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„Neural synchrony in mother-infant dyads: The role of proto-conversational turn-taking and interhemispheric functional connectivity "

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Theoretical Background

From birth, children are surrounded by an environment that includes a variety of impressions and social contacts, whom they learn from as embodied agents (Markova et al., 2019). As early as infancy, children are able to detect social contingencies, particularly in maternal behavior including child directed vocalizations or eye gaze (Murray & Trevarthen, 1986). As a result, infants engage in their first contingent social interaction immediately after birth (Feldman, 2012). Infant's engagement in these early interactions depends, amongst others, on the newborn's biological maturation, which in turn shapes the development of infant-caregiver interaction (Feldman & Eidelman, 2007).

In addition to the infant's maturity, the matching of behavior or biological rhythms is also suggested to be important for early interactions (Feldman, 2017). More precisely, reciprocal and temporal coordination with another person is referred to as interpersonal synchrony and can occur at behavioral and biological levels (Feldman, 2017; Hoehl et al., 2021). Furthermore, developmental research distinguishes between concurrent and sequential synchrony (Markova et al., 2019). For instance, mutual gaze between two individuals is classified as a form of behavioral synchrony that occurs concurrently. In contrast, when the behavior of one person predicts behavioral changes in the other person, such as alternating vocalizations during conversations, this is classified as sequential synchrony (Wass et al., 2020).

Previous research has provided evidence that concurrent synchrony is related to neural synchrony in children and adults (Piazza et al., 2020). While there is some evidence on the link between sequential synchrony and interpersonal neural synchrony (INS) for adults (Hasson et al., 2012; Jiang et al., 2012; Pérez et al., 2017) and for preschoolers (Nguyen et al., 2021), uncertainty remains about this relation in infants and their caregivers. However, studying synchrony in infants is important, as the ability of recognizing temporal regularities and adapting to the given temporal regularity of another person is linked to several developmental benefits. For example, studies have shown that synchrony facilitates information exchange and learning, enhances the predictability of the other person, and strengthens social bonding (Pan et al. 2018, 2020; for reviews see Feldman, 2017; Hoehl et al., 2021; Konvalinka & Roepstorff, 2012). To conclude, temporal regularities in general, and behavioral cues, such as gaze, affect or vocalizations in particular are suggested to contribute to INS (for a review see Wass et al., 2020).

Moreover, INS studies have revealed that sequential synchrony in form of alternating vocalizations (i.e., turn-taking) between two adults is linked to successful learning (Pan et al.,

2018, 2020). Important learning outcomes of early conversations in infancy include language processing and acquisition. Accordingly, child research highlights some conversational patterns, such as turn-taking between caregiver and child as beneficial for language development (Levinson, 2016). In addition, changes in prevailing conversational patterns of infants are linked to maturation (Ginsburg & Kilbourne, 2009).

Next to INS, alignment can also be measured within an individual's brain. In infancy research, neural synchrony between the left and right hemispheres, termed inter-hemispheric functional connectivity (ihFC), has been proposed as a marker for neural maturity (Allievi et al., 2016; Meijer et al., 2014; Thomason et al., 2013). Yet, little is known about ihFC in infants and its relation to infant social-cognitive development on the one hand, and its relation to neural components of early social interactions on the other hand.

In the present paper, we aim to shed light onto the relationship between neural and behavioral synchrony in early mother-infant-dyads, examining behavioral synchrony in form of non-verbal, proto-conversational turn-taking. Additionally, we address the question whether and how infant neural maturity measured via ihFC is related to turn-taking and INS.

Proto-conversational turn-taking in early social interactions

Long before children develop the capacity to communicate verbally, pre-linguistic vocalizations are observed to have a similar rhythm to adult speech (Provasi et al., 2014). In addition to rhythm, the structure of infants' vocalizations is not random, but contains turns (Henning et al., 2005). By two months of age, infants across various cultural communities are engaged in conversation-like exchanges with their caregivers that are termed proto-conversations (Bornstein et al., 2015; Gratier et al., 2015). These proto-conversations consist of turn-taking sequences and overlapping vocalizations of both interactors (Gratier et al., 2015). Although overlapping sequences are predominant in infancy, overlapping turns compared to turn-taking patterns of infants were reduced in the first six months of life (Harder et al., 2015). Moreover, the rate of turn-taking sequences initiated by infants increases continuously, so that higher amounts of turn-taking in comparison to overlapping is linked to advanced child development (Abney et al., 2017; Ginsburg & Kilbourne, 2009).

By analyzing the structure of vocal interactions between infants and their mothers, Gratier et al. (2015) demonstrated that infants play an active role in turn-taking, including the ability to anticipate and initiate turns. Consistent with this finding, Levinson (2006) proposed the *interaction engine hypothesis*, which suggests universal, conversational patterns of turn-taking. In order to interact and exchange information with others, turn-taking relies on the

ability to anticipate vocalizations on the one hand, and the timing of turns on the other. In contrast to the rate of turn-taking, infants' timing of turns is characterized by a nonlinear, alternating development. While in the first 6 months, the timing of preverbal conversations approximates the timing of adult conversations, turn duration slows down at the age of 9-month, and decreases again within the end of the first year of life (Hilbrink et al., 2015). Accordingly, as language processing matures, children start having their first more complex question-answer conversations, which in turn influences conversational patterns. Whereas children initiate simple answers quickly from an early age, children's response latencies increase with the complexity of the preceding vocalization (Casillas et al., 2016). Possibly, these developmental differences coincide with the coordination of several new cognitive and conversational processes (Hilbrink et al., 2015; Levinson, 2016).

Moreover, turn-taking seems to play a crucial role in social learning and has profound effects on language processing and acquisition (Levinson, 2016). Hence, the rate of turn-taking has been linked to the process of infant language development (e.g., Bloom et al., 1987; Donnelly & Kidd, 2021). A growing body of research underscores this relationship by showing, for instance, that infant involvement in turn-taking leads to more speech-like vocalizations (Bloom et al., 1987), whereas weaker vocal coordination of preverbal infants has been linked to poorer cognitive outcomes in these infants as they age (Jaffe et al., 2001). Furthermore, well-coordinated interaction of mother-infant-dyads (Rohlfing & Nomikou, 2014) and the amount of turn-taking (Donnelly & Kidd, 2021) was closely related to vocabulary development and growth in 2-year-olds. Next to empirical evidence from longitudinal studies, neurobiological evidence also emphasizes this positive association. By relating infants' conversational experiences to neural correlates, Romeo et al. (2018) showed that higher amounts of turn-taking in 4- to 6-month-old infants during home audio recordings were reflected in greater brain activation in Broca's area (left inferior frontal cortex) during a story-listening task. Neural activation in turn explained the relation between the extent of turn-taking and language skills. With regard to the development of turn-taking described above, higher amounts of turns seem to be associated with higher maturation and advanced language skills (Abney et al., 2017; Ginsburg & Kilbourne, 2009; Hader et al., 2015). Additionally, neural activation possibly shapes this association (Romeo et al., 2018). However, to the best of our knowledge no study has examined the reverse relationship, namely, the extent of maturation in neural activity and its relation to turn-taking behavior.

Taken together, turn-taking is shaped on the one hand by the child and its developmental stage. However, on the other hand, the social interaction of both actors also

plays a crucial role in the occurrence and appropriate coordination of turn-taking (Wass et al., 2020). For instance, as early as 5-month of age, children start expecting that their preverbal babbling leads to responses of their caregivers (Elmlinger et al., 2019). Further, especially contingent in contrast to noncontingent maternal responses facilitate more advanced vocalizations in infants (Goldstein et al., 2003) and the number of words used in these contingent vocalizations predict the vocal maturation of the child (Elmlinger et al., 2019). However, less in known about the underlying neural components within infants and between infants and their mothers during these important proto-conversational interactions.

Interpersonal neurobehavioral synchrony

As mentioned above interpersonal behavioral synchrony, especially conversational turn-taking has been shown to positively influence children's development (Abney et al., 2017; Hoehl et al., 2021; Markova et al., 2019). However, current research indicates that interpersonal synchrony in early infant-caregiver interactions occurs not only behaviorally, but also at physiological and neural levels (Feldman, 2017; Markova et al., 2019). While basic empirical evidence is available for both behavioral and physiological synchrony, the investigation of INS has been developed in the last decade, using hyperscanning, a method to measure the coupling of brain activity between two or more individuals (Dumas et al., 2011).

Several studies provide evidence that behavioral synchrony is associated with neural synchrony (for reviews see Dumas et al., 2011; Hasson et al., 2012). Accordingly, INS is suggested to play a fundamental role in conversational turn-taking as a form of sequential behavioral synchrony (Wass et al., 2020; Wilson & Wilson, 2005). The emerging evidence shows that communicative rhythms are related to neural synchrony, and furthermore, neural synchrony supports verbal and even non-verbal communication (Hasson et al., 2012), which in turn is associated with enhanced mutual understanding (Kuhlen et al., 2012). In fact, neural oscillations synchronize between two adults, who are talking to each other (Pérez et al., 2017). Further adult studies revealed that the speaker's activity is spatially and temporally coupled with the listener's activity, however, when the communication failed the coupling vanishes (Liu et al., 2017; Stephens et al., 2010). Moreover, findings of a study by Jiang et al. (2012) revealed that neural synchronization in the left inferior frontal cortex between two adults increases during a face-to-face-dialog, but not during other conditions including monologue or dialog without facing each other. Thus, successful vocal interaction seems to be related to INS in adults.

As aforementioned, turn-taking behavior is associated with the development of language (Abney et al., 2017; Donnelly & Kidd, 2021; Levinson, 2016). Moreover, the process of language development (e.g., learning) is not only shaped by individual neural activation (Romeo et al., 2018), but also suggested to be linked to neural coupling between instructor and learner. In naturalistic learning situations Pan et al. (2018, 2020) examined dual-fNIRS and found that instructor-learner brain coupling predicted learning outcomes, especially, when interactive instructions were used in comparison to monologue-like explanations. These outcomes indicate a special role of conversational reciprocity for neural synchrony and learning (Hoehl et al., 2021).

Taken together, many empirical studies suggest a link between conversations and neural synchrony, but mostly only in unrelated adult-adult-dyads. However, neural synchrony is not only relevant for adult interactions, but is also thought to develop during caregiver-child interactions (Wass et al., 2020). Furthermore, a close relationship is suggested to be advantageous for interpersonal synchrony (Hoehl et al., 2021). Combining these aspects in a fNIRS hyperscanning study, Nguyen et al. (2021) recently investigated during a free verbal conversation between preschoolers and their mothers, whether communicative patterns, such as turn-taking, are associated with neural synchrony. Results showed that higher amounts of turn-taking were associated with increases in INS over time. However, the role of turn-taking in neural synchrony in preverbal children and their mothers has not been studied so far, although some studies propose evidence for neural alignment through non-verbal communicative signals. For instance, Piazza et al. (2020) measured brain coupling and communicative behavior during a naturalistic interaction between 9-15-month-old infants and their mothers compared to unfamiliar individuals. Here, neural synchrony was found to be significantly higher when the infant communicated with his/her mother than with a stranger. By taking a closer look at communicative signals in mother-infant dyads, prefrontal activity was found to be significantly coupled to the time course of mutual gaze, which implies an underlying neural process of prediction and anticipation that leads to joint eye contact. This finding is in line with previous research in unrelated adult-infant-dyads, where direct gaze, but not gaze aversion was found to strengthen neural coupling during communication and may facilitate communicative exchanges. Again, it was evident that the child was actively involved in the communicative process, as infants with higher amounts of vocalizations, showed higher neural synchrony with the adult. (Leong et al.,2017).

Considering that communicative signals in preverbal children are positively linked to neural synchrony (Leong et al., 2017; Piazza et al., 2020) and that turn-taking in verbal

children lead to enhanced neural synchronization (Nguyen et al., 2021), the present study aims to extend these findings by clarifying the role of turn-taking in preverbal infants for neural synchrony.

Interhemispheric functional connectivity in infants

Up to now, our understanding of how neural synchrony occurs is limited. Evidence reviewed above suggests that INS is supported by behavioral entrainment, including turn-taking and gaze (Jiang et al., 2012; Pérez et al., 2017; Piazza et al., 2020; Nguyen et al., 2021) and/or by pre-existing relationships (Pan et al., 2017). However, some studies suggest that neural synchrony cannot be explained solely by behavioral cues or affiliation, but by temporal regularities of higher-order cognitive processes, such as understanding (Liu et al., 2017; for a review see Wass et al., 2020). To explore this further, neural synchrony should not only be studied between dyads, but also within the brain of an individual.

One promising type of intraindividual neural entrainment is functional connectivity. This is described as the concurrent activity in specific distributed brain regions that temporally align and, consequently, build functionally connected brain networks (Khan et al., 2018). Studies suggest that functional connectivity is linked to cognitive, affective and/or behavioral differences in both, adults (Kaiser et al., 2015) and infants (Allievi et al., 2016; Kelsey et al., 2021). From a developmental perspective, research shows that the complexity of brain signals increases during the first years of life (e.g., Meyer-Lindenberg, 1996; Lippé et al., 2009). This can be explained by an increased integration of distributed brain regions, and thus a development of new functional connections. More specifically, developmental changes in from 1-month infants to preschool-aged children were characterized by an increase in processing of a variability of brain signals across widely distributed brain regions. In addition, the changes were characterized by a decrease of locally processed information (Vakorin et al., 2011).

A growing body of research on functional connectivity, particularly during rest, has mapped and identified functional brain networks in newborns (Fransson et al., 2009; for review see Zhang et al., 2019). While higher-order networks exist in a rudimentary form and develop through infancy and childhood, homologous-interhemispheric networks are already in place at birth. Also, functional connectivity between hemispheres varies across infants and is for example associated with individual differences in behavioral temperament (Kelsey et al., 2021) and further, positively linked to postnatal sensory and motoric experience (Allievi et al., 2016). Variabilities in this early developed network can also be used for clinical

assessments of maturation in (preterm) infants as interhemispheric connectivity develops analogously to electrocortical maturation (Meijer et al., 2014). In line with these findings, Thomason et al. (2013) showed that in fetuses in the second and third trimesters of pregnancy the strength of functional connectivity between hemispheres increases with gestational age. Thus, higher ihFC provides a neurobiological marker for neural maturity.

Although there is promising evidence for ihFC as a basic neural brain network linked to developmental differences available, studies examining its relationship to behavioral and neural synchrony between two individuals are missing. Accordingly, exploring the association between infant brain connectivity and INS between infants and caregivers is important to add to the existing evidence on INS. The present study attempts to clarify these relationships as possible findings at behavioral and neural levels could help to better understand the development of infants being an embodied agent in social interactions.

Present Study

In early, preverbal infant-caregiver interaction interpersonal synchrony is essential to facilitate social interaction and enhance bonding (Feldman, 2017; Hoehl et al., 2021). Research in this field is indispensable to detect behavior and/or neural components that support child development and lead to beneficial mechanism in these early social interactions.

Taken together, this study aimed to clarify the role of proto-conversational turn-taking for INS and integrates the assessment of neural synchrony within an infant's brain in current interpersonal neurobehavioral research. Based on previous findings (Nguyen et al., 2021), we focused on the replication attempt on the association between neural synchrony and turn-taking in caregiver-child conversations within a preverbal infant sample. Furthermore, evidence reviewed above has shown that the development of early social interactions between caregivers and infants is shaped to some extent by the infant's maturity (Abney et al., 2017; Feldman & Eidelman, 2007). In our study, we assessed neural maturity via analyses of brain connectivity to gain deeper insight onto infant´s socio-cognitive development. More precisely, we aimed to shed light on the association between functional connectivity and behavioral synchrony in form of turn-taking, on the one hand, and neural synchrony between mother-infant dyads, on the other hand. Using dual-functional near-infrared spectroscopy (dual-fNIRS), we simultaneously measured brain activity in frontal regions of mothers and their 4- to 6-month-old infants during a naturalistic free-play situation and, during a passive video-watching phase. Dual-fNIRS is a non-invasive, safe method that accommodates a certain amount of movement and is therefore commonly used in infant research (for a review see

Lloyd-Fox et al., 2010; Kelsey et al., 2021; Piazza et al., 2020). Accordingly, the following hypotheses were tested:

H1: Higher amounts of proto-conversational turn-taking are associated with an increase in neural synchrony in mother-infant dyads over time.

H2: Higher interhemispheric functional connectivity in infants is associated with higher amounts of proto-conversational turn-taking between infants and their mothers.

H3: Interhemispheric functional connectivity in infants is associated with neural synchrony in mother-infant dyads.

Methods

Participants

The project is being conducted as part of a larger study investigating longitudinal associations of neural, physiological, and behavioral synchrony in mother-infant dyads. Eighty-one mothers and their 4- to 6-month-old infants were tested from January to July 2019. The sample that was analyzed for the first hypothesis consisted of 57 mothers and their infants (27 female infants, 30 male infants; *M* age = 4 months, 24 days, *SD* = 17.30 days). Twenty-four dyads of the original sample size were excluded from current analysis due to early termination of the experiment (*n* = 14), inability to produce vocalizations (*n* = 5), noisy neural data (*n* = 4) or persistent crying during the free-play condition (*n* = 1). Based on a previous study (Nguyen et al., 2021) the given sample size was estimated to be sufficient to show at least small effect sizes. We also conducted a post-hoc analysis for statistical power assuming moderate and large effect sizes (Cohen's f = 0.25–0.4), which resulted in 1-ß = 0.74-0.99. Accordingly, our sample size is appropriate for the planned analysis of our first hypothesis.

The sample that was analyzed for the second and third hypotheses consisted of 49 mothers and their infants (22 female infants, 27 male infants; *M* age = 4 months, 23 days, *SD* = 16.38 days). Additionally, eight dyads were excluded due to failure in the passive video watching condition, because of crying or fussiness (*n* = 3), touching (*n* = 3) or noisy neural data (*n* =2). Both analyzed samples were characterized by high educational status, with 74,4% (for sample of H1) and 77,8% (for sample of H2 and H3) of mothers graduated with a university degree. Post-hoc statistical power analysis assuming moderate and large effect

sizes (Cohen's f = 0.25-0.4) for the second and third hypothesis resulted in 1-ß=0.67-0.97. Accordingly, this sample size is also appropriate for our analyses.

Participants were recruited from a pre-existing database of the Department of Developmental Psychology (Wiener Kinderstudien). Most of the registered families were first recruited at the birthing station at Vienna General Hospital (Allgemeines Krankenhaus der Stadt Wien) and their children were added to the database after they have given their written consent. Infants that were born preterm (before the 37th gestation week) or with a birth weight less than 2.500g were not included in the current sample. The families received 6 euros, a toy, and a certificate for the infant for their voluntary participation.

Experimental Procedure

Mothers and their infants were invited to the laboratory of *Wiener Kinderstudien* of the Faculty for Psychology, University of Vienna for one testing session that lasted 45 minutes to 1 hour. An online demographic questionnaire was filled out by mothers before arriving to the laboratory. Upon arrival, the participants were brought to a reception room where infants were familiarized with the two experimenters, and mothers signed a consent form. Afterwards, they were led to the laboratory room. For dual-fNIRS recordings sources and detectors were arranged on a fitted cap for both mothers and infants. During a watching condition, mother-infant dyads were seated side by side and watched a calm aquarium video on a tablet screen for 90 seconds. Mothers were instructed not to verbally interact with or touch their child. This passive video watching condition was used as a form of eye-opened resting phase (Emerson et al., 2015; Kelsey et al., 2021). Afterwards a naturalistic free-play condition of 5 minutes duration followed. Infants and their mothers sat face-to-face, and mothers were instructed to play with their child as they would at home, without using toys or singing. For later behavioral coding the whole session was video recorded from three different angles. ECG electrodes were also attached throughout the experiment, a second video watching condition preceded the free-play and a heartbeat counting task followed. However, these three aspects were unrelated to the present investigation.

Data acquisition

fNIRS recordings

Two NIRSport 8-8 (NIRx Medizintechnik GmbH, Germany) devices were used to simultaneously record changes in oxy-hemoglobin (HbO) and deoxy-hemoglobin (HbR) concentration in mother and infant during 5-minute free-play condition and in 90s resting

phase. The probe sets were attached to an EEG cap with 10-20 configuration in order to locate the regions of interest (ROIs) more precisely. Brain activity was recorded from 22 channels that covered bilaterally frontal regions like medial prefrontal cortex (mPFC), lateral prefrontal cortex (lPFC) and inferior frontal gyrus (IFG), because these regions seem implicated in neural synchrony in adult-adult and caregiver-children-dyads (Czeszumski et al., 2020; Nguyen et al., 2021) and in language processing in infants (Minagawa-Kawai et al., 2008; Romeo et al. 2018). The locations of these channels were homologous across mother and infant. However, the distance between these optodes was approximately 2.3cm between infants' optodes and 3cm between the mothers' optodes. The absorption of near-infrared light was measured at wavelengths of 760 and 850 mm and the sampling frequency was 7.81 Hz. Regarding ROIs, channels 1-4 and 19-22 were assigned to IFG, channels 5-9 and 14-18 to lPFC and channels 10-13 to mPFC (see Appendices, Figure S1).

Data analysis

Neural synchrony in mother-infant dyads

Neural data were pre-processed, including motion correction, band-pass filtering, and conversion to HbO and HbR values, using MATLAB-based functions derived from Homer2 (Huppert et al., 2009). Based on previous hyperscanning studies only HbO values were used for further analyses as it is reported that these values are more sensitive to alternations in the cerebral blood flow (Hoshi, 2007; Nguyen at al., 2021). Next, neural synchrony between mother and infants was analyzed using wavelet-transform-coherence (WTC) analysis in MATLAB (see Figure 1, A.). Based on visual inspection and earlier studies investigating free verbal conversation, we analyzed the frequency band of 0.06-0.15 Hz (Jiang et al., 2012; Nguyen et al., 2021). For the first hypothesis, coherence values, ranging from 0 to 1 (1 indicating high coherence), were calculated separately for 1-minute intervals for each channel per mother-infant dyad, resulting in 5 (intervals) x 22 (channels) coherence values for each dyad. Intervals of one minute were used as this is an appropriate timescale for measuring coherence of brain activity with fNIRS (Wass et al., 2020) and, as this division is important to subsequently analyze changes in neural synchrony over time. To prepare data for testing the third hypothesis, coherence values, again ranging from 0 to 1 were averaged for the whole 5-minute condition for each channel. Additionally, for further investigation data were separated in the specific ROIs, being mPFC, lPFC and IFG, and again averaged WTC values were calculated for each dyad per ROI, ranging from 0 to 1.

Interhemispheric functional connectivity in infants

To analyze interhemispheric functional connectivity, fNIRS data of the infant during 90s resting phase was used. fNIRS data of mothers were measured but will be reported in another paper. The processing of ihFC data was analogous to that of INS data, as ihFC fNIRS data were pre-processed and, subsequently, WTC values were calculated in MATLAB (Bastos & Schoffelen, 2016). The frequency band of interest was determined to be 0.04-0.32Hz by visual inspection and spectral analyses (see Appendices, Figure S2). The channels were assigned to the right and left hemisphere, respectively, resulting in 10 channel combinations connecting both hemispheres (see Figure 1, B). The two channels placed in the middle (channels 12-13, see Appendices Figure S1) were excluded for this analysis, as no calculation of ihFC was possible due to their spatial proximity to each other. Coherence values were calculated per channel combination and then averaged, resulting in one WTC value ranging from 0 to 1 (again 1 indicating high coherence) for each infant.

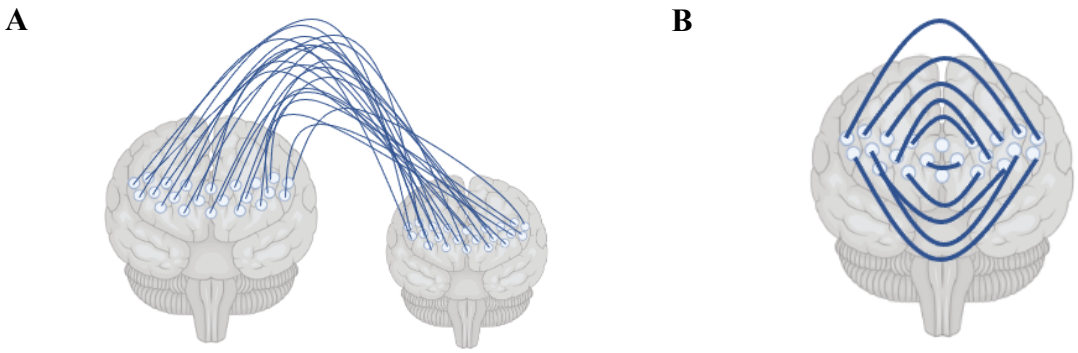


Figure 1. A): Measurement of INS during free-play condition. B): Measurement of ihFC in infants during resting phase.

Proto-conversational turn-taking

To assess turn-taking in mother-infant proto-conversations during free-play condition, in a first step, individual vocal sounds and pauses were coded in ELAN (Version 5.9) by reviewing visualization of spectrograms and video recordings. The aim was to micro-code the vocal behavior of both separately frame-by-frame to be able to determine turns in general and distinguish between turns initiated by infants and mothers, respectively, afterwards. Codes were adapted from Gratier et al. (2015) and Oller et al. (2013) (see Table 1). In general, a maternal or infant (positive or negative vocalization or cry) vocalization was defined as a

vocal sound that was either continuous or includes unvoiced segments of less than 300ms. Unvoiced segments of mother or infant lasting at least 300ms were coded as pauses. Sequences that were categorized as cry were excluded from further analysis.

Table 1

Description of codes to categorize vocal sounds of mother and infant.

Mother/Infant	Code	Description
Mother	Vocalization	Vocal sound including vegetative sounds and laughing
	Pause	≥ 300ms without vocalizations
Infant	Positive vocalization	laughing, vegetative sounds, neutral vocal sounds (squeals, vowel-like sounds, growls)
	Negative vocalization	Non-persistent vocal sound expressing fussiness or anger
	Cry	Persistent crying
	Pause	≥ 300ms without vocalizations

In a second step, turn-taking sequences were determined, that include at least one alternation between mother and infant. These sequences end when a speaker produces at least two successive vocalizations. The 5-minute free-play condition was divided in five intervals, each of it lasting 1 minute. A composite score was calculated for these 1-minute-intervals per dyad, resulting in 5 intervals. In addition, the composite scores were distinguished in whether the mother responded to her infant's vocalization (infant-to-mother) or whether the infant responded to her/his mother (mother-to-infant). For exploratory analysis, the duration of turns, meaning the duration until the mother or the infant responded to vocalizations from the other was calculated.

A second trained research assistant double coded twenty percent of randomly chosen videos for maternal and infant vocalizations to establish inter-rater-reliability, which was calculated with kappa2 function in R. Kappa for vocalizations of mother and infant ranged between 0.78 and 0.98 and averaged at 0.89, therefore showing very high reliability between coders.

Statistical analysis

Statistical analyses were carried out using Generalized linear mixed models (GLMMs) with the package 'glmmTMB' in R Studio. Each hypothesis was tested separately using an alpha level of .05 for all statistical tests. In all analyses random intercepts for dyad were included. For the first and third hypothesis, INS WTC values, and for the second hypothesis ihFC WTC values were entered as response variables, assuming a beta distribution, as the values can range from 0 to 1, indicating the degree to which WTC values are linked with each other. A value of 1 would therefore indicate either high neural synchrony between mother and infant and high infants ihFC, respectively.

The continuous predictor variables turn-taking and duration were corrected for outliers using 'winsorize' function in R and were subsequently z-standardized. Models were estimated using Type II Wald Chi-Square Test. Model fit was compared using Type Chi-Square Tests. Model outcomes of main analyses are separated by hypothesis and can be found in Appendices (H1 in Table 2, H2 in Table 3–Table 4, H3 in Table 5–Table 6). Also, model outcomes of exploratory analyses are provided in Appendices (Table S1–Table S2).

Results

Descriptive statistics

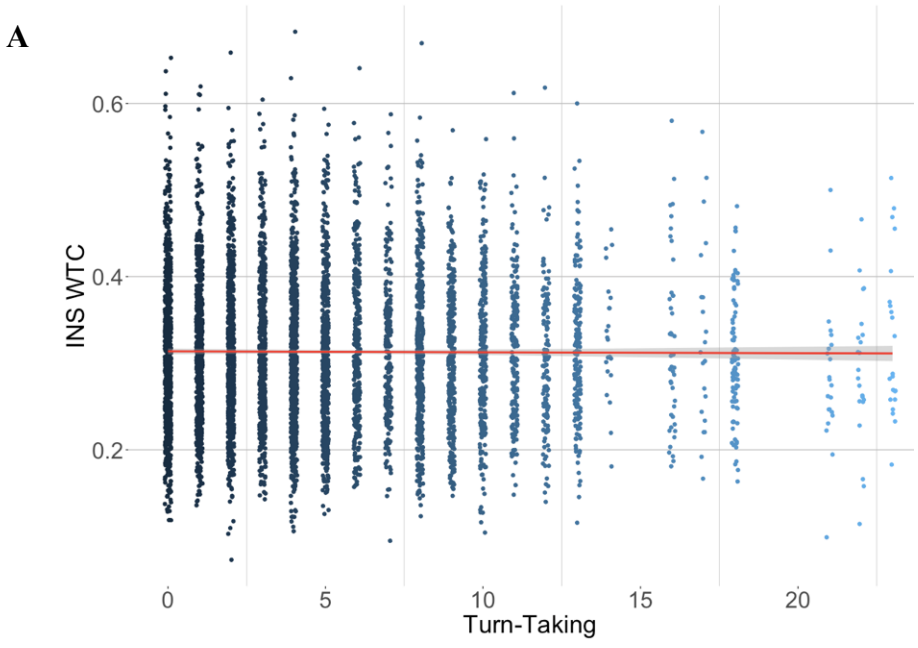
Overall number of turns per dyad ranged from 0 to 61 turns, with mean 25 (*SD* = 14.69). Mothers and infants did not show differences in initiating and/or responding to turns of the other (*M* turn infant = 12, *SD* = 7.33, range = 0-31; *M* turn mother = 13, *SD* = 7.79, range = 0-30). Visual inspection of the distribution of turns depicted that both types of turns were equally distributed in each of the 5 intervals. Exploratory descriptive analysis of duration of turns per dyad showed that the overall duration ranged from 0.24s to 2.77s, with mean 1.21s (*SD* =0.60). However, the duration of turns of mothers and infants revealed differences, more specifically, on average mothers responded quicker compared to their infants (*M* duration infant = 1.48s, *SD* = 0.86, range = 0.19-4.12; *M* duration mother = 1.29s, *SD* = 0.84, range = 0.23-4.40).

Descriptive analysis of the neural data showed that INS WTC values ranged from 0.29 to 0.34 (*M* = 0.31, *SD* = 0.01), whereas ihFC WTC values ranged from 0.26 to 0.44 (*M* = 0.35, *SD* = 0.04). Thus, analyses indicated that dyadic WTC values assessed in the free-play condition were less scattered than individual ihFC WTC values assessed in the resting phase.

Analysis of main hypotheses

First, we tested the association between turn-taking and neural synchrony in mother-infant dyads over the 5 minutes of free-play, more specifically, we tested whether higher amounts of proto-conversational turn-taking were associated with increases in neural synchrony over time (H1). The null model comprised WTC as response variable and random intercepts for each dyad. To test for the main effect of turn-taking, we first entered turn-taking as fixed-effect predictor variable (Model 1.1). Model fit did not improve significantly in comparison to the null model, indicating no association between turn-taking and neural synchrony (see Figure 2A). Next, we added interval as fixed-effect predictor (Model 1.2). Again, the model fit did not improve significantly in comparison to Model 1.1, depicting that interval was not significantly associated with neural synchrony. Finally, we added the interaction effect between interval and turn-taking (Model 1.3) but results again revealed no improvement of model fit. Contrary to our hypothesis, higher amounts of proto-conversational turn-taking were not significantly associated with an increase of neural synchrony over time (see Figure 2B & Table 2).

In a subsequent exploratory analysis, we found a significant interaction effect of interval and duration, $p = .029$ (see Appendices, Table S1). To further investigate this interaction effect, we separated duration of infant and mother and found a significant effect of infants' duration and interval, $p = .009$ (see Appendices, Table S2), indicating that higher turn-taking durations of infants were significantly associated with an increase of neural synchrony over time.



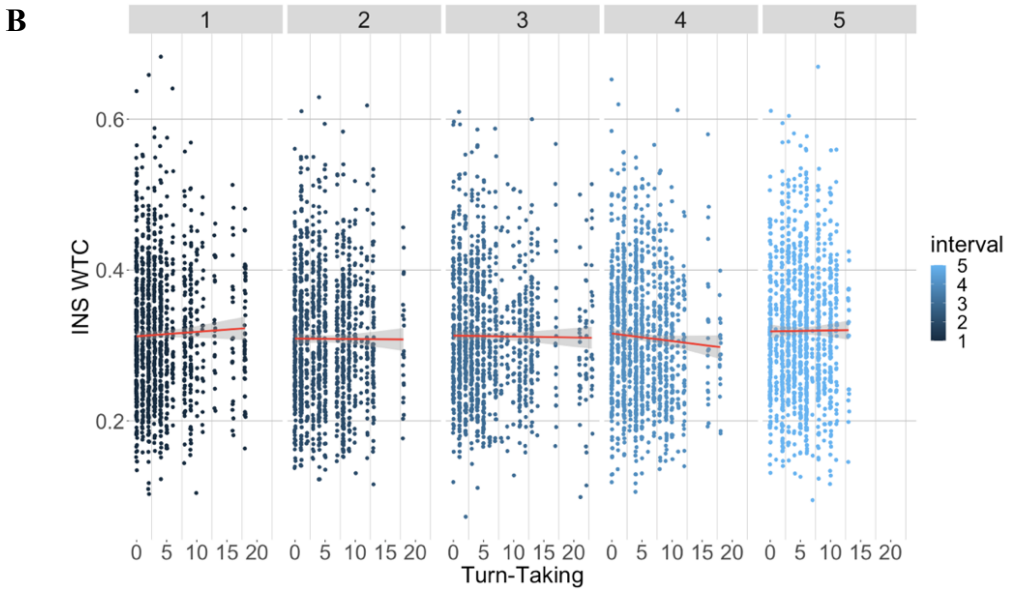


Figure 2. A): Plot of the association between turn-taking (x-axis) and INS (y-axis) during free-play condition. B): Illustration of the relation of turn-taking and INS in each interval (facets). INS during free-play was not significantly associated with turn-taking over the five intervals.

To test whether higher ihFC in infants was associated with higher amounts of proto-conversational turn-taking (H2), we first entered ihFC WTC as response variable and random intercepts for each dyad to the null model. In Model 2.1 we added turn-taking as fixed-effect predictor variable, but results indicated that turn-taking did not explain more variance. Thus, in contrast to our hypothesis, higher amounts of turn-taking were not associated with higher ihFC (see Figure 3A). Next, we entered duration as fixed effect predictor variable. Although model fit did not improve significantly, analyses revealed a marginal trend for duration. To further investigate the trend of duration, we separated turn duration of mothers and infants and conducted another model with ihFC WTC as response variable, random intercepts for each dyad and, turn-taking, turn duration of mothers and turn duration of infants as fixed-effect predictor variables. Interestingly, results showed a significant main effect for infants' turn duration, estimate±SE = -0.072±0.031, $\chi 2(1) = 5.369$, $p = .021$, 95% CI = [-0.133; -0.011], but not for mothers' turn duration (see Figure 3B & Table 3).

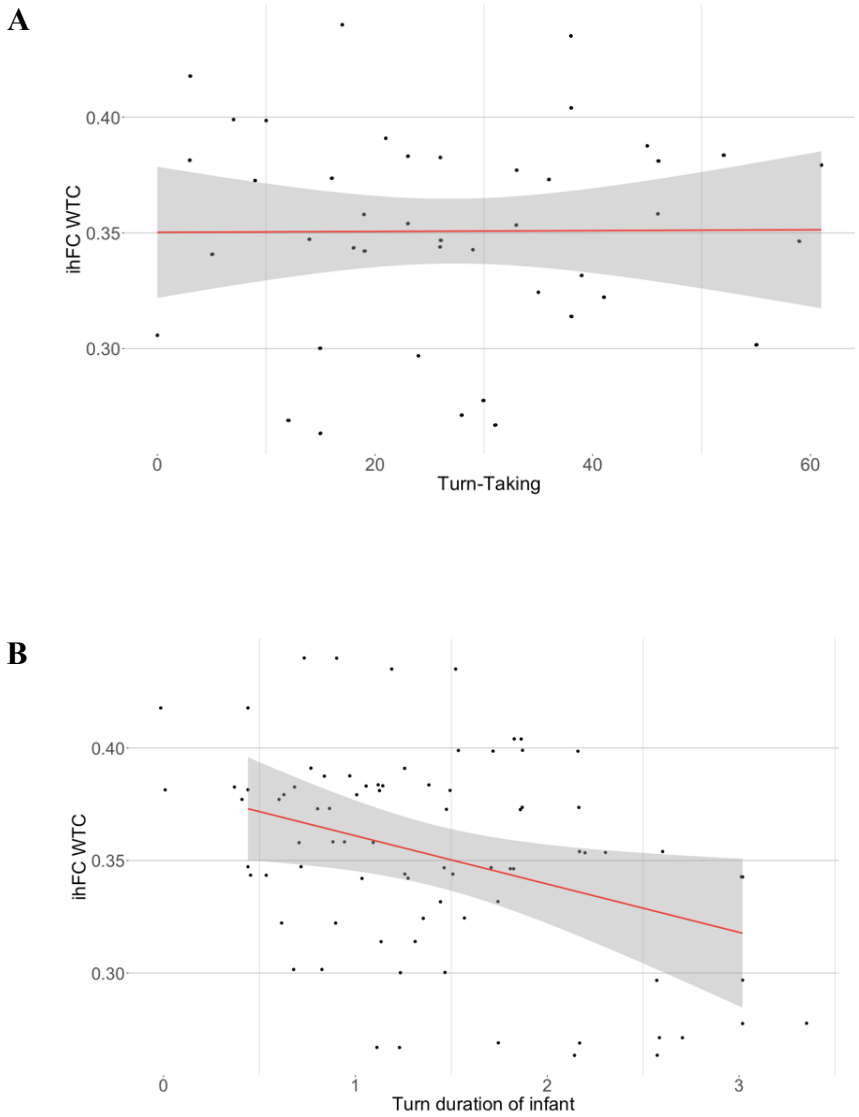


Figure 3. A): Plot of the association between turn-taking (x-axis) and ihFC WTC (y-axis). ihFC during resting phase was not significantly associated with turn-taking during free-play. B): Plot of association between turn duration of infant (x-axis) and ihFC WTC (y-axis). ihFC during resting phase was significantly associated with turn duration of infant during free-play.

Finally, with the third hypothesis, we tested the association between ihFC in infants and neural synchrony in mother-infant dyads. We entered WTC values of neural synchrony in mother-infant dyads as response variable, averaged WTC values of ihFC in infants as fixed-effect predictor variable and random intercepts for each dyad. Model fit did not improve significantly in comparison to the null model. Accordingly, results did not indicate a significant association between dyadic neural synchrony and infants' ihFC (see Tale 5). Further, we separated the WTC values for neural synchrony in three regions of interest, being

mPFC, lPFC and IFG and conducted three separate models for testing the association of INS and ihFC in these three ROIs. Results revealed a trend for lPFC, estimate±SE = 0.361±0.195 $\chi 2(1) = 3.44$, $p = .06$, 95% CI = [-0.002; 0.743], but no statistical significance (see Figure 4 & Table 6).

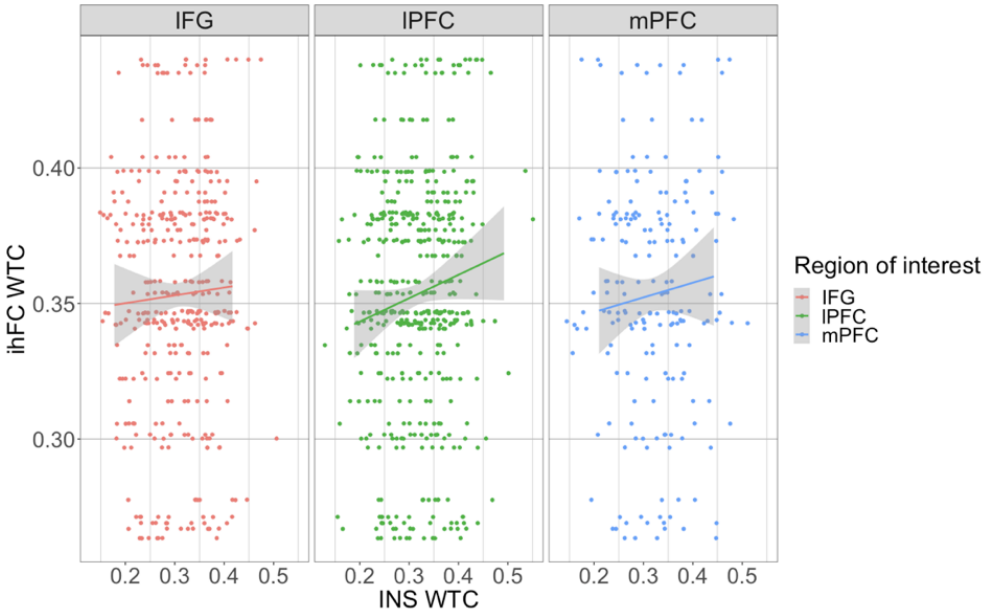


Figure 4. Plot of the association between INS WTC (x-axis) and ihFC WTC (y-axis) for each ROI (facets). ihFC during resting phase was not significantly associated with INS during free-play.

Discussion

On the one hand, the aim of the present study was to replicate previous findings regarding the association between conversational turn-taking and neural synchrony (Nguyen et al., 2021) in a younger, preverbal sample (H1). On the other hand, we tested whether higher ihFC in infants is associated to higher amounts of turn-taking (H2), and exploratively, whether there is a relationship between ihFC in infants and neural synchrony in mother-infant dyads (H3).

Interestingly, descriptive data revealed that on average both mothers and infants initiated approximately the same amounts of turns, although there were differences across dyads. While some dyads showed up to 61 turns, others did not take any turns at all during the 5-minute free-play. When there was high dyadic turn-taking, it seems that both were involved in the (proto-)conversation to a similar extent. This finding falls in line with the assumption

that parental vocalizations adapt to infant vocalizations and thus to infant age (Abney et al., 2017). It also shows that inter-individual variability in vocal interaction indeed occurs at an early stage (Dominguez et al., 2016).

In contrast, duration of turns differed marginally between mothers and infants, with infant turns lasting longer than maternal turns. Considering that the infant timing at 6-month of age nearly approximates adult timing, nevertheless, the maternal cognitive anticipation and initiation process of turns is already mature and as a result, the timing is faster (Hilbrink et al., 2015; Ruiter et al., 2006). Overall, duration of turns lasted longer compared to previous studies in which the duration of maternal and infant vocalizations ranged from 500ms to 1s (Jaffe et al., 2001).

However, we failed to replicate the findings of Nguyen et al. (2021) in a younger, preverbal sample. Nguyen et al. (2021) demonstrated that a higher number of turns in dyads of preschool-aged children and their caregivers was related to neural synchronization and, more importantly, neural synchronization over time, whereas we did not find this association in infant-mother-dyads. We assume, that this discrepancy might be due to methodological differences in the assessment of both, turn-taking and neural synchronization, and underlying developmental changes during infancy and preschool age. First, whereas turn-taking has been studied in preschooler-caregiver-dyads during a task, in which they were explicitly instructed to talk to each other, in the present study mothers were just asked to play with their child, without focusing on verbal interaction. Second, in line with previous research in both studies neural synchronization was measured in prefrontal areas (Jiang et al., 2012; Leong et al., 2017; Piazza et al. 2020), however, Nguyen et al. (2021) additionally measured brain activity in the left and right temporo-parietal junction. Especially the temporal area is known to process social-emotional meaning of sensory input (e.g., conversational exchanges), is activated during social contingent interactions in infants and, in general supports the temporal alignment to others (Hakuno et al., 2020; Hoehl et al., 2021). The importance of the temporal region, especially the left temporal cortex for language processing was also highlighted in a fNIRS study in 6-9-months-old infants (Bortfeld et al., 2009). Accordingly, it could be that both areas together are important for neural synchronization during conversational turn-taking, and in further studies brain measurement in temporo-parietal regions should be added to fully understand this association. Third, as pointed out by Nguyen et al. (2021) turn-taking was the one that best described the association with neural synchrony in preschoolers and their caregivers, compared to other conversational patterns, such as contingency and intrusiveness. However, not finding significant associations between the amount of proto-

conversational turn-taking and INS also provides important insights. It is likely that in infants the amount of turn-taking is not yet associated with INS, but other conversational patterns. For instance, according to our exploratory results the duration of infant turns, rather than the number of turns may play a crucial role in neural synchronization processes. Also, especially in infants from the age of 4 months midrange vocal coordination was observed as pleasant for both mothers and infants, as it allows flexibility and variability (Jaffe et al., 2001). Thus, in infancy midrange turn-taking could potentially be associated with neural synchrony rather than high amounts of turn-taking.

Our results regarding turn-taking and INS could also be explained by predictive processing accounts, as our brains and internal models are constantly evolving and adapting to the environment to optimize predictions. Synchrony between at least two individuals might facilitate predictions and lead to less prediction errors (Hoehl et al., 2021), as it was found in a study examining neural processes of joint eye gaze in 9- to 15-month- old infants (Piazza et al., 2020). In order to successfully anticipate to vocalizations of others, both syntactic and semantic information must be processed (Riest et al., 2015). However, vocalizations of mothers and infants differ in these aspects and, infants' internal models regarding proto-conversational turn-taking are less experienced than those of their mothers. Mothers might predict accurately the end of their infant's vocalization, plan the answer, and consequently respond directly after the current vocalization (Casillas et al., 2016; Ruiter et al., 2006). Possibly, as predictions of vocalizations of not only the mother but also the infant mature, neural synchrony may become linked to turn-taking processes.

As opposed to the association between neural synchrony and unimodal conversational turn-taking, current research suggests a variety of social ostensive cues, such as eye gaze or facial affect, that are sent during social interactions and influence interpersonal neural entrainment (Leong et al., 2017; Wass et al., 2020). In one study with 5-month-olds, for example, eye gaze and vocalizations revealed similar patterns of activation in infants' frontal brain areas (Parise & Csibra, 2013). Rohlfing et al. (2020) proposed a phenomenon called *multimodal turn-taking*, meaning that responses to vocalizations may be multimodal, rather than only verbal. Especially preverbal children take turns through smiling, gazing or moving and, as infants get older, turn-taking between mothers and infants is characterized by more symmetric modalities (Leclère et al., 2014). The lack of significant findings on amounts of vocal turn-taking in regard to neural synchrony of mother-infant-dyads can be at least partly explained by this approach. However, exploratory analyses showed that infants turn duration was negatively associated with neural synchrony over time, indicating greater infant delay

was associated with higher coherence between maternal and infant neural activity over time. It is possible that other modalities of turn-taking emerged during these delays that could explain synchrony processes. Connecting the above-mentioned variety of behaviors and similar neural patterns with neural synchrony, it would be interesting to additionally assess facial affect and eye gaze. Thus, post-hoc-analyses could be conducted to clarify whether higher amounts of multimodal turn-taking are associated with neural synchrony.

A growing body of evidence has indicated that turn-taking is positively linked to advanced language skills (Bloom et al., 1987; Donnelly & Kidd, 2021; Jaffe et al., 2001; Romeo et al., 2018). To extent these findings, the present study was the first to date that examined the relationship between turn-taking and infant maturity at a neural level measured via brain connectivity. Going against our hypothesis, higher ihFC in infants was not associated with higher amounts of turn-taking (H2), however, due to exploratory findings, higher ihFC in infants was significantly associated with lower duration of infant turns, but unrelated to maternal turns. Rochat et al. (1999) have shown that infants begin to be sensitive to the timing of proto-conversations at 4 months of age, which can be considered the first sign of anticipation. Moreover, to take turns quickly, individuals need to predict the end of the turn of the other accurately, while planning their response (Ruiter et al., 2006). Thus, vocal turn-taking duration seems to indicate how fast children can understand a question (Casillas et al., 2016), meaning that more mature infants anticipate vocalizations faster, our results fall in line with this assumption. However, note that although turn duration gets quicker during the first nine month, there are mixed findings regarding its development afterwards (Hilbrink et al., 2015). In summary, our results regarding this association show that differences in ihFC can be identified, map onto behavioral differences in infants and extend prior findings regarding the link between ihFC and individual differences in infants (Allievi et al. 2016; Kelsey et al., 2021).

In contrast to our exploratory expectation, ihFC in infants was not significantly associated with neural synchrony in mother-infant dyads (H3). Nevertheless, we could find a marginal trend regarding a positive association between higher ihFC in infants and higher neural synchrony in one of our ROIs, namely lPFC. Note that while all our ROIs are parts of a coordinated system, namely the social interaction network (Redcay & Schilbach, 2019), empirical evidence suggests different associations. However, while activation of mPFC and IFG, among others, is linked to affective processes in early social interactions (for a review see Grossmann, 2013a; Saito et al., 2010), lPFC is linked to higher-order sensory processing, such as attention processes in both, adults and infants (Grossmann, 2013b; Wood & Grafman,

2003). Further, findings regarding the lPFC and conversational patterns revealed inconsistency regarding activation of the right and left lPFC during communication (Urakawa et al., 2015). Thus, the lPFC should be studied in future research to further explore its associations and examine a possible relation between inter- and intra-individual neural synchrony.

Limitations and implications for future research

Our study also had several limitations. First, we analyzed neural data only by using HbO values. Current studies offered mixed evidence regarding concordance of findings in HbO and HbR values. Whereas in an adult study, findings could be replicated (Pan et al., 2017), in a preschooler study, findings differed (Nguyen et al., 2021). To fully understand neural synchronization and its specialties in childhood, future studies should address both, HbO and HbR values. Second, we had not conducted control analyses for INS and ihFC to test whether neural data of original dyads and original infants, respectively, showed higher concordance than randomly chosen pairs. Accordingly, significant results regarding the association between ihFC and infant turn duration should be interpreted with caution. Third, as in previous studies with children and infants, we used an eye-opened resting-phase to measure ihFC (Emerson et al., 2015; Kelsey et al., 2021). However, the resting-phase in our study lasted only 90 seconds, whereas other studies conducted resting phases at least four times as long. In addition, in these studies channels covering not only prefrontal areas, but also parietal and temporal regions were used. In our study, channels covering the mPFC were located close to each other, thus, possibly too close to distinguish adequately between the two hemispheres as required for ihFC analyses. However, the two channels directly in the middle were excluded anyway. Thus, further studies exploring ihFC in infants should extend the duration of resting phase and investigate temporal and parietal areas in addition to prefrontal areas (Kelsey et al., 2021). As mentioned above, measurement of temporo-parietal regions could also be useful in INS assessment to fully understand neural synchronization processes during (proto-)conversation in children (Nguyen et al., 2021).

Considering that we could not find a relationship between turn-taking and neural synchrony in infants, whereas empirical evidence has already been provided in preschoolers (Nguyen et al., 2021), further studies could focus on a developmental stage between the two samples. For instance, 2-year-olds, who have rudimentary verbal language skills could be studied to replicate the association between ihFC and infant turn duration, and moreover

could again attempt to replicate findings of Nguyen et al. (2021) in younger but also verbal children.

While our study focused on neural correlates of development of turn-taking in preverbal infants, other studies reported evidence that infant participation in proto-conversations is positively linked to language development (Bloom et al., 1987; Donnelly & Kidd, 2021). For future research, it would be interesting to longitudinally investigate the effect of amounts of turn-taking or duration of turn-taking and its neural components on later language skills.

Conclusions

All in all, the present study added to the complexity of current neurobehavioral developmental research. In contrast to previous studies in verbal children and adults (Jiang et al., 2012; Nguyen et al., 2021), we observed that interpersonal neural synchrony was not associated with conversational turn-taking in infants. As it was the first study investigating this relationship in preverbal children, it could encourage further studies focusing on both, multiple non-vocal modalities of social exchanges, such as gaze or affect, and further conversational patterns, such as, turn duration, that together might support neural synchrony in infants (Rohlfing et al., 2020). Accordingly, exploratory findings indicate that duration of infant turn-taking might be crucial for interpersonal neural synchrony over time. Moreover, as the infant brain connectivity could not be reflected in the rate of turn-taking, but again in infant turn-taking duration, studies should investigate the link further to possibly detect behavioral outcomes and extend previous neuro-behavioral findings (Allievi et al. 2016; Kelsey et al. 2021). Exploring the link between interpersonal and intrapersonal synchrony is a promising branch of research, although according to our findings brain regions should be analyzed separately. These perspectives could open up needed research to understand how neural synchrony within an individual and between individuals emerges in infancy and how it relates to infant development, particularly language acquisition, to finally derive implications for caregivers to support their infants.

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Appendices

A. Abstract

In this study, we examined neuro-behavioral components of early social interactions between infants and their mothers by analyzing brain activity recorded with dual-functional near-infrared spectroscopy (dual-fNIRS) and micro-coded vocalizations. More precisely, we focused on turn-taking as a conversational pattern that occurs early in preverbal conversations between infants and their caregivers. Recently, the amount of conversational turn-taking between preschoolers and their caregivers has been linked to an increase in interpersonal neural synchrony (INS) over time. Using a naturalistic free-play situation, we expected to replicate these previous findings at an earlier stage of development. Furthermore, we investigated the relation between proto-conversational turn-taking and interhemispheric functional connectivity (ihFC) in infants, measured in a resting phase. Both ihFC and turn-taking increase with age and ihFC is also considered to be a marker for neural maturity. Therefore, we expected ihFC in infants to be positively associated with proto-conversational turn-taking in mother-infant interactions. Additionally, we exploratively examined the association between ihFC and INS. Neural and behavioral data from 57 and 49 dyads of mothers and their 4- to 6-month-old infants, respectively, were analyzed. According to our results, neither the amount of turn-taking nor INS was associated with ihFC. Our replication attempt regarding INS and turn-taking in a younger, preverbal sample also failed. However, exploratory findings suggest that the duration of turns is linked to ihFC. More precisely, higher ihFC was associated with shorter duration of infant turns. Accordingly, our study raises possible directions for future neuro-behavioral developmental research.

B. Zusammenfassung

In dieser Studie untersuchten wir neuro-behaviorale Komponenten früher sozialer Interaktionen zwischen Säuglingen und ihren Müttern, indem wir die mit dualer funktionaler Nahinfrarotspektroskopie (dual-fNIRS) aufgezeichnete Gehirnaktivität und mikrokodierte Vokalisationen analysierten. Genauer gesagt, konzentrierten wir uns auf das Turn-Taking als Konversationsmuster, das früh in präverbalen Gesprächen zwischen Säuglingen und ihren Bezugspersonen auftritt. Kürzlich wurde die Häufigkeit von Turn-Taking zwischen Vorschulkindern und ihren Bezugspersonen mit einer Zunahme der interpersonellen neuronalen Synchronität (INS) über die Zeit in Verbindung gebracht. Mit Hilfe einer naturalistischen freien Spielsituation erwarten wir, diese Befunde in einem früheren Entwicklungsstadium zu replizieren. Darüber hinaus untersuchten wir die Beziehung zwischen Turn-Taking und interhemisphärischer funktioneller Konnektivität (ihFC) bei Säuglingen, die in einer Ruhephase gemessen wurde. Sowohl ihFC als auch Turn-Taking nehmen mit dem Alter zu und ihFC wird zudem als Marker für neuronale Reife angesehen. Daher erwarteten wir, dass ihFC bei Säuglingen positiv mit Turn-Taking in Mutter-Säuglings-Interaktionen assoziiert ist. Zusätzlich untersuchten wir explorativ den Zusammenhang zwischen ihFC und INS. Neuronale und behaviorale Daten von 57 bzw. 49 Dyaden von Müttern und ihren 4- bis 6-monatigen Säuglingen wurden analysiert. Unsere Ergebnisse zeigten, dass weder die Häufigkeit von Turn-Taking noch INS mit ihFC assoziiert war. Unser Replikationsversuch bezüglich INS und Turn-Taking in einer jüngeren, präverbalen Stichprobe schlug ebenfalls fehl. Die explorativen Befunde deuten jedoch darauf hin, dass die Dauer des Turn-Takings beim Säugling mit ihFC zusammenhängt. Genauer gesagt war eine höhere ihFC mit einer kürzeren Dauer von Turn-Taking des Säuglings assoziiert. Dementsprechend zeigt unsere Studie mögliche Richtungen für zukünftige neuro-behaviorale Forschung der Entwicklung auf.

C. Tables

Table 2

Model Outputs (Hypothesis1, Model 1.1-1.3)

	Estimates	*SE*	*CI Lower*	*CI Upper*	*RE SD*	*X²*	*df*	*p*
Model 1.1: *INS WTC ~ turn-taking + (1 | dyad)*								
Comparison to Nullmodel *INS WTC ~ 1 + (1 | dyad)*						0.137	1	.711
Model 1.2: *INS WTC ~ interval + turn-taking + (1 | dyad)*								
Comparison to Model 1.1						1.970	1	.160
Model 1.3: *INS WTC ~ interval * turn-taking + (1 | dyad)*								
Comparison to Model 1.2						1.374	1	.241
(Intercept)	-0.798	0.012	-0.822	-0.774	0.022			
interval	0.005	0.004	-0.002	0.001		1.970	1	0.160
turn-taking	0.011	0.013	-0.014	0.036		0.203	1	0.653
interval: turn-taking	-0.005	0.004	-0.013	0.003		1.372	1	0.242

Table 3

Model Outputs (Hypothesis 2, Model 2.1-2.2)

	Estimates	*SE*	*CI Lower*	*CI Upper*	*RE SD*	*X²*	*df*	*p*
Model 2.1: *ihFC WTC ~ turn-taking + (1 | dyad)*								
Comparison to Nullmodel *ihFC WTC ~ 1 + (1|dyad)*						0.005	1	.943
Model 2.2: *ihFC WTC ~ turn-taking + duration + (1 | dyad)*								

Comparison to Model 2.1						3.253	1	.071
(Intercept)	-0.617	0.029	-0.674	-0.559	0.051			
turn-taking	0.017	0.030	-0.424	0.076		0.313	1	0.576
duration	-0.056	0.031	-0.116	0.004		3.31	1	0.069

Table 4

Model Output (Hypothesis 2, Model 2.3)

	Estimates	*SE*	*CI Lower*	*CI Upper*	*RE SD*	*X²*	*df*	*p*
Model 2.3: *ihFC WTC ~ (turn-taking + duration.infant + duration.mother) + (1 | dyad)*								
(Intercept)	-0.611	0.030	-0.669	-0.553	0.073			
turn-taking	-0.006	0.031	-0.068	0.055		0.041	1	.839
duration. infant	-0.072	0.031	-0.133	-0.011		5.369	1	.021*
duration. mother	0.015	0.030	-0.443	0.075		0.253	1	.615

Table 5

Model Output (Hypothesis 3, Model 3.1)

	Estimates	*SE*	*CI Lower*	*CI Upper*	*RE SD*	*X²*	*df*	*p*
Model 3.1: *INS WTC ~ ihFC WTC + (1 | dyad)*								
Comparison to Nullmodel *INS WTC ~ 1 + (1|dyad)*						3.03	1	.082
(Intercept)	-0.876	0.050	-0.975	-0.778	0.014			
ihFC WTC	0.018	0.013	-0.027	0.524		3.118	1	0.077

Table 6

Model Outputs (Hypothesis 3, 3.2(mPFC), 3.3(lPFC), 3.4 (IFG))

	Estimates	*SE*	*CI Lower*	*CI Upper*	*RE SD*	*X²*	*df*	*p*
Model 3.2 (mPFC): *INS WTC ~ ihFC WTC + (1 | dyad)*								
Comparison to Nullmodel (mPFC) *INS WTC ~ 1 + (1|dyad)*						0.633	1	.426
(Intercept)	-0.861	0.122	-1.100	-0.612	0.013			
ihFC WTC	0.274	0.343	-0.398	0.945		0.637	1	.425
Model 3.3 (lPFC): *INS WTC ~ ihFC WTC + (1 | dyad)*								
Comparison to Nullmodel (lPFC) *INS WTC ~ 1 + (1|dyad)*						3.329	1	.068
(Intercept)	-0.907	0.069	-1.043	-0.771	0.005			
ihFC WTC	0.361	0.195	-0.002	0.743		3.441	1	.064
Model 3.3 (lFG): *INS WTC ~ ihFC WTC + (1 | dyad)*								
Comparison to Nullmodel (IFG) *INS WTC ~ 1 + (1|dyad)*						0.162	1	.687
(Intercept)	-0.8467	0.084	-0.367	0.557	0.003			
ihFC WTC	0.095	0.236	0.013	0.087		0.162	1	.687

D. List of Figures

E. List of Tables

F. List of Abbreviations

INS	Interpersonal neural synchrony
ihFC	Interhemispheric functional connectivity
dual-fNIRS	Dual-functional near-infrared spectroscopy
mPFC	Medial prefrontal cortex
lPFC	Lateral prefrontal cortex
IFG	Inferior frontal gyrus
HbO	oxy-hemoglobin
HbR	deoxy-hemoglobin
WTC	Wavelet-transform-coherence
ROI	Region of interest

G. Supplementary Information

1. Instruction for the distal watching condition

   "In the next task, you will both watch a short video. During this short time, please try to look at the screen and not look at, interact with, or touch your child. However, if your child gets fussy or cries, you can of course comfort him/her."

2. Instruction for the free-play condition

   "For the next few minutes, you should play with your child as you would at home. We would like to ask you not to use any toys or other objects and not to sing."

3. Supplementary figure

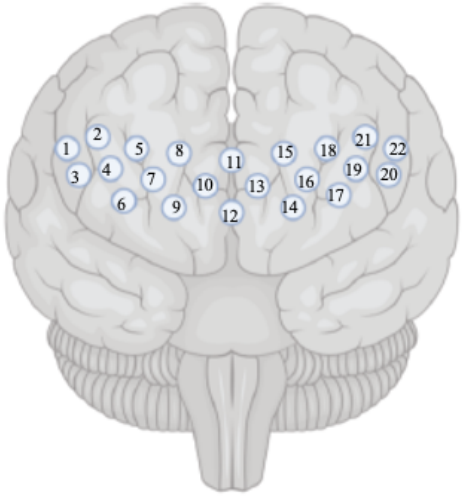

Figure S1. Assignment of channels to ROIs. IFG (channels 1-4 and 19-22), lPFC (channels 5-9 and 14-18) and mPFC (channels 10-13).

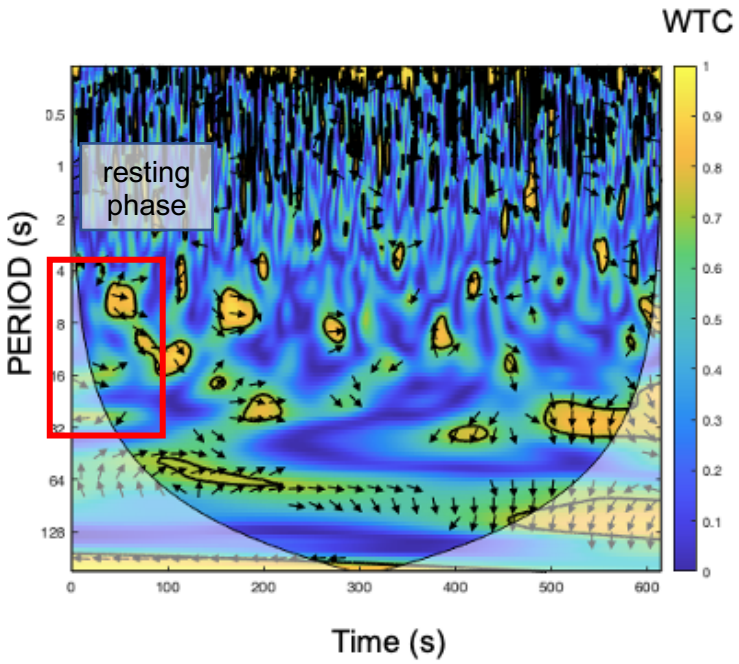

Figure S2. Spectrogram of range of ihFC WTC values (indicated by the color bar) over the frequency band (y-axis) for the whole experimental procedure (x-Axis). The coherence based on HbO values from channel 8 and 15 in a representative infant.

4. Supplementary tables

Table S1

Model Output S1.1

	Estimates	*SE*	*CI Lower*	*CI Upper*	*RE SD*	*X²*	*df*	*p*
Model S1.1: *INS WTC ~ interval * (turn-taking + duration) + (1 | dyad)*								
(Intercept)	-0.798	0.012	-0.822	-0.774	0.051			
interval	0.004	0.004	-0.002	0.012		2.004	1	.157
turn-taking	0.014	0.013	-0.013	0.037		0.104	1	.747
duration	-0.025	0.012	-0.013	0.008		0.245	1	.621
interval: turn-taking	-0.006	0.004	-0.013	0.003		1.896	1	.168
interval: duration	0.008	0.004	0.001	0.015		4.778	1	.029*

Table S2

Model Output S1.2

	Estimates	*SE*	*CI Lower*	*CI Upper*	*RE SD*	*X²*	*df*	*p*
Model S1.2: *INS WTC ~ interval * (turn-taking + duration.infant + duration.mother) + (1|dyad)*								
(Intercept)	-0.791	0.019	-0.829	-0.754	0.073			
interval	0.004	0.005	-0.007	0.014		0.420	1	.517
turn-taking	0.007	0.020	-0.032	0.045		0.512	1	.474

duration. infant	-0.045	0.017	-0.077	-0.012		0.619	1	.431
duration.mother	0.006	0.0190	-0.032	0.043		0.847	1	.357
interval: turn-taking	-0.017	0.008	-0.017	0.008		0.430	1	.512
interval: duration.infant	0.003	0.023	-0.017	0.023		6.730	1	.009**
interval: duration.mother	-0.010	0.010	-0.010	0.010		0.005	1	0.946