presence and respect for autonomy, child agency, behavioral reciprocity (CSMCI), and maternal sensitivity (INTAKT) were performed. First, maternal supportive presence was rated as high when mothers voiced encouragement or praise and showed emotional support throughout the interaction. Additionally, respect for autonomy indicated if the mothers acted in a way that recognized and respected the validity of the children's individuality, motives, and perspectives. We further included a general maternal sensitivity scale to assess whether mothers adequately and promptly responded to children, as well as was whether they were able to take over the children's perspective (Hirschmann et al., 2011). The scale used is a German variation of Ainsworth's sensitivity scale and was adapted to the preschool age range. In addition, child agency was coded for how active and confident children approached working on the task and initiated goal-directed behavior. Behavioral reciprocity was furthermore marked by contingent responses resulting in a turn-taking quality of interactions as behavioral flow. Finally, communicative reciprocity was marked as turn-taking quality of verbalizations. Each subscale was rated on a 7-point Likert-type scale (1 = no occurrence, 7 = continuous occurrence). The cooperation tasks were coded for each block and coding values were averaged over both blocks. To calculate coding reliability, we selected 20% of the interactions and compared observations by intraclass correlations (ICC). ICC estimates and their 95% confidence intervals were calculated based on consistency employing a 1-way mixed-effects model. Coders showed moderate to excellent reliability over all assessed scales, ranging from $ICC = .76$-.93 and averaging at $ICC = .86$. When coders disagreed on ratings, the scores of the most experienced coder were used. We further assessed the number of templates solved in each condition.

2.6. Maternal stress

Maternal current stress levels were assessed with the General Stress Level Questionnaire (Bodenmann, 2000). This self-report questionnaire comprises questions on stressors regarding general issues, relationship, family, and finances on a 5-point scale ranging from 1 (not at all) to 5 (very strong). Internal consistency was adequate with Cronbach's a = .80.

2.7. Child temperament

To measure individual differences in temperamental negative affectivity in children, the very short form of the Children's Behavior Questionnaire (CBQ) (Putnam & Rothbart, 2006) was used. Temperament scores are based on parent's report on a 7-point scale ranging from 1 (extremely untrue of your child) to 7 (extremely true of your child). We only used the subscale Negative Affectivity (NA), which is marked by Sadness, Fear, Anger, Frustration, Discomfort, and Difficulties in Soothing.

Internal consistencies of the subscales were high with Cronbach's a = .86.

2.8. Statistical analysis

Statistical analyses were calculated with R packages. In particular, linear mixed models were fitted with package "lme4" (Bates, Mächler, Bolker, & Walker, 2015). Raw data was examined prior to any calculations and if necessary corrected for normal distribution as well as outliers. This step was deemed necessary for maternal stress and child temperament scores due to their right skewed distribution. Outliers were defined by values over or under three standard deviations (SD) from the mean. Outliers were then winsorized to the respective lower and/or upper boundaries in each subscale and over all coherence values (Wilcox, 2017).

To analyze individual cortical activation patterns, standardized beta coefficients were entered as the response variable in a linear mixed effects model with condition (cooperation vs. individual vs. rest) and region of interest (ROI; four per dyad) as predictors and with random slopes for each ROI and condition in each dyad and channel. The grouping of channels in our statistical model was done to enhance reliability of region specification accounting for minimal variance in optode positioning during testing. Channel clustering provides a more meaningful and realistic interpretation of the results (Azhari et al., 2019). The results for individual brain activation analyses are reported in the supplements (SI Section 3).

For neural synchrony analyses, WTC values were entered as the response variable in a separate linear mixed effects model with condition (cooperation vs. individual vs. rest) and region of interest (ROI; four per dyad) as fixed factors and with random slopes for each ROI and condition in each dyad. To test for the effects of individual differences on neural synchrony, we extended the above mentioned linear mixed model by the predictor variable of interest and its random slope. To derive effects for single predictors we used a Kenward-Roger approximation and parametric bootstrap approach (Halekoh & Højsgaard, 2014). To further examine significant effects, contrasts of factors were conducted by using post-hoc analyses with Tukey's Honest Significant Difference to correct for multiple comparisons (Abdi & Williams, 2010). When significant, we then calculated multiple linear mixed models to further analyze the relations according to our hypotheses and corrected p-values with a false discovery rate (FDR) when multiple conditions were compared ($q < .05$). Behavioral data analysis was conducted with Pearson correlations and we corrected p-values with FDR ($q < .05$) for multiple comparisons.

3. Results

3.1. Behavioral results

Correlational analyses for task performance, behavioral reciprocity, maternal sensitivity, child agency, and maternal stress level are reported in Table 1, while descriptive and correlational analyses for all assessed ratings and

Table 1 – Correlation Statistics for Task Performance, interaction qualities, and questionnaire variables.

	1	2	3	4	5	6
Dyadic task performance	–	–	–	–	–	–
Individual task performance (child)	$\beta = -.61, -.88$ $R^2 = .04$	–	–	–	–	–
Behavioral reciprocity	$r = .22$ $R^2 = .02$	$\beta = -.18, -.27$ $R^2 = -.05$	–	–	–	–
Maternal sensitivity (rating)	$r = -.09$ $R^2 = -.02$	$\beta = .17 - .76$ $R^2 = .02$	$r = .64^{**}$ $R^2 = .39$	–	–	–
Child agency	$r = .21$ $R^2 = .02$	$\beta = -.20, 0.27$ $R^2 = -.04$	$r = .33$ $R^2 = .09$	$r = .29$ $R^2 = .06$	–	–
Maternal stress	$r = -.17$ $R^2 = .01$	$\beta = -.45, -.05$ $R^2 = .02$	$r = -.14$ $R^2 = .00$	$r = -.04$ $R^2 = -.02$	$r = -.30$ $R^2 = .07$	–

Note. Pearson correlations were corrected with FDR for multiple comparisons. $^{**} = q < .01$, $^* = q < .05$. Adjusted R^2 are reported underneath correlation coefficients. Due to the factor structure of individual task performance, linear regressions were calculated and also corrected with FDR.

questionnaires are presented in supplementary Tables S1 and S2. Overall, task performance was associated with no other behavioral measure, $q > .24$. Behavioral reciprocity was related to maternal sensitivity, $r = .64$, $q = .08$, as well as weakly related to child agency, $r = .34$, $q = .08$, but not related to other assessed measures, $q > .24$.

3.2. Neural synchrony during problem solving

We used fNIRS to assess brain activity from temporo-parietal and prefrontal areas in mother and child simultaneously. WTC was used to assess cross-correlation between the fNIRS time series in each dyad and measurement channel as a function of frequency and time. First, we examined whether neural synchrony during the cooperative problem-solving task was higher in comparison to individual problem solving and resting phases. Analyzing neural synchrony across all three conditions revealed a strong main effect of condition, estimate±SE = $-.008 \pm .003$, $F(2,2015) = 8.52$, $p = .001$, 95% CI $= -(.023 - .008)$, and no effect of region, $p = .12$. In a subsequent exploratory analysis, we also found no significant interaction effect of condition and region, $p = .44$ (see SI Appendix, Section 3 and Figure S2). Post-hoc analysis showed that neural synchrony averaged over all regions of interest (ROI) was higher during cooperation in contrast to the individual condition, estimate±SE = $.014 \pm .005$, $t(1340) = 3.29$, $p = .006$, 95% CI $= .009 - .02$, which is depicted in Fig. 3. Additionally, neural synchrony during cooperation was higher than during resting phases, estimate±SE = $.017 \pm .004$, $t(1340) = 3.76$, $p < .001$, 95% CI $= .01 - .02$. These effects remained significant when we further controlled for child sex, mother and child age, maternal education, task order and familiarity with the task during conditions.

To control for spurious correlations between both neural signals, we conducted a random validation analysis. 1,000 permutations of neural synchrony between a mother's and a random child's signal were calculated and compared to neural synchrony of original dyads using Welch t-tests with FDR corrected p-values ($p < .05$). Results revealed that neural synchrony in original dyads was significantly higher than in random pairings during the cooperation condition only,

$t(781.19) = 3.21$, $p = .001$ (see supplementary Figure 3). In the two other conditions, findings showed lower neural synchrony in original dyads as compared to random dyads, $t(776.23) = 2.11$, $p = .04$ and $t(834.67) = 2.65$, $p = .01$ respectively. To conclude, the random validation analysis further supported our findings of higher neural synchrony selectively in the cooperation condition.

3.3. Interaction qualities and neural synchrony

Identifying interaction qualities during cooperative problem solving (see Table 1), which are either facilitating or mitigating neural synchrony, was one of our main research questions in
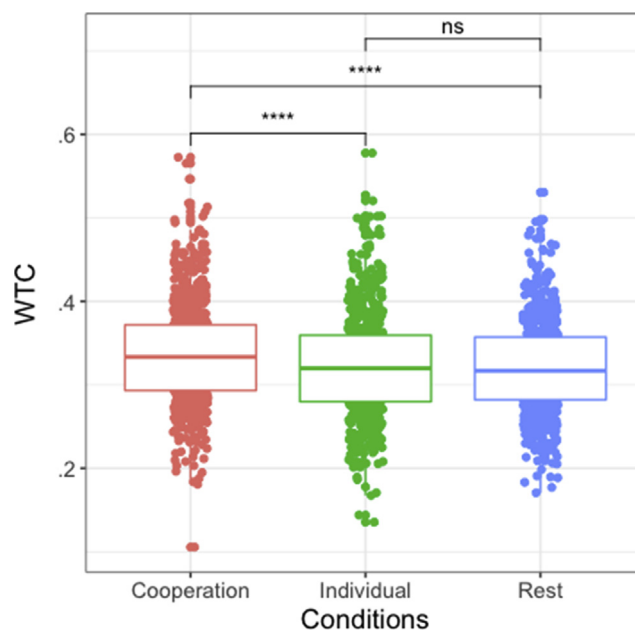

Fig. 3 – Plot of the main effect of condition. Neural synchrony during cooperation was significantly higher than during individual and resting phases (averaged across all ROIs). ns = non-significant, **** = $p < .0001$.

the present study. Thus, we assessed whether specific inter-action qualities, measured from video recordings of the cooperation condition, were linked to increased neural synchronization during the cooperative task. To test the hypotheses, we entered behavioral reciprocity as a fixed effect into the above mentioned linear mixed model, which resulted in a main effect of behavioral reciprocity, *estimate* ± SE = .005 ± .003, $F(1,1871) = 4.45$, $p = .003$, 95% CI = .0002−.0112, and an interaction effect with condition, estimate±SE = .008 ± .003, $F(2,1871) = 3.69$, $p = .02$, 95% CI = −.0151−.0013. Post-hoc analysis conducted with a further specified linear model revealed that the interaction was driven by the effect of behavioral reciprocity in the cooperation condition. This means that only when the dyad was instructed to work together, neural synchrony was positively correlated with behavioral reciprocity, $t(624) = 6.51$, $p = .01$, 95% CI = .0001−.0121. These findings are depicted in Fig. 4A.

As we hypothesized that higher neural synchrony should indicate successful task performance, we examined whether neural synchrony was associated with the number of templates solved together in the cooperation phase. Results suggested that regardless of experimental condition, neural synchrony indeed significantly predicted overall mutual task performance, estimate±SE = .008 ± .003, $F(1,1967) = 6.26$, $p = .003$, 95% CI = .001−.013 (see Fig. 4B). Looking further into condition-related neural synchrony, we found that neural synchrony during the cooperation condition specifically was significantly related to overall task performance, $F(1,656) = 7.30$, $p = .007$, 95% CI = .002−.013 ($q = .02$). Neural synchrony during individual problem solving and rest showed no or just a weak effect on cooperative problem-solving success, $p = .12$-.88 ($q = .18$-.88). When correlating task performance with behavioral reciprocity, we did not find any significant effect, $q = .24$.

3.4. Individual factors to neural synchronization

3.4.1. Maternal factors
First, we predicted that neural synchronization should be facilitated by maternal sensitivity, because sensitivity is

proposed to be essential for behavioral synchrony. Our findings, however, showed that *interaction-based maternal sensitivity* did not significantly predict neural synchrony, $p > .40$, despite its strong correlation with behavioral reciprocity, $\beta = .74$, $p < .001$. Next to a caregiving measure, we probed into the role of *maternal stress* on neural synchrony. Interestingly, our results displayed a weak main effect of the self-reported general maternal stress level on neural synchrony, estimate±SE = −.004 ± .003, $F(1,1992) = 1.97$, $p = .05$, 95% CI = −.009−.002, and a weak interaction effect of maternal stress with condition, estimate±SE = .008 ± .003, $F(3,1992) = 3.52$, $p = .03$, 95% CI = −.002−.014. During the cooperation condition, general maternal stress seemed to somewhat attenuate neural synchrony, $t(672) = 1.94$, $p = .05$, 95% CI = −.004−.003. General maternal stress levels showed no effect on neural synchronization during individual problem solving and resting phases, $p = .12$, $p = .38$, respectively. Findings are illustrated in Fig. 5A.

3.4.2. Child factors
We also investigated whether *child agency* positively influenced neural synchrony. We found that child agency was weakly associated with neural synchrony, estimate±SE = .006 ± .003, $F(1,1848) = 1.92$, $p = .05$, 95% CI = .001−.012 (see Fig. 5B), but the interaction effect with task was not significant, $p = .47$. When the child engaged autonomously in the joint task, the dyad thus showed indications of overall increased neural synchrony. In an exploratory post-hoc analysis, the regressions showed that child agency was again weakly related to neural synchrony in the cooperation condition, $F(1,624) = 1.92$, $p = .09$, 95% CI = .000−.012, but not in the individual or resting conditions, $p > .50$. The trending effect in the cooperation condition, however, was estimated as non-robust. In further analyses we found no indications for an effect of child temperament in terms of negative affectivity on neural synchrony, $p = .34$.
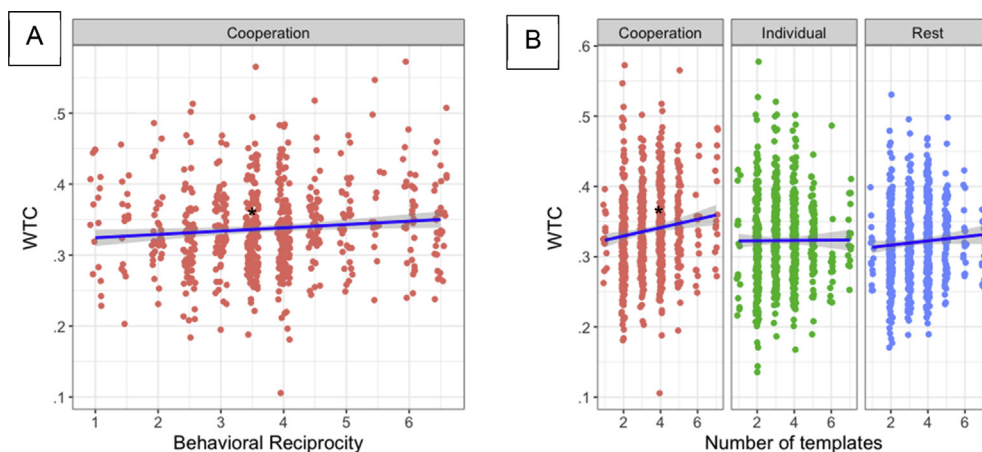

Fig. 4 − (A) Plot of the association between behavioral reciprocity and neural synchrony during the cooperation condition. When mother and child acted more reciprocally during cooperation (x-axis), the dyad also displayed higher neural synchrony (y-axis). (B) Illustration of the relation between neural synchrony in each condition (y-axis) and overall task performance (x-axis). * = $p < .05$.
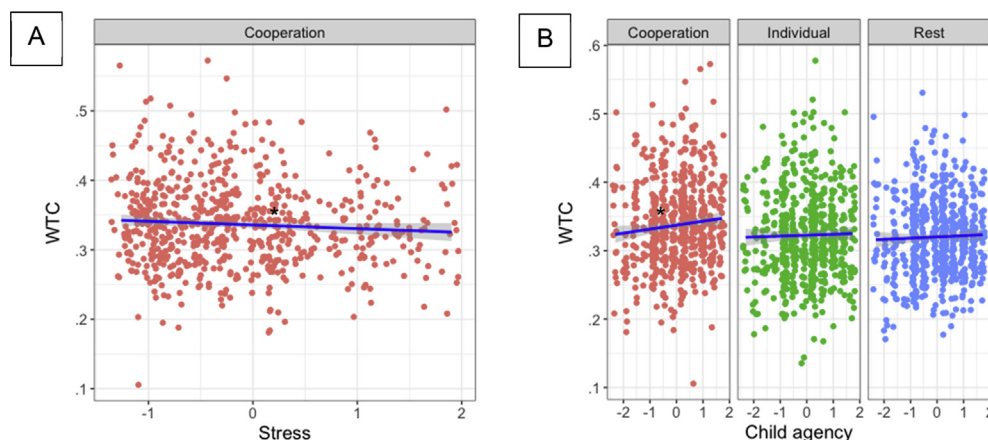
Fig. 5 − (A) High levels of maternal stress (x-axis) correlated negatively with neural synchrony during the cooperation condition (y-axis). This pattern of association was found across all ROIs. (B) The plot of the association between child agency (x-axis) and overall neural coherence (y-axis) highlights a positive linear relation between the two variables across all ROIs with the strongest indication in the cooperation condition.

3.5. Cortical activation patterns

3.5.1. Child cortical activation patterns

Extending neural synchrony analyses, we explored individual cortical activation patterns. Child brain activation analyses showed a different pattern between conditions. The linear mixed effect model revealed a significant effect of condition, $F(2, 1872) = 4.84$, $p = .008$, as well as a significant interaction of condition with region, $F(6, 1872) = 2.72$, $p = .01$. Post-hoc contrasts of conditions depict higher cortical activation patterns in both resting phases as compared to the individual condition, $t(1612) = 2.62$, $p = .02$. The cooperation and resting condition did not differ significantly in cortical activation patterns, $p > .15$. When we separated the contrast of conditions by ROI, the results show a higher cortical activation in resting phases in right temporo-parietal areas in comparison to cooperation and individual task phases, $t(1612) = 2.80-3.61$, $p = .01$ and $p = .001$. The other ROI showed no separation in cortical activation regarding conditions, $p > .16$.

We also included individual as well as dyadic task performance, behavioral reciprocity and agency as predictor variables in the model, which yielded a significant interaction between condition and individual task performance, $F(4, 1628) = 3.33$, $p = .01$. Only children, who were able to solve the task by themselves from the beginning, showed higher brain activation in frontal and temporo-parietal areas during the cooperation condition in comparison to individual and resting phases, $t(1628) = 2.57-3.89$, $p = .000-.027$, respectively. Child brain activation patterns were also related to dyadic task performance in interaction with condition and ROI, $F(6,1760) = 2.33$, $p = .03$. Particularly, higher cortical activation in the left frontal region during the cooperation condition was associated with more templates solved. Agency and behavioral reciprocity showed no effect on child cortical activation patterns, $p > .23$.

3.5.2. Mother cortical activation patterns

When individual mother brain activation were analyzed, the linear mixed effect model revealed a significant effect of condition, $F(2, 1672) = 4.82$, $p = .01$. Post-hoc contrasts of conditions show higher cortical activation patterns in all ROI in the cooperation condition as compared to the individual condition, $t(1733) = 2.99$, $p = .01$. Brain activation in resting phases were only marginally lower than in the cooperation condition, $t(1733) = 2.20$, $p = .07$.

Here, we again included dyadic task performance, but also maternal sensitivity, behavioral reciprocity and general stress level as predictor variables, which yielded a significant interaction between condition and maternal sensitivity, $F(2, 1680) = 3.32$, $p = .04$. Mothers, who had higher sensitivity ratings, showed lower brain activation in all ROI. Maternal brain activation patterns were marginally related to dyadic task performance in interaction with condition, $F(2,1672) = 2.62$, $p = .07$. Higher cortical activation in all ROI during the cooperation condition were marginally associated with more templates solved. Furthermore, behavioral reciprocity and general stress level showed no effect on maternal cortical activation patterns, $p > .16$.

4. Discussion

In the present study, we aimed to clarify the relation between interaction quality and neural synchrony during a naturalistic caregiver-child interaction involving cooperative problem solving. In contrast to previous studies, we tested whether interpersonal neural synchrony between mothers and children can be measured during a complex task without an inherent rhythmicity − in comparison to control conditions without direct engagement. Here, we integrated measures of complex social behavior with concurrent brain imaging to gain new insights into caregiver-child interactions. By concentrating on interaction quality and individual differences in the functioning of the caregiving system in the mother as well as temperament in the child, our goal was to measure how such dyadic and individual differences would be related to neurobehavioral synchronization during induced

cooperation. In line with previous studies using more controlled and artificial tasks (Miller et al., 2019; Reindl et al., 2018), our findings demonstrate that mother-child dyads showed higher neural synchrony in the temporo-parietal and lateral prefrontal areas when solving a naturalistic task in cooperation, in comparison to when they solved the same task individually. Extending these findings, we found that neural synchronization was accompanied by higher behavioral reciprocity during joint problem solving in caregiver-child dyads. Strikingly, only neural synchronization but not behavioral reciprocity was associated with the dyad's task performance. This indicates that the function of neural synchrony may go beyond behavioral attunement as far as it can be assessed from video-recorded behavior. In other words, neural synchrony may indicate levels of mutual task engagement and shared attention that cannot be easily inferred from the observed behavior alone. Regarding individual factors on neural synchronization, we found that interaction-based measures, such as child agency, even though only marginally, correlated positively with neurobehavioral synchrony, while trait-like, self-report measures did not seem to be linked to synchronization. Hence, these results further highlight the complexity and time-specificity of neural synchronization between two individuals (Hasson et al., 2012), particularly in the caregiver-child context.

First, our results confirm the role of frontal and temporal areas for neurobehavioral synchronization in caregiver-child interactions. Neural synchrony in temporal areas has been previously linked to adequate and effective cooperation within a dyad (Jiang et al., 2012; Miller et al., 2019). While cooperating, mother and child constantly engage in mentalizing processes to predict each other's intentions while attending to the same object (Baimel, Severson, Baron, & Birch, 2015). Understanding the other person might thus have been facilitated by higher neural synchronization, meaning that when the mothers' and children's brain activity was temporally aligned, less effort may have been required to reason about and react to the other person (Keller et al., 2014; Koban, Ramamoorthy, & Konvalinka, 2019). At the same time, mother-child dyads displayed neural synchrony in frontal areas. Interactive social decision making and effective communication have previously been associated with interpersonal synchrony in the dlPFC (Zhang, Liu, Pelowski, Jia, & Yu, 2017). Our results thus corroborate earlier studies showing the involvement of frontal and temporal areas in caregiver-child interactions (Miller et al., 2019; Reindl et al., 2018), but the functions of neural synchronization in specific regions are to be tested in future studies.

Our findings also indicate, in line with previous proposals (Hasson et al., 2012), that neural coupling is essential to social information exchange. Overall neural synchronization in the caregiver-child dyads was associated with task performance as an interactional outcome of the problem-solving task. This finding corroborates recent similar findings in more controlled caregiver-child interactions (Miller et al., 2019; Reindl et al., 2018) and a tangram puzzle task with adults (Fishburn et al., 2018). The more the dyads synchronized in their brain activity, the more tangram templates they solved, which underlines the role of neural synchronization for optimal information exchange and cooperative task performance.

Moreover, we find that neural synchrony occurs not only during verbal communication, but expands to non-verbal information exchange, similar to the multi-modal turn-taking behavior reported in adults earlier (Fishburn et al., 2018; Jiang et al., 2012). Particularly responsive and contingent turn-taking behavior, i.e., reciprocity, in a dyad was related to coordination between caregivers and children. More reciprocally behaving dyads showed higher neural synchronization. Interestingly, reciprocity was exclusively related to neural synchrony between mother and child, while task performance could also be predicted by cortical activation patterns of the child (see SI Section 3). Our findings extend results from an earlier study (Levy, Goldstein, & Feldman, 2017) during which mothers and their 9-year old children watched vignettes of their own interactions. The perception of social synchrony in those interactions was linked to interpersonal neural coupling in the superior temporal sulcus of mother and child. Here, we were able to identify additional cortical regions beyond the temporo-parietal area, i.e., the dlPFC, involved in the perception and active engagement of reciprocity, as mother and child were concurrently assessed in a live social interaction. This set of findings on the one hand highlights the necessity to take behavioral coordination into account when investigating neural synchrony, as behavioral processes may facilitate interpersonal synchronization of brain activities (Markova, Nguyen, & Hoehl, 2019). On the other hand, our findings emphasize the need for second-person neuroscience approaches to investigate the mechanisms of social interaction (Redcay & Schilbach, 2019).

When we looked closer into the effect of neural synchrony on joint problem solving, we found that both neural synchrony during cooperation as well as during resting phases, even though the latter only weakly, was related to task performance. This finding raises an important question: might there be a default coherence between caregivers and children at rest, which increases or decreases by context? The assumption of a default synchrony between mothers and children is supported by studies showing physiological synchrony in cortisol responses within families (Papp, Pendry, & Adam, 2009; Pratt et al., 2017): Synchrony in cortisol responses increased in interactive contexts but was still evident in non-interactive contexts. Moreover, physiological synchrony declined when the relationship between caregivers and children was disrupted, for instance in cases of maternal depression or child disorganized attachment (Leclère et al., 2014). Therefore, synchrony in physiological markers is discussed to be involved in the intergenerational transfer of stress physiology, and neural synchrony may serve a similar function in the development of attachment (Vrticka, 2017). We also observed a relatively high overlap in coherence between conditions. Resting phase neural synchrony between mothers and children could therefore stem from sustained processing or layover effects from participation in the whole task procedure. Mothers and children might still have engaged in thought processes regarding the other person as well the task as such. As Trapp, Havlicek, Schirmer, and Keller (2018) illustrate, attentional entrainment to stimuli only disintegrates gradually after the stimuli disappear. Thus, resting phase neural synchrony in our study could include layover effects from the mutual engagement in the tangram puzzle

task. Layover effects could also stem from the experience of task order, as Over and Carpenter (2013) suggest that initial context information can induce either a focus on social or learning goals in a given task setting. More studies will have to be conducted to probe whether there is a function to resting phase neural synchrony within dyads and to tease apart possible layover effects from prior conditions.

Our findings showed high interdyadic variance within neural synchronization during caregiver-child interaction. Hence, we investigated individual factors that have previously been related to behavioral reciprocity (Harrist & Waugh, 2002). We looked at both state-like measures assessed by video-based ratings, as well as trait-like measures assessed by self-reports. We found that child agency was linked to neural synchronization, indicating the role of autonomy in social interactions during preschool age. The greater a child's agency, the more a child is able to engage in a task instead of being led by others (Clark & Ladd, 2000). Thus, mutual task engagement might have led to better behavioral coordination and in turn successful joint-problem solving, as previous studies display evidence for such a link between autonomy support and problem-solving (Bernier, Carlson, & Whipple, 2010; Clark & Ladd, 2000; Raver, 1996). This comes to show that encouraging child agency at preschool age might have important implications, especially in a challenging problem-solving situation. In addition, this finding supports the notion of a more balanced interaction from preschool age on, as children's social-cognitive abilities mature (Harrist & Waugh, 2002). Interestingly, the effects of child agency acted on the general neural synchronization of the dyad and were not specific to the cooperation condition. These findings might point towards a layover effect of neural synchronization from the mutual task engagement in the cooperation condition, as found for sustained neural entrainment in an attention task (Trapp et al., 2018). To conclude, neural synchrony might be a biomarker for mutual task engagement and therefore create an optimal learning environment for the child (Hoehl & Markova, 2018).

In addition to these interaction-based measures of reciprocity and agency, we tested the effects of maternal self-reported stress on neural synchrony in caregiver-child dyads. Even though our findings do not replicate the relation between maternal stress and maternal sensitivity as shown in earlier literature (Booth et al., 2018), they are in line with the reported effects of stress on bio-behavioral processes (Swain et al., 2017). Particularly, neural alterations show that parental stress affects brain regions connected to reflective self-awareness and the decision-making neurocircuitry, which may mitigate a parent's ability for perspective taking. In line with these results, we find that self-reported parental stress was related to reduced neural synchronization between mothers and their children.

There were, however, no effects of broader, trait-like factors related to attachment and caregiving on mother-child neural synchrony in our data. There could be several reasons for this result. As proposed by Hasson et al. (2012), neural coupling occurs via signal transmission through the environment. This model thus points towards a time-localized occurrence of neural synchronization, which is rather influenced by concurrent, immediate behavior, such as the role of

eye gaze and vocalizations as found in a study by Leong et al. (2017), as well as concurrent physiological processes (Feldman et al., 2011; Pratt et al., 2017). To further explore the role of various variables indicating different components of interaction quality, it would be important to assess event-related measures of behavioral synchrony, enabling the relation of certain behaviors to events of neural synchronization. This approach could lead to further insights into what leads to neural coupling. For instance, assessing mind-related comments could yield further insight into the relation between stress and neural synchrony (Zeegers, Colonnesi, Stams, & Meins, 2017). The measures we used as maternal attachment and caregiving variables, as well as the lack of a direct child attachment measure pose another limitation. The self-report measures are efficient to assess and share variance with the underlying constructs, but it might be indispensable to use additional tools derived from attachment research, such as semi-structured narrative interviews like the adult attachment interview or the story stem battery in children to more precisely assess parent-child attachment processes (George, Kaplan, & Main, 1996). It should also be noted that the maternal sensitivity subscale (Hirschmann et al., 2011) is normally used for much longer interactions and might not be as reliable when rated in shorter interactions like in our case. Finally, the lack of variance in our sample with overall middle to high economic status may have attenuated the range of shown behavior and personality factors (Roubinov & Boyce, 2017). The missing variation, therefore, might have impeded our investigation of dyadic and individual factors.

Here we demonstrated interpersonal neural synchronization in frontal and temporal areas during mother-child cooperative problem solving in comparison to individual problem solving. We showed that neural synchronization between mothers and children also occurs in a naturalistic cooperation task, thus increasing external validity beyond highly standardized and artificial settings used previously (Miller et al., 2019; Reindl et al., 2018). Critically, the naturalistic task enabled us to look for variations in dyadic behavior that modulate neural synchrony and task performance. We showed that behavioral reciprocity, an important indicator of caregiver-child interaction quality, was positively associated with neural synchrony. In addition, we found a relation of neural synchrony with cooperative task performance beyond behavioral reciprocity, and we identified first potential factors, namely child agency and maternal stress, influencing neurobehavioral synchronization. Our results shed light on cooperation as a function of neural synchronization during caregiver-child interaction and point towards neural synchrony being a neurobiological marker of mutual engagement and successful coordination in social interactions.

To reach a better understanding of neural synchrony in caregiver-child dyads, it will be indispensable to extend the investigation of individual and dyadic factors for neural synchronization (Hoehl & Markova, 2018). Future research may examine father–child interactions as well as how individual risk-factors such as postnatal depression and preterm birth (Feldman, Rosenthal, & Eidelman, 2014; Granat, Gadassi, Gilboa-Schechtman, & Feldman, 2017) may attenuate neural synchronization. Our study also offers a first glimpse into

potential neural implications of attachment-based constructs. Overall, hyperscanning may be able to provide important insights into neurobiological mechanisms underlying dynamic processes in caregiver-child interactions from a second-person approach (Hoehl & Markova, 2018; Redcay & Schilbach, 2019). More specifically, our findings highlight the potential in yielding a deeper understanding of the mechanism and preconditions of how caregivers can support children to not only understand themselves, but also others and the world around them.

Financial disclosure

Open practices

The study in this article earned Open Materials and Open Data badges for transparent practices. The preregistration for the study is available at: https://aspredicted.org/i7k95.pdf.

NIRS, demographics, questionnaire and behavioral data as well as all digital study materials are stored on OSF: https://osf.io/75fet/.

MATLAB analysis code has been made publicly accessible here: https://github.com/tnguyen1992/MPI-CBS_Caregiver-Child-Interactions.

The conditions of our ethics approval do not permit public archiving of video data. Readers seeking access to the data should contact the lead author Trinh Nguyen. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. Specifically, requestors must meet the following conditions to obtain the data: completion of a formal data sharing agreement.

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

Declaration of Competing Interest

The authors assert that they have no competing interests.

Acknowledgements

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cortex.2019.11.020.

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