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„Mother-infant dyads: Effects of maternal vocalizations on infant brain activity"

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Table of contents

Theoretical background

Humans are social animals and one thing that distinguishes us from other animal species is language. Especially through speech, we are able to communicate our thoughts, feelings and therefore bond and maintain our relationships with each other. Language is therefore a crucial aspect of our everyday lives as we can engage with each other by actively expressing what is on our mind. In times of globalization and the advance of new technologies, a huge part of our communication has shifted to virtual activities such as talking to the other person on the phone, video chatting or sending text messages. However, language learning does not start with technical devices. In fact, vocal development in infants' early lives starts with their primary caregivers, in most cases, their mothers, through naturalistic face-to-face interaction. Since communication through speech is important for human beings to impact our environment and social surroundings, it is critical to support early vocal development as studies have demonstrated that infants need the experience of their caregivers' attempts to vocalize with them in order to learn how to communicate, and thereby, how to express their own and understand other people's feelings – crucial abilities for bonding with others and maintaining healthy relationships with our loved ones.

Early vocal mother-infant interactions

Literature has shown that early mother-infant interactions play a crucial role for cognitive, social and language development of the infant (Ainsworth & Bell, 1974; Bakeman & Brown, 1980; Feldman, 2007; Bornstein & Bruner, 2014) and that early language development is severely limited in the absence of social interactions (Kuhl, 2007). Even in the first year of life, language experience in the form of communicative behaviors with their primary caregiver seems to already be very crucial for infants' speech learning and the overall course of language development (Kuhl, 2007; Karousou & López-Ornat, 2013). According to Bigelow and Power (2014), mothers are typically seen as the primary caregivers for their infants. In fact, they are infants' most frequent and consistent social partners (Bigelow & Power, 2014; Bornstein, 2013; Bell, 2020). Thus, as it is assumed that mothers play an essential role for infant vocal development, this work will primarily focus on maternal vocalizations (Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001; Goldstein, King, & West, 2003).

Early infant language development

Early infant vocalization is a precursor to interpersonal communicative skills and language development (Bateson, 1975; Stark, Rose, & Benson, 1978; Hsu & Fogel, 2003). Infants' prelinguistic vocalizations contain cues that could serve to stimulate maternal responses that in turn provide opportunities for infant vocal learning (Albert, Schwade, & Goldstein, 2017). Previous research findings have linked early vocal production to later language outcomes (Baumwell,Tamis-LeMonda, & Bornstein, 1997). For instance, Stoel-Gammon (2011) found that infants who produced greater number of prelinguistic vocalizations such as canonical babbling acquired more advanced vocabulary and speech skills in later developmental stages. Similar results were shown by Masur and Olson (2008) where imitative responses between mothers and infants during daily settings such as free play and bath sessions were investigated. This longitudinal study reported that highly responsive and reactive infants showed greater lexical advancement than those who were less responsive and imitated fewer sounds and actions (Pelaez, Borroto, & Carrow, 2018). In contrast, delayed onset of canonical babbling might predict delayed productive vocabulary (Paul & Jennings, 1992; Albert et al., 2017). This has also been investigated in connection with language-disordered children. Here, results also indicated that language delays can lead to long-term deficits in language as well as academic and social skills (Aram, Ekelman, & Nation, 1984; Patten et al., 2014). Based on these findings, the encouragement of infant vocalizations and communication can be seen as a prerequisite and essential for continuous language development.

Primarily mothers seem to lay a foundation for the infant to be part of a dyadic communication system where the language advancement can occur through continuous interdependent mother-infant interactions. Moreover, literature has shown that the communication within mother-infant dyads is shaped and facilitated by numerous variables and mechanisms. Two mechanisms that have been most commonly investigated by developmental research and marked as particularly important are turn-taking behavior and contingent responses to vocalizations.

Turn-taking and contingency. Infants begin to express their affective states and needs in their very first months of life by using prelinguistic vocalizations such as babbling and vowel-like sounds, providing a framework within which an interactive relationship can develop (Papoušek, 1992; Franklin et al., 2015). At only 2 months of age, they already become more aware and interested in social partners and begin to actively engage in

alternating communicative interactions with their caregivers, showing rhythmic cycles of turn-taking within a dyad (Karousou & López-Ornat, 2013; Bloom, Russell, & Wasserberg, 1987). These patterns of vocal interactions between infants and adults in early infancy are called "protoconversations" and occur prior to any lexical information (Trevarthen & Aitken, 2011; Bateson, 1975).

More specifically, turn-taking has been described as a synchronous dialogue where one partner responds to the social cues of the other within a lag of seconds (Feldman, 2003; Tronick, 1989; Feldman & Eidelman, 2007). By alternating their vocalizations, they dynamically co-regulate their behavior with respect to the ongoing and anticipated actions of their partner and create communitive patterns (Hsu & Fogel, 2003). For example, mothers tend to pause their vocalizations with the aim to wait for the infant to vocalize when seeing prespeech mouth movements of young infants as these are indicators for onset of vocalization (Hsu & Fogel, 2003; Trevarthen & Marwick, 1986). Further, it has been demonstrated that while mothers responded to infants' babbling with more simplified speech (Elmlinger, Schwade, & Goldstein, 2019), infants might send social signals to their mother through their vocalizations to regulate her responsive actions (Hsu & Fogel, 2003). This indicates that through a give-and-take pattern of vocalizations between mother and her infant, both partners can influence the other person's interactions. Taken together, these results suggest that during turn-taking, mothers indeed adapt their vocalizations to those of the infant and vice versa. This kind of successful alternation of vocalizations has particularly been demonstrated to be critical for language development. For instance, Jaffe et al. (2001) were able to show that greater vocal coordination between infant and adult was associated with better language, cognitive, and perceptual ability later in life.

One type of behavior that goes hand in hand with successful turn-taking are contingent maternal responses. Contingency is defined as the temporal relation between the occurrence of two events (Tarabulsy, Tessier, & Kappas, 1996). Especially the second half of the first year of life marks significant gains in infants' contingent responding to vocalizations (McFarland, Fortin, & Polka, 2020; Kuchirko, Schatz, Fletcher, & Tamis-LeMonda, 2019). During this period of time, between 6 and 10 months, infants start to produce canonical and syllabic babbling, which enable the infants to build language capabilities that eventually lead to the transition to their first word productions even before 1 year of age (Sung, Sterling, Coll, & Seifer, 2013; Oller, 2000). In order to engage in smooth face-to-face interactions during communication, contingent turn-taking vocalizations are fundamental as they allow mother-

infant dyads to mutually enable accurate timed anticipation of each other's expressions by constructing a shared timing of behavior (Gratier, 2003).

Besides, coordinated contingent maternal vocalizations with those of their infant facilitates learning of more advanced vocal patterns and induces more mature infant vocalizations (Elmlinger et al., 2019; Höhl, Fairhurst, & Schirmer, 2020; Goldstein et al., 2003). For instance, Goldstein et al. (2003) found that infants produced more speech-like syllabic sounds while the rate of nonspeech sounds decreased when the adult maintained a give-and-take pattern of vocal interaction. These findings can be interpreted taking into the concept of the social feedback loop (Warlaumont, Richards, Gilkerson, & Oller, 2014). The social feedback loop suggests that when the adult responds contingently to speech-related infant vocalizations, infant's vocalization characteristics are in turn contingent to previous adult responses. Warlaumont et al. (2014) conclude that this might be due to the fact that when a child produces a sound that contains speech or speech-related material, the child is more likely to receive an immediate, positive response from an adult than when the child's vocalization does not contain speech or speech-related material.

All in all, these findings on contingent and turn-taking behavior in mother-infant dyads highlight the importance of the mother for the coordination and mutual adjustment of behavior during vocalizations as they seem to act as the pulse giver during these dyadic interactions (Gratier & Magnier, 2012; Harrist & Waugh, 2002; Fairhurst & Dumas, 2019).

Early maternal vocalizations

The essential role of maternal interactions in infant vocal development has been stressed continuously throughout developmental research (Albert et al., 2017; Goldstein et al., 2003). Mothers often drive the conversational flow in dyadic interactions with their infants (Jaffe et al., 2001). They talk to their infants significantly longer and more frequently than infants talk to their mothers (Messer & Vietze, 1984). Hart and Risley (1995) investigated linguistic progress among infants during interactions with their caregivers starting from 7 months of age for 2.5 years and found that higher rates of parental vocalizations predicted faster growth of their children's vocabulary. In accordance, Pelaez et al. (2018) found that apart from an extended vocabulary in later life, improved literacy skills can emerge through early communicative behaviors between infants and their parents.

However, not solely the number of maternal inputs, but also the way mothers attempt to engage with their infants is associated with healthy language development (Zimmerman et al., 2009). As described before, dynamic interactions such as turn-taking and contingent vocal

interactions require mothers to respond adequately to their infants' vocalizations and therefore strengthening the infant's perceived ability to willingly influence dyadic interactions (Bell, 2020). When mothers are not able to contingently respond to their infant, their behavior can negatively affect their infant. For example, studies with depressed mothers have indicated that infants whose mothers showed minimal responsiveness to their vocalizations tend to be less responsive to voices and show fewer negative reactions to their mother's non-contingent behavior (Field, Diego, & Hernandez-Reif, 2009; Nadel, Soussignan, Canet, Libert, & Gerardin, 2005; Lavelli & Fogel, 2013). It can therefore be concluded that maternal responsiveness can encourage infants' attempts at communication and thereby contributes to the shaping of infants' early vocal development (Gros-Louis, West, & King, 2014).

Although contingent maternal vocalizations are important for infant vocal learning, it seems that there might be a certain level of contingency that is ideal for infants (Kidd, Piantadosi, & Aslin, 2012; Beebe et al., 2010). Research has suggested an "optimum midrange model" in which maternal over- and understimulation can be detrimental for infant development (Beebe et al., 2010). A study by Belsky, Rovine and Taylor (1984) indicated that 1-year-old infants with more responsive and sensitive mothers were more likely involved in intermediate levels of interaction which were neither over- nor understimulating (Isabella, Belsky, & von Eye, 1989). Further, Feldman (2007) found that clinically anxious mothers engaged in overstimulating social behavior such as vocalizing to their infants especially in situations in which their infants signaled a need for rest. Their high frequency vocalizations were therefore non-contingent on infant vocalizations and because of this, presumably highly intrusive. Jaffe and colleagues (2001) have therefore suggested that a midrange level of stimulation leaves more room for uncertainty, initiative, and flexibility within the experience of correspondence and contingence, leaving a room for infants to explore and improve their verbal activities. For this to happen, mothers need to sensitively respond to their infants' vocalizations and distress signals in order to establish a non-intrusive setting (see, e.g., Belsky et al., 1984).

To summarize, it is necessary for mothers to finely tune their vocalizations to their infants' needs and behavior. This has also been shown empirically as a growing body of evidence has demonstrated that mothers provide verbal feedback to infant vocalizations that differ in acoustic features from vocalizations directed at adults (Papaeliou, Minadakis, & Cavouras, 2002; Yoo, Bowman, & Oller, 2018; Oller, 2000). This specific modification of fine-tuned maternal vocalizations when talking to their infants is called infant-directed speech (IDS).

Infant-directed speech. Research has demonstrated that adults adapt and modify their speech based on their interaction partner (Golinkoff, Can, Soderstrom, & Hirsh-Pasek, 2015; Lam-Cassettari & Kohlhoff, 2020). More specifically, it has been shown that adult-adult vocalizations differ from adult-infant vocalizations. IDS differs from adult-directed speech (ADS) in terms of prosodic, phonological as well as lexical features and seems to be crucial for vocal development (Fernald et al., 1989). Specifically, in comparison to typical ADS, rhythmic and melodic patterns of IDS are more enriched while it is linguistically more simplified. Further acoustic features of IDS are higher overall pitch and more exaggerated pitch contours, shorter duration, and slower tempo (see, e.g., Fernald & Simon, 1984; Fernald et al., 1989; Golinkoff et al., 2015; Trainor, Austin, & Desjardins, 2000) have been found across languages and cultures (Werker, Pegg, & McLeod, 1994; Fernald et al., 1989). Based on these modifications, IDS matches the capacities of infants at different ages quite precisely (Gratier & Magnier, 2012).

There are a number of functions that have been attributed to IDS. First of all, IDS seems to provide an important foundation for infant attention (Golinkoff et al., 2015; Lam-Cassettari & Kohlhoff, 2020). Throughout their first year of life, infants pay more attention to IDS than to ADS (Cooper & Aslin, 1994). Due to the nature and timing of IDS that have been already described above, 1-month-old infants are already able to discriminate IDS from ADS and seem to prefer to listen to IDS over ADS (Soderstrom, 2007; Cooper & Aslin, 1994; Lam-Cassettari & Kohlhoff, 2020). Hence, IDS can be used to obtain and maintain infants' attention which can facilitate mother-infant social interactions.

By eliciting infants' attention, IDS aids language learning in infants, especially during their first year of life (Lam-Cassettari & Kohlhoff, 2020; Leong, Kalashnnikova, Burnham, & Goswami, 2017). For instance, a recent study by Ramírez, Lytle and Kuhl (2020) indicated that the use of IDS can improve infants' social language skills including turn-taking behavior due to the contingent and sensitive vocalizations by the mother. Further, due to its exaggerated intonational characteristics, IDS can facilitate language comprehension (Fernald & Simon, 1984; Cristia, 2011). This can be explained by the fact that its acoustic features help with the discrimination of different sounds (Cristia, 2011) and provide information about the organization of speech such as structures of patterns of the language (Golinkoff et al., 2015). Thiessen, Hill and Saffran (2005) demonstrated this by showing that IDS facilitates word segmentation as infants were able to distinguish words from a set of nonsense sentences only after being exposed to IDS but not after hearing ADS. The importance of IDS for infant vocal

development has also been shown in studies with depressed mothers. Lam-Cassettari and Kohlhoff (2020) examined the effect of postnatal depression on different aspects of the use of IDS and infants' later language outcomes. Preliminary results indicated that mothers with low mood used less IDS with infants aged 4-7 months. In turn, other studies showed that infants who were exposed less to IDS also engaged less in social interactions compared to those whose caregivers who talked to their infants with exaggerated intonation (Ramírez-Esparza, García-Sierre, & Kuhl, 2017). In this regard, Kaplan, Bachorowski, Smoski and Hudenko (2002) suggested that infants of mothers who used IDS were more likely to engage in associative learning crucial for language development compared to infants of depressed mothers who did not reflect positive emotions during speech (Golinkoff et al., 2015).

Taken together, these findings highlight the importance of IDS for social vocal interactions between mother and infant and therefore the importance of maternal responsiveness in adult-infant interactions (Golinkoff et al., 2015).

The social brain and IDS

A growing body of research examining maternal vocalizations have provided evidence that IDS not only plays an important role on a behavioral, but also on a neural level for infant vocal development. Literature has shown that coordinated social interactions between a mother and her infant are first encoded in the infant's brain during the early sensitive periods and provide critical input for the maturation of the social brain (Levy, Goldstein, & Feldman, 2017; Feldman, 2007). The social brain is comprised of a network of specific brain areas that are involved in social cognition, the processing of social information and coordination of actions that arise between two or more individuals during a social interaction such as vocalizations (Grossmann, 2015; Brothers, 1990; Sebanz, Bekkering, & Knoblich, 2006; Konvalinka & Roepstorff, 2012). In this regard, it has been suggested that the key brain areas of the social brain that seem to support social interactions including communication might be located in the frontal brain areas such as the prefrontal cortex (PFC) and medial prefrontal cortex (mPFC) (Babiloni & Alstolfi, 2012; Kinreich, Djalovski, Kraus, Louzoun, & Feldman, 2017; Piazza, Hasenfratz, & Lew-Williams, 2018; Frith, 2007).

A number of neurological and brain imaging studies have indeed linked stronger activation in these brain regions of infants to maternal vocalizations. Naoi et al. (2012) examined neural substrates underlying IDS functions using near-infrared spectroscopy (NIRS) with infants aged 4-13 months. Here, they recorded the activation of cerebral hemodynamic responses to IDS compared to ADS. Findings showed that IDS resulted in

more brain activation than ADS, specifically in the PFC. In accordance, Saito et al. (2007) who also used NIRS to examine auditory perception of maternal vocalizations by neonates reported that brain activation in mPFC was significantly increased by IDS compared to ADS. The authors therefore suggest that this effect in mPFC activation in neonates might have been elicited by the characteristic acoustic features of IDS that characterize positive affect. They also concluded that the exaggerated intonation of IDS helps to yield information about the speaker's emotional intention. In accordance to behavioral studies, these studies stress that infants seem to prefer IDS over ADS and that this preference is driven by the prosodic and phonological qualities of IDS (Kalashnikova, Peter, Liberto, Lalor, & Burnham, 2018).

Despite these findings, mechanisms that explain why infant brain activation is more enhanced when they hear speech with certain acoustic features of their preference are mostly still unknown. Recent research with adults has proposed that when listening to another person talking, one's brain might entrain to the rhythm of the speech and therefore show stronger activation (Pérez, Carreiras, & Duñabeitia, 2017; Hasson, Ghazanfar, Galantucci, Garrod, & Keysers, 2012). This phenomenon has been termed neural entrainment and will be further depicted and discussed in the following chapter.

Neural entrainment: speech as an inherently rhythmic stimulus

Speech is defined as an inherently rhythmic stimulus which oftentimes occurs within dyadic social exchanges between listener and speaker (Hasson et al., 2012). It has been proposed that oscillatory brain activity can entrain to speech (Ding, Melloni, Zhang, Tian, & Poeppel, 2016). During successful communication, the rhythmicity of speech patterns often matches the brain rhythms at specific frequencies that are commonly involved in sound production and auditory sampling (Ghitza & Greenberg, 2009; Lakatos, Gross, & Thut, 2019; Giraud & Poeppel, 2012). In other words, neural oscillations can adapt and thereby even synchronize to the rhythm of speech (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008). Chait, Greenberg, Arai, Simon and Poeppel (2015) describe the process of human speech perception as "multi-time resolution processing" where auditory information is processed on multiple time scales. According to the authors, neural oscillations concurrently entrain to speech amplitude modulations at corresponding frequencies in the signal. This has been proposed to support speech intelligibility as information carried in the different frequency bands is integrated and therefore helps to parse the signal into linguistically relevant units (Leong et al., 2017; Chait et al., 2015; Giraud & Poeppel, 2012). This mechanism, through which brain oscillations become coupled by adapting to the rhythm of a regular stimulation, is

called neural entrainment (Bauer, Debener, & Nobre, 2020). Neural entrainment therefore describes the synchronization of neural oscillations that enables the coordination of rhythmic activity between individuals (Bauer et al., 2020). In regard to speech, neural entrainment emerges due to environmental sounds produced by the motor system of a speaker that entrain the sensory oscillatory system of the listener (Hasson et al., 2012; Lakatos et al., 2019).

Despite these findings, most studies investigating neural mechanisms of speech have only been implemented with adults. In adults, it has been shown that such entrainment of neural oscillations to rhythmic stimulation can be of great importance for successful communication as it seems to influence auditory perception as well as speech comprehension (Bauer et al., 2020). According to Dikker, Silbert, Hasson, and Zevin (2014), this matching of motor production and sensory perception in speaker-listener dyads seems to facilitate the transfer of shared information. As the rhythmic sensing of speech sounds by a receiver aligns to rhythmic patterns of auditory inputs, it enables individuals to take the predictability of upcoming stimuli into account when anticipating and producing speech acts (Dikker et al., 2014; Bauer et al., 2020). For instance, in a speaker-listener task, Stephens et al. (2010) suggested that listeners whose brain activity patterns were more similar to those of the storyteller showed higher story comprehension rates which shows that these listeners were more enabled to predict the speaker's intentions due to more extensive neural speaker-listener coupling. Another study by Dai, McQueen, Terporten, Hagoort, and Kösem (2018) has demonstrated the importance of neural oscillations for speech processing by showing that neural entrainment can also facilitate comprehension of speech in noisy environments. Thus, optimal communication across two individuals might be facilitated by the enhanced processing of predicted future events and may have a compensating effect for noisy or ambiguous input (Bauer et al., 2020; Hasson et al., 2012). In turn, increases of predictability of communicative acts also results in the increase of brain activation within the dyad when the brains of speaker and listener are temporally coupled through oscillatory signals (Hasson et al., 2012; Dikker et al., 2014). All in all, these studies provide evidence that neural entrainment can facilitate speech processing and communication in adults.

Until date, there is only a small number of studies that explored mother-infant vocal interactions on a neural level as most studies were conducted with adult participants. However, results of recent investigations involving infants have revealed that neural entrainment to speech already plays an important role for infant speech processing, especially because there are major differences in entrainment of oscillatory activity to IDS as opposed to ADS. For instance, Kalashnikova et al. (2018) measured cortical tracking using

electroencephalography (EEG) of speech in 7-month-old infants while they listened to IDS and ADS recordings. Results of this study showed stronger cortical tracking of speech in the low frequencies when infants followed the dynamic patterns of IDS compared to when they listened to ADS. The authors concluded that IDS seems to facilitate cortical tracking in infants and therefore augments infants' early speech processing. Another infant study by Leong et al. (2017) found supporting evidence for the impact of structural acoustic differences of IDS and ADS on early language learning as their results implicated that rhythmic synchronization was stronger in IDS compared to ADS. In summary, studies' results imply that the exaggerated intonation of IDS might facilitate speech processing and language acquisition of the infant by helping the infant brain to effectively entrain to the speech rhythm (Leong et al., 2017), thus highlighting the importance of maternal vocalizations for infant vocal development.

Frequency bands in infants and adults

The EEG-signal can be functionally separated into typical frequency ranges including delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (10-30 Hz), and gamma band (30-100 Hz) (Saby & Marshall, 2020; Buzsaki, 2006). Ding and Simon (2012) have demonstrated that because the dominant rhythm of natural sensory inputs such as speech is usually below 10 Hz, synchronized neural activity falls into these ranges of neural oscillations. Therefore, neural entrainment in the brain and the external speech stimulus seems to occur in the lower frequencies (Dumas, Nadel, Soussignan, Martinerie, & Garnero, 2010).

Many studies have focused on theta frequency band as it has been shown that this frequency may be a sensitive measure to reflect brain-to-brain coordination between individuals during speaker-listener tasks, implicating that neural entrainment of speech occurs in these frequencies (Luo & Poeppel, 2007; Ding & Simon, 2012; Pérez et al., 2017). In fact, theta activity in adults is often associated with neural speech entrainment that seems to most strongly occur at the rate of 3-7 Hz (Leong et al., 2019). According to Hasson et al. (2012), this might reflect the matching of the speech stimulus rhythm that ranges between 3-8 Hz to the structure of 4-7 Hz neural theta activity. Hence, as the speech signal falls into the theta range, it is suggested that the speech signal could be coupled to ongoing oscillations in the theta band (Leong et al., 2019; Giraud & Poeppel, 2012). However, this has mainly been observed in interactions between adults and thus remains unclear whether this can also be applied to neural entrainment to speech in infants.

Importantly, it needs to be considered that EEG rhythms of infants differ from those of adults. This is reflected in the EEG signal which is slower during infancy compared to early childhood and adulthood (Orekhova, Stroganova, Posikera, & Elam, 2006; Markova, Nguyen, & Hoehl, 2019). Although frequency range for infant theta band has not been ultimately determined, it has been primarily defined between 3-6 Hz across studies as theta frequency range of infants does not seem to change between the age of 4 and 12 months whereas adults' theta frequency range from 4-7 Hz (Saby & Marshall, 2020; Stroganova & Orekhova, 2007; Wass, Whitehorn, Haresign, Phillips, & Leong, 2020). Infant theta activity has not only been shown to occur during naturalistic settings, but also to be more enhanced during social as compared to non-social settings (Jones, Venema, Lowy, Earl, & Webb, 2015). For example, Jones and colleagues (2020) have highlighted the importance of task-dependent modulation of frontal theta power for concurrent and later cognitive development. In their study, the authors found individual differences of percentual changes in frontal theta when watching semi-naturalistic videos at the age of 12 months to be associated with verbal and nonverbal cognitive skills at ages 2, 3 and 7. In addition, they noted that 82% of the variance in verbal skills of 3-years-old children with autism was predicted by theta power. Further, Orekhova et al. (2006) compared infant theta power during IDS and toy play to a baseline condition of visual attention. In contrast to the baseline, they observed greater infant theta responses in the social conditions where mothers interacted with their infants using IDS. In accordance, Zhang et al. (2011) also reported an increase in infant theta oscillatory activity in response to IDS. Although these studies indicate that infant theta band modulation is associated with infant learning as well as IDS, evidence on whether infant theta band is in fact modulated by maternal vocalizations or, in other words, if infants' brain oscillations entrain to particular speech rhythms in theta band is still sparse.

Research question and hypothesis

Research has shown that mothers are infants' primary, most frequent and most consistent social partners (Bigelow & Power, 2014; Bornstein, 2013; Bell, 2020). Infants acquire speech skills by engaging in alternating communicative interactions with their mothers (Karousou & López-Ornat, 2013). Especially contingent and fine-tuned maternal vocalizations seem to be crucial for establishing dynamic and coordinated social interactions with their mother, and therefore for early infant vocal development (Gratier & Magnier, 2019; Harrist & Waugh, 2000; Fairhurst & Dumas 2019).

Language learning of infants emerges during the first years of life through ongoing communicative interactions with their caregiver and other speakers (Vygotsky, 1978). In this regard, Liu, Kuhl and Tsao (2003) explored language learning of English infants and showed that infants were sensitive to Chinese phonemes during direct interactions with a Chinese speaker, but not when they were presented the same information on a screen. These results particularly stressed the importance of live interactions for language acquisition.

As stated earlier, compared to ADS, maternal vocalizations directed to infants might have specific features that induce greater entrainment of infants' brain activity to their mothers' speech in specific frequency bands. Together with this fact, it is important for scientific research to further investigate maternal vocalizations and infant neural oscillatory activity in order to gain new insights into the underlying mechanisms involved in early speech processing and therefore infant vocal development. In fact, neural entrainment has been proposed to support speech processing and comprehension in theta band frequency (Luo & Poeppel, 2007; Ding & Simon, 2012; Pérez et al., 2017). In addition, in a speaker-listener coupling study with adults, fronto-parietal regions of both participants were enhanced during verbal communication, indicating that when interacting with another person, these brain regions might be involved in facilitating the dynamic flow of these actions. (Stephens, Silbert, & Hasson, 2010).

Despite the importance of early language learning, most studies investigating neural entrainment have only been implemented with adults. Of the few studies that have focused on mother-infant dyads, most have only been implemented in laboratory settings. Findings indicated that infants might prefer specific acoustic features of speech. In fact, it has been shown that infants prefer IDS over ADS and that theta band might in fact not only play a role in adult, but also infant speech processing (Leong et al., 2017; Orekhova et al., 2006; Kalashnikova et al., 2018). In fact, infants showed higher brain activation when listening to IDS compared to ADS (Leong et al., 2017). However, evidence is still ambiguous and further research is needed to explore the neural underpinnings of speech perception and comprehension in infants during dynamic mother-infant interactions, especially in regard to the involvement of specific frequency bands. Studying the effects of maternal vocalizations on infant brain activity will allow us to investigate the importance of specific acoustic features on vocal learning. Further, insights on mother-infants can be drawn by understanding the mechanisms of how they naturally work together and thereby facilitate speech processing and learning (Piazza et al., 2018). Due to the fact that studies on vocal interactions between mothers and their infants on a neural level are still limited, instead of solely focusing on IDS,

we will first look for a general effect of the acoustic features of maternal vocalizations on infant brain activity. This is a promising approach given the fact that IDS has been proposed as being a central component of mother vocalizations. Taken together, the aim of this current study is to investigate whether maternal vocalizations modulate infant theta band activity during naturalistic mother-infant interactions. In order to answer this question, the following hypothesis will be examined:

H1: High duration of maternal vocalizations predict increased brain activation in infant theta band.

In adults, neural entrainment to speech in theta frequency band has been associated with the facilitation of communication (Ding et al., 2016). Further, studies showed enhanced brain activation during adult-adult vocal interactions (Stephens et al., 2010). Considering that infant studies have shown that IDS can facilitate cortical tracking in infants and increased theta oscillatory activity of infants in response to IDS (Kalashnikova et al., 2018; Zhang et al., 2011), we expect higher activation in infant theta frequency band in dyads where mothers spent more time on interacting through communicative acts with their infants compared to those with lower duration of maternal vocalizations.

For exploratory analyses, we plan to examine whether mother vocalization duration might modulate infant brain activity in a different frequency band. As the natural rhythm of the speech stimulus ranges between 3-8 Hz, it could be possible that infant brain activity might entrain to speech in even lower rhythms than theta frequency because maternal vocalizations are rhythmically slower than normal speech. This has already been proposed by Leong et al. (2019) who also argued that the modulation spectrum of IDS has its strongest amplitude modulation and rhythmic regularity at delta rate while the peak modulation rate for ADS is found at theta rate. However, this has not been empirically explored. Thus, we will specifically test whether enhanced maternal vocalization duration might predict increased infant delta power.

Methods

Participants

Out of a total sample of 69 mother-infant dyads that participated in the study, 50 dyads were excluded due to missing audio files or later removed during EEG-data preprocessing.

Further, 7 dyads had to be removed as they were used for behavioral coding training. Thus, the resulting sample used for the analyses consists of 12 dyads of mothers (M = 32.42 years, SD = 2.59 years) and infants (M = 8.30 months, SD = .06 months) at 8 months of age as studies have shown that mother-infant vocal interactions evolve in the second half of their first year of life (see, e.g., Goldstein, King, & West, 2003). All experiments took place in the Cognitive Neuroscience department of the Max-Planck Institute in Leipzig. Mothers were given informed consent on behalf of their children prior to the experiment and received monetary compensation for their participation.

Design and Procedure

The current study is part of a larger project called "Synchronization in mother-infant contingency" (coSMIC) which investigated whether inter-brain connectivity in mother-infant dyads is enhanced through different social cues during naturalistic interactions using EEG-hyperscanning. The coSMIC project is comprised of three conditions that focused on different levels of contingency in real-life exchanges: free-play condition, low contingency condition and high contingency condition. In this current study, we particularly investigated how mother's vocalizations might influence their infant's brain activity during free play condition. In contrast to the other two experimental conditions where mothers were instructed to respond to their infants either irrespective of their child's behavior (low contingency condition) or as fast as possible (high contingency condition) every time their infant made a sound or action, the degree of contingency was not manipulated during free play. Thus, free play condition is assumed to most likely reflect naturalistic interactions between a mother and her child.
In this condition, mothers were instructed to interact with their 8-month-old infants like they would do at home while their brain activity was recorded using dual EEG-hyperscanning. Further, they were told to only include interactions that they would do frequently, rather than just on occasion, in order to recreate a daily life home situation. In addition, as a precaution for better EEG signal quality, they were asked to possibly minimize big and sudden movements. The free play condition lasted 160 s and was preceded by a 45 s resting state measurement where the participants jointly observed blown bubbles by the experimenter while the mother was instructed not to respond to the infant and remain still.

Video recordings

In a laboratory room, mother and infant were seated on two chairs facing each other. Mother-infant dyads were audio- and videotaped during the whole free play condition using

Mangold VideoSyncProIP (Mangold, 2010). This program allows syncing of audio and video channels and provides accurate time codes to the respective video frames. A total of four video cameras were used to capture the interactions between mothers and their infants. All cameras were equipped with a microphone to obtain high-quality audio recordings. Camera 1 and 2 were stationary cameras, one positioned to capture the frontal view – head and torso – of the mother and the other one to capture the infant's face and body completely right from the front. Cameras 3 and 4 were portable cameras that were located such that they could capture facial expressions as well as movements of both participants.

EEG-hyperscanning setup and data acquisition

In addition to videotaping the social interactions between the mother and her infant, their brain activity was also recorded using a dual EEG-hyperscanning setup. EEG measurements were conducted with two actiCAP 32-channels electrode sets placed with an actiCAP snap cap (EASYCAP GmbH, Germany) on the head of each participant. All electrodes were surrounded by silicone rings that could be prefilled and held with a conductive gel. The electrodes were placed in accordance to the international 10-20 system of electrode placement which included Fz, F3, F7, FT7, FC3, FC1, Cz, C3, T7, CP3, Pz, P3, P7, PO9, O1, O2, PO10, P8, P4, CP4, TP10, T8, C4, FT8, FC4, FC2, F4, F8 as well as TP9 (reference electrode) and FPz (ground electrode). Two electrooculography (EOG) electrodes, F9 and F10, were placed next to the left and right eye to monitor horizontal eye movements as well as two eye electrodes above and below the left eye to monitor vertical eye movements. Due to infants' high risk of non-compliance and signal contamination (Noreika et al., 2019), the eye electrode below the eye for monitoring of vertical eye movements was solely placed on the mother's face. Both BrainProducts DC amplifiers (Brain Products GmbH, Germany) were coupled to one computer and received triggers during the whole free play condition to record the brain activity of the dyad simultaneously via BrainVision Recorder (Brain Products GmbH, Germany). The collected data was sampled at 500 Hz.

EEG data preprocessing

EEG data was preprocessed and analyzed using BrainVision Analyzer (Brain Products GmbH, Germany) as well as a custom pipeline with the toolbox Fieldtrip in MATLAB (Oostenveld, Fries, Maris, & Schoffelen, 2011; Mathworks Inc., Version R2019a; xxx). As the interest of this study lies in the frontal and central brain areas, 16 electrodes, most of which are located in the periphery, were omitted from further analyses after visual inspection

of these channels showed a high number of continuous artifacts in the data. In accordance, a number of studies have indicated electrodes located in this area are more likely to be very noisy because of for example speech myogenic artifacts (Santamaria et al., 2019; Porcaro et al., 2015). Thus, we selected the following electrodes for EEG data preprocessing: Fz, F3, F9, FC3, FC1, Cz, C3, CP3, CP4, C4, FC4, FC2, F4 and F10.

Raw EEG data was visually inspected to detect and repair noisy channels by interpolating the data with the weighted neighbor approach and bass-pass filtered in the range of 1-48 Hz to reduce the amount of muscular artifacts caused by movements of mother and infant during the experiment. For the detection of eye-movement artifacts, an ocular correction was applied with Spatial Independent Component Analysis (ICA). In this step, correlations between horizonal and vertical eye electrodes with the signal were calculated followed by Common Average Reference Method to correct for the influence of blinks and horizontal eye movements. Components that exceeded the threshold of 0.8 were removed. Next, data preprocessing continued with automatic artifact detection which included all channels and occurred with standard deviation thresholds of 50 μV for both mother and infant within 200 μs sliding windows.

EEG Power analyses. To calculate the power spectrum, detected artifacts from previous preprocessing steps were rejected. Preprocessed data of free play condition was then segmented in epochs of one second with 75 percent overlap starting from the onset of the conditiomn. Power spectrum of all electrode channels in each frequency between 1-50 Hz was then calculated using Welch's method (Welch, 1967). In order to derive mean power values (μV^2) for theta frequency bands within free play from the output, we applied a script for EEG power analyses in MATLAB (Mathworks Inc., Version R2019a). Channels of interest and respective frequencies for infant theta (3-6 Hz) and delta (1-3 Hz) (Saby & Marshall, 2020; Stroganova & Orekhova, 2007; Wass et al., 2020; Leong et al., 2019) were determined to get a power value for each of the selected channels and frequencies. Next, we averaged across channels to get power values for these frequencies. As a last step, we averaged across single frequencies within theta frequency bands for both mother and infant which resulted in average theta power values for each mother and each infant within free play and rest condition.

Behavioral analyses

Video coding of vocalizations during free play condition was carried out in INTERACT Software (Mangold, 2010). All videos of mother-infant interactions were micro-

coded frame by frame (25 fps). Before starting coding, videos of each dyads were checked in terms of whether they were correctly synchronized. In case video recordings were dyssynchronous to the time codes, they were adjusted accordingly. Further, audios of the videos were checked before coding as the recordings had to be of optimal quality for analyses.

Acoustic segmentation

First, an acoustic segmentation was carried out in order to determine the on- and offsets of mother and infant vocalizations. *Maternal vocalization* was coded whenever the mother produced a vocal sound that was either continuous or without pauses longer than 1s. *Infant vocalization* was coded whenever the infant produced a vocal sound that was either continuous or without pauses longer than 1s (Markova & Legerstee, 2008). *No vocalization* was coded for periods that lasted longer than 1s when no vocal sound was produced by neither mother nor infant.

An agreement of 80% between two coders across all behaviors had to be reached before categorizing vocalizations and coding independently (McHugh, 2012). To assess the inter-rater reliability, two coders coded 20% of all videos of the dyads used for this study which were chosen randomly. For these videos, Intraclass Correlation (ICC; Fleiss & Cohen, 1973) was calculated. Here, the mean kappa agreement between the two coders for *maternal vocalization, infant vocalization* and *no vocalization* was $\kappa = 0.817$.

Categorization of vocalizations

In the latter step, vocalizations were already classified into broad categories of *mother* and *infant vocalization.* Next, *mother vocalization* was categorized into *singing* (melodic vocalizations) and *speech* (IDS, verbalizations and rhymes). *Infant vocalization* was categorized into *positive* (rather melodic vocal sounds or babbling with varied pitch contours which are emitted with positive or neutral facial expression) and *negative vocalization* (vocal nasal sounds with rather uniform pitch produced somewhat forced or with effort such as whimpers, fusses, cry sounds and wails).

Inter-rater agreement between two coders for randomly chosen videos that comprised 20% of all videos for *mother vocalization* was $\kappa = 0.941$. For *infant vocalization*, a mean kappa agreement of $\kappa = 0.998$ was reached.

Statistical analysis

Statistical analyses were conducted using IBM SPSS® 24 (xxx) with. All statistical tests were two-tailed with an alpha level set to p = 0.05 (Benjamin & Hochberg, 1995). Thus, in the context of these analyses, all p-values below .05 were determined as significant. We also reported effect sizes as defined by Cohen (1988) with r = 0.1 considered as a low, r = 0.3 as a medium, and r = 0.5 as a large effect size.

First, we ran analyses for descriptive statistics of demographic as well as subject vocalization characteristics. Before testing our hypothesis, normal distribution of data was assessed with graphic analyses via boxplots and with the Wilk-Saphiro Test as this method was designed to test normality for small sample sizes (Shapiro & Wilk, 1965).

To assess our main hypothesis of whether duration of mother vocalization positively modulates neural activity of infant theta band, we conducted a simple linear regression with mother vocalization duration as the independent variable (IV) and infant theta power as the (DV). Model assumptions for simple linear regression model were tested before statistical analyses. Multicollinearity of variables was detected with VIF-Factor (Hair, Black, Babin, & Anderson, & Tatham, 2014). Further, Durbin-Watson statistics were performed to determine whether there were autocorrelations of residuals and homoscedasticity was visually detected using a scatter plot.

For exploratory analyses, to test whether increased mother vocalization duration predicts increased infant delta frequency band activity, we applied a simple linear regression with mother vocalization duration as the independent variable (IV) and infant delta power as the (DV).

Results

Descriptive statistics analyses

Sample of our current study

In total, 12 dyads and thus 24 participants were analyzed in this current study. At the time of the experiment, mothers were between 27 and 36 years old (M = 32.42 years, SD = 2.59 years) while the average age of infants was 8.30 months (SD = .06 months). The infant sample was comprised of 5 male (41,7%) and 7 female (58,3%) participants.

Variables

Visual inspection of the variables with graphic plots implicated that there were no extreme outliers in the data. All variables were approximately normally distributed, as assessed by the Shapiro-Wilk-Test, $p > .05$. Within free play condition across all dyads, the difference between the longest and shortest total mother vocalization duration was 96.68 s with the shortest total vocalization duration being 46.40 s and the longest total vocalization duration being 143.08 s (M = 111.85 s, SD = 29.46 s). The mean average power of infant theta was 7.11 (SD = 1.94) while delta band activity showed a mean of 16.58 (SD = 4.21).
In the following, descriptive statistics of all variables used for further as well as vocalization characteristics are summarized in Table 1.

Table 1

Descriptive statistics of key variables

Variable	*N*	Min	Max	*M*	*SD*
Mother vocalization duration	12	46.40	143.08	111.85	29.46
Infant theta band power (3-6 Hz)	12	3.81	9.69	7.11	1.94
Infant delta band power (1-3 Hz)	12	10.03	26.38	16.58	4.21
Frequency of maternal vocalizations	12	7	26	16.92	5.76

Main analysis

A test to see if the data met the assumption of collinearity indicated that multicollinearity was not a concern (Mother vocalization duration, Tolerance = 1.00, *VIF* = 1.00; Infant theta band power, Tolerance = 1.00, *VIF* = 1.00). Further, indicated by the Durbin-Watson value of 2.17, a histogram of distribution of residuals and normal P-P plot of standardized residuals, the data met the assumption of independent errors. To test our main hypothesis, we ran a simple linear regression to predict infant theta band power based on mother vocalization duration. No significant regression was found ($F(1,10) = 1.495$, $p = .249$), with an R^2 of .130, indicating that 13% of the total variance of the DV can be explained by the defined predictor. Also, Cohen's effect size value ($r = .36$) suggested a moderate effect (see Table 2).

Exploratory analysis

For exploratory analysis, a simple linear regression was calculated to predict infant delta band power based on the total duration of mother vocalization. Again, multicollinearity was not a concern (Mother vocalization duration, Tolerance = 1.00, *VIF* = 1.00; Infant delta band power, Tolerance = 1.00, *VIF* = 1.00). Although analyses revealed a Durbin-Watson value of .944, due to our small sample size it still can be assumed that no autocorrelations of residuals exist (Savin & White, 1977). In addition, a histogram of distribution of residuals and normal P-P plot of standardized residuals indicated that the data met the assumption of independent Results showed a significant regression equation ($F(1,10) = 6{,}548$, $p = 0.28$), with R^2 of .396. Further, findings of this exploratory analysis revealed a large effect size (r = .63; see Table 2).

Table 2

Simple linear regressions: Main Statistics

Independent variable	Dependent variable	*B*	*SE B*	ß	*t*	*p*
Mother duration vocalization	Infant theta power	-.02	.02	-.36	-1.22	.249
	Infant delta power	-.09	.04	-.63	-2.56	.028*

* $p < 0.05$

Discussion

Studies examining early mother-infant interactions during speech on a neural level can reveal information about the underlying mechanisms of speech processing and thus play an essential role in investigating underlying mechanisms of vocal development. For this reason, in this current study, we examined whether mother vocalizations might modulate infant brain activity. More specifically, as literature has implicated that maternal vocalizations might have an effect on infant theta band and that speech might entrain to brain oscillations, we focused on modulations of mother vocalization duration in infant theta frequency band. The current study was based on vocal interactions between mothers and their infants during free play condition, a more naturalistic setting than previous studies on mother-infant interactions have implemented their experiments in. Results did not show a significant effect of mother

vocalizations on infant theta power. However, exploratory analyses revealed a significant effect of maternal vocalizations on infant delta power.

Overall, our results suggest that mother vocalization duration does not have a significant effect on infant theta frequency band. Although studies have implicated that in adults, brain oscillations can entrain to speech in theta frequency range (Ding et al., 2016), that increased theta oscillations in infants have been associated with infant learning (Begus & Bonawitz, 2020), and that maternal vocalizations can facilitate infant cortical speech tracking (Kalashnikova et al., 2018), our study did not show significant enhancement of infant brain activity in theta band by maternal vocalization duration over the whole free play condition.

There are several reasons why this effect might not have been found in this current study. First of all, this study only looked at overall infant theta band power and did not discriminate between different brain regions because in comparison to for example fMRI, EEG recordings have a rather poor spatial and anatomical resolution. However, recent studies have found increased activity in frontal brain areas such as the mPFC during infant learning situations and concluded that increased frontal brain activity plays an important role for social interactions and that frontal brain activity might even be enhanced by IDS compared to ADS (Saito et al., 2007; Naoi et al., 2012). Therefore, as we included the activity of both frontal as well as central electrodes together as one variable in our analyses, statistical variance in regard to specific brain areas involved has therefore not been taken into account.

In addition, the testing of our hypothesis revealed a moderate effect size. Despite the fact that in a small sample size, random effects of predictors can be falsely overestimated due to missing statistical information (Field, 2013), this finding might still be relevant for our current study. As Field (2013) and Cohen (1988) have suggested, effect sizes are standardized measures of the magnitude of an observed effect. In comparison to *p*-values which are dependent on sample sizes and solely examine whether findings are likely to be due to chance, the effect size stresses the magnitude of differences found (Sullivan & Feinn, 2012). It follows that, in contrary to our assumption, the negative moderate effect size found in this study might implicate that mother vocalization duration increase predicts a decrease in infant theta band power during free play condition. Following the optimum midrange model which states that over- and understimulation by the caregiver can be detrimental for the infant (Beebe et al., 2010), this finding could indicate that infants were overstimulated during this condition. A bigger sample size is needed to investigate whether this effect could be of statistical significance. This moderate negative effect size must therefore be interpreted with caution.

In accordance, it is possible that no significant effect of mother vocalization duration on infant theta band was found because although literature has pointed out the importance of maternal vocalizations for infant vocal learning, the level of contingency plays an essential role and needs to be considered when investigating dyadic mother-infant vocal interactions (Beebe et al., 2010). Free play condition was assumed to reflect a more naturalistic setting compared to high and low contingency conditions. Regardless, Belsky (1980) has stated that compared to home settings, mother activity and responsiveness is higher in laboratory settings. This could be explained by the fact that mothers, knowing that they were observed and their actions have a meaningful impact on the experiment, might have been more motivated to interact with their infants and therefore creating a higher level of vocalization input. A study by Yoo and colleagues (2018) also showed that in all-day recordings compared to research in structured settings, caregivers responded less often to infant vocalizations. As the experiment was still conducted in a laboratory, the fact that mothers did not interact with their infants contingently cannot be ruled out.

Another argument might also be that enhanced infant brain activity does not solely reflect the entrainment of neural oscillations to the mother's speech, but rather the coordinated interactions such as turn-taking and contingency between the infants and their mothers as they coordinate and mutually adjust their behavior during vocalizations and thereby create observable patterned ongoing dyadic interactions (Fairhurst & Dumas, 2019; Harrist & Waugh, 2002). In this context, turn-taking and contingent behavior have been proposed to be an example for interpersonal synchrony (Leclère et al., 2014). Interpersonal synchrony is described as the simultaneous and coordinated adaptation of one individual to the rhythmic and biological responses of the interaction partner across the time course of social interactions, depicting the degree of congruence between behavioral cycles of engagement and disengagement (Delaherche et al., 2012; Leclère et al., 2014; Bell, 2020; Fairhurst & Dumas, 2019). In contrast to common rapport, synchronous interaction may not be interpreted as a perfect symmetric timing exchange as breaks as well as variations seem to be critical for the process of adaptation and stimulation of behavior (Leclère et al., 2014). Thus, Harrist & Waugh (2002) have proposed that interpersonal synchrony should be seen as a continuous variable and should therefore be thought of as dyadic interactions approaching synchrony or moving away from synchrony rather than synchrony as an "all-or-none condition". More specifically, interpersonal synchrony can be seen as a timed relationship that exists when things occur concurrently (e.g. joint action, mutual gaze, mirroring), sequentially (e.g. turn-taking, imitation, reciprocity), or just generally organized in an ongoing patterned format,

between two or more events that cohere into a single process (Leclère et al., 2014; Feldman, 2007). In the second half of the first year, interpersonal synchrony becomes a more mutual relationship between mother and her infant as change is observed in the infants' motivational organization for communication (Bell, 2020; Trevarthen, 1993; Papaeliou et al., 2002). During turn-taking, both infant and mother play an active role in initiating interactions and maintaining conversational turns (Dominguez, Devouche, Apter, & Gratier, 2016; Jaffe et al., 2001; Farran, Yoo, Lee, Bowman, & Oller, 2019). Further, with each member of this dyad being an active participant, they both participate in a dynamic mutual shaping of patterns and expression such as turn-taking (Lewis & Freedle, 1972; Gratier, 2003). Hence, the dyadic relationship between a mother and her infant should be thought of as a dynamical interaction system of mutual and reciprocal influence as this relationship seems to be bidirectional in nature (Sameroff, 2009). Interestingly, on a neural level, temporal dynamics of coordinated behavior between two individuals are reflected by specific patterns of brain activities called neural synchrony, or interneural-brain synchronization (INS) (Hasson et al., 2012; Babiloni & Astolfi, 2012; Fishburn et al., 2018). These patterns of brain-to-brain coupling emerge through continuous moment-to-moment coordination of two individuals' behaviors when their brains and bodies are immersed in an interaction and thereby become a single unit (Hasson et al., 2012; Konvalinka & Roepstorff, 2012). Importantly, a growing body of studies investigating social interactions on a neural level has proposed that interpersonal synchrony might be associated with INS (Konvalinka & Roepstorff, 2012; Novembre, Knoblich, Dunne, & Keller, 2017). For this reason, a more refined coding scheme is needed where turn-taking behavior as well as contingency will be also coded as this will allow us to get a further look into whether coordinated behavior rather than just the mother vocalization duration might have an effect on infant brain activity. Consequently, the variable mother vocalization duration also needs to be revised as in this study, we considered all types of maternal vocalizations as part of this variable even though Markova et al. (2019) have suggested that infant-directed singing induces greater neural entrainment in infants than speech.

Importantly, the reason for our studies' results could also be that infants' brain oscillations do entrain to speech, but not in theta band frequency. As Leong et al. (2019) have proposed delta frequency band to play the role of master oscillator due to the acoustic features of IDS to be at the delta rate, we also conducted an exploratory analysis where we explored whether mother vocalization duration predicts infant delta band power. Interestingly, our results revealed a significant negative effect of mother vocalization duration on infant delta frequency band. Crucially, similar to our main results that did not reveal a significant but still

a moderate negative effect size, these findings indicate that there might indeed be a negative relationship between mother vocalization duration and infant delta power. Above, we have already mentioned that it might be crucial to take into account whether free play condition truly reflected the contingency level as stated by the "optimum midrange model". Our not significant results of our main hypothesis and the negative influence of mother vocalization duration on infant delta power could therefore perhaps be explained by over- or under stimulation by the mother as well as unsuccessful turn-taking behavior between mother and infant.

Limitations

We are aware that our study has suffered serious drawbacks due to many sources of limitations. Given that the data of this study solely investigated free play, our experimental session was quite short. The short duration of free play condition might have not allowed us to assess the contingency and reciprocal interactions that could have had evolved within a longer interactive period. In addition, even though our free play condition reflected a more naturalistic setting, our experiment was still implemented within a laboratory setting. As mentioned earlier, generalization of laboratory results is limited, for instance because of mothers' higher engagement and language input when interacting with their infants in a non-natural environment (Kurchirko et al., 2019).

Since there were problems with audio tapes as well as noisy EEG data, it was inevitable to investigate a larger sample size. Results of our small sample cannot be generalized and hardly compared, implicating that future studies with a larger sample size are required to examine vocal interactions in mother-infant dyads. Concerning the gender of the adults recruited and tested in this study, fathers were not included. As studies with parent-infant dyads have shown that there are in fact gender differences in regard to the effects on neural brain activity within the dyad, a larger sample including father-daughter and father-son dyads besides mother-daughter and mother-son dyads are needed to investigate gender effects (Reindl, Gerloff, Scharke, & Konrad, 2018; Lewis & Freedle, 1972).

Further, a challenge that arises when conducting EEG studies with infants is especially the high rate of data attrition resulting from motion-related artifacts that contaminate the EEG signal (Bell & Cuevas, 2012; Noreika, Georgieva, Wass, & Leong, 2020). For EEG power measures and data analyses, a certain amount of concurrent artifact-free data is needed (Noreika et al., 2020). Since infants are not able to follow instructions given by the experimenter, the acquired data is oftentimes comprised of a huge number of contaminated

segments that cannot be used for further analyses (Noreika et al., 2020). Generally, EEG was originally developed for adults (Reindl et al., 2018; Noreika et al., 2020). Thus, adjusting this method to studies including infants is still an issue that is currently explored in the active field of neuroscientific research. The amount of artifact-free data could for example be increased through the collection of more data (Atzaba et al., 2016).

Another limitation of this study was that other social cues such as gaze have not been taken into account. As studies have suggested, infants' learning might not only be influenced by maternal vocalizations, but also by eye contact (Fogel, 1981; Singh, Morgan, & White, 2004). Bloom et al. (1987) have indicated that oftentimes, infants' eye contact can be the elicitor of their parent's vocalizations directed at them. Mother vocalization duration could have therefore been influenced by infants' gaze. Future studies therefore to keep in mind that mother-infant interactions are multidimensional with many variables involved that influence the dynamics within the dyad (Gros-Louis, Goldstein, & King, 2006).

Finally, a major limitation is that several factors such as turn-taking behavior or level of contingency were not included when coding mother-infant vocal interaction and were therefore not considered for further analyses. Above, links between turn-taking and contingent behavior and brain activity have already been discussed. Future data collection will be required to determine how exactly mother vocalizations affect infant brain activity.

Conclusion and future directions

First of all, it must be noted that our study was one of the few that investigated mother-infant vocalizations within a naturalistic setting on a neural level. In contrary to previous research, results of our current study indicated that an increase in mother vocalization duration does not significantly predict an increase in infant theta band. On the contrary, a non-significant moderate effect size was found that implicated a negative effect of mother vocalization duration on infant theta band activity. In line with this finding, exploratory analyses showed a significant negative effect of maternal vocalization duration on infant delta power band. Considering the latter limitations, findings need to be treated with utmost caution. However, this result indicates the need to further investigate whether there might be a perfect level of contingent vocalizations where infant brain activity is most enhanced, and thus facilitates speech processing.

Our work has led to conclude that further research is needed to investigate underlying mechanisms involved in speech processing and infant vocal learning. It seems as for infants, it is not maternal input alone that is crucial for vocal development but rather also the

experience of dynamic interactions with their mothers. In order to investigate these interactions, we therefore need to include infant vocalizations in future studies as well to gain a deeper understanding of mother-infant interactions. In addition, our findings point out the complexity of mother-infant vocal interactions and the need to include different factors such as contingent turn-taking behavior to explore how they might influence these interactions in future analyses.

We have previously described the possibility of successful coordination of vocalizations within mother-infant dyads being responsible for enhanced brain activity in infants. More interestingly, mother's and infant's brain activity might be concurrently enhanced when their actions are aligned, for example during turn-taking vocalizations. In order to directly observe these dynamic interactions across two brains, one needs to measure brain activity of individuals simultaneously (Babiloni & Astolfi, 2012). In our study, we used an EEG-hyperscanning setup. This non-invasive approach allows a shift from single-brain neuroscience to a "two-person neuroscience", and thereby the recording of real-time reciprocal social interactions between two or more individuals at the same time (Burgess, 2013; Jones et al., 2020; Liu & Pelowski, 2014). Due to its high temporal resolution, EEG-hyperscanning is often the method of choice for interaction studies that involve timing in interpersonal coordination as it is able to capture short time scales that operate at the level of natural face-to-face interactions (Konvalinka & Roepstorff, 2012). Because of its temporal precision, dynamic moment-to-moment changes during interaction itself can be detected with dual EEG (Saby & Marshall, 2020; Liu & Pelowski, 2014). This is particularly relevant when investigating communication for the reason that the timing of interpersonal coordination of speech acts can be examined in detail (Kuhlen, Allefeld, & Haynes, 2012; Kawasaki et al., 2013). As stated before, a growing body of adult studies using hyperscanning have linked interpersonal synchrony to INS, hinting at that INS might be a neural marker for social interaction (Dumas, Lachat, Martinerie, Nadel, & George, 2011; Konvalinka & Roepstorff, 2012; Fishburn et al., 2018; Cui, Bryant, & Reiss, 2012; Müller & Lindenberger, 2014).

Despite the evidence that synchrony is first experienced and encoded in the brain during early sensitive periods, most studies investigating INS have only been implemented with adults-adult dyads (Levy et al., 2017). Of the few studies that have focused on mother-infant and parent-child dyads, findings indicated that INS can facilitate behavioral coordination as well predict cooperative task performance (Leong et al., 2017; Reindl et al., 2018). In accordance, Vygotsky (1978) has shown that language learning emerges during the first years of life through ongoing communicative interactions with their caregiver and other

speakers. For this reason, Piazza and colleagues (2018) predicted that the ability of the infant brain to be dynamically coupled with adults' brains may serve as a necessary precursor for early learning.

Taken together these findings, studying dynamic interactions between infants and adults on a neural level will allow us to investigate how individuals relate across time and how interpersonal coordination is related to neural synchrony (Gates & Liu, 2016). Further, it will give us a deeper understanding of how mother-infant dyads naturally work together to facilitate shared communication as well as developmental differences in early processing and learning (Piazza et al., 2018).

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List of tables

List of Abbreviations

ADS	adult-directed speech
coSMIC	“Synchronization in mother-infant contingency”-project
DV	dependent variable
EEG	electroencephalography
ICC	Intraclass Correlation
IDS	infant-directed speech
IV	independent variable
mPFC	medial prefrontal cortex
PFC	prefrontal cortex

Appendix

Abstract

In everyday life, we use speech to actively express our feelings, engage with each other, and thereby impact our environment and social surroundings. Literature has demonstrated that speech learning already starts in early infancy where mothers, as their primary caregiver, play an essential role. By finely and sensitively tuning their vocalizations to their infants' needs and behavior, mothers provide a setting in which infants can explore and experience vocal interactions. In fact, it has been proposed that infants' brain oscillations in theta band might entrain to particular acoustic features of mother vocalizations. This mechanism called neural entrainment has been shown to facilitate speech processing in adults. However, this has sparsely been investigated with infants. Thus, this study aims to investigate whether enhanced duration of maternal vocalizations predicts increased infant theta power. 12 mother-infant dyads were observed and videotaped during free play condition. Mothers were instructed to interact with their 8-month-old infants like they would do at home while infants' brain activity was recorded using dual EEG-hyperscanning. A simple linear regression showed no significant effect of mother vocalization duration on infant theta power, but a moderate negative effect size. Exploratory analyses revealed a significant negative effect of mother vocalization duration on infant delta power. Findings of this study stressed the complexity of dyadic vocal interactions. Future studies need to not solely focus on single maternal vocalizations, but rather on the bidirectionality of mother-infant dyads and their dyadic interactions in order to gain deeper insights into the underlying mechanisms of vocal learning.

Keywords: maternal vocalizations, neural entrainment, infant brain activity, naturalistic social interactions, dual EEG, mother-infant dyads

Zusammenfassung

Sprache ist aus dem alltäglichen Leben nicht wegzudenken. Wir verwenden sie, um unsere Gefühle auszudrücken und miteinander in Kontakt zu treten, wodurch wir unsere soziale Umwelt gezielt beeinflussen können. Studien zeigen, dass der Spracherwerb bereits in der frühen Kindheit beginnt, wobei Müttern als primäre Bezugspersonen eine essenzielle Rolle zukommt. Mütter bieten den Kindern durch feinadjustierte Vokalisierungen eine Lernumgebung, die das Erfahren und Explorieren von sprachlichen Interaktionen ermöglicht. Weiterst zeigen Studien, dass mütterliche Kindersprache bei den Kindern neuronales Entrainment im Theta Frequenzband auslösen kann, und dass das neuronale Entrainment Sprachverarbeitungsprozesse bei Erwachsenen erleichtern kann. Es gibt zu diesem Zeitpunkt wenige Studien, die dieses Phänomen bei Kindern untersuchen. Daher wird in der vorliegenden Studie untersucht, ob mütterliche Vokalisierungen einen positiven Einfluss auf die Gehirnaktivität im Thetaband ihrer Kinder haben. 12 Mutter-Kind-Dyaden wurden in einem nicht-kontrollierten Setting beobachtet. Hierbei sollten Mütter mit ihren Kindern möglichst natürlich interagieren, während die Gehirnaktivität der Kinder mittels EEG-Hyperscanning aufgezeichnet wurde. Eine einfache lineare Regression konnte keinen signifikanten Effekt der mütterlichen Vokalisierungen auf die Thetaaktivität der Kinder zeigen. Es wurde jedoch eine negative moderate Effektstärke gefunden. Explorative Analysen ergaben einen signifikant negativen Effekt der mütterlichen Vokalisierungen auf die Deltaaktivität. Die Befunde dieser Studie heben die Komplexität von dyadischen sprachlichen Interaktionen hervor. Weitere Untersuchungen, die die Bidirektionalität von Mutter-Kind-Dyaden und Komplexität mütterlicher Vokalisierungen erheben, werden für ein umfassendes Verständnis benötigt.

Schlagwörter: mütterliche Vokalisierungen, neuronales Entrainment, Gehirnaktivität, natürliche soziale Interaktionen, duales EEG, Mutter-Kind-Dyaden