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„Alpha-Desynchronization and Theta-Synchronization During Naturalistic Mother-Infant Interaction"

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Content

Theoretical Background

Social Interaction and Neurodevelopment

Atzil and colleagues define a social species as a group of individuals, whose continuous regulation of fundamental physiological processes, and therefore their survival, relies on social community and interaction (Atzil et al., 2018). Human beings are a social species and the importance of social bonds for human survival is most evident in infancy and early childhood, a period marked by the infant's immediate dependency on its caregivers (Atzil & Barrett, 2017). In order to survive, an organism is required to continuously adapt to its dynamic environment. This process is called allostasis (Sterling, 2012). After birth the infant's allostatic processes rely almost entirely on its caregivers (Winberg, 2005). Therefore, sociality becomes a fundamental dimension of human life and a requirement for survival (Atzil et al., 2018). Atzil and colleagues argue that the development and refinement of social behavior might be primarily motivated by allostasis (Atzil et al., 2018).

The connection between social behavior and allostatic regulation corresponds with the current understanding of their underlying neural structures (Atzil et al., 2018). Neuroimaging studies of adult brains found overlaps between neural systems linked to social behavior and allostatic regulation (Atzil et al., 2018; Kleckner et al., 2017). These were located in neural structures associated with the default mode network and the salience network, two domain-general networks consistently involved in various mental processes, inter alia interoception and social functioning (Kleckner et al., 2017). High-spatial-resolution methods like functional magnetic resonance imaging (fMRI), enabling most of the findings in adults, are difficult to apply in infants, because they require the subject to stay still for a relatively long period of time. Therefore, most studies on children below 2 years old rely on methods that are more robust against movement, namely electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) (Redcay & Warnell, 2018). Those methodological restrictions prevent scientists to study neural correlates of social interaction (i.e. the social brain) with the same spatial precision as in adults, especially in subcortical regions (Redcay & Warnell, 2018). Nonetheless, evidence suggests that, when processing social stimuli, infants show activity in neural areas corresponding to the networks associated with social behavior in adults (Grossmann et al., 2008; Redcay & Warnell, 2018). However, these structures are not yet fully developed in newborn children. Instead, they form and mature while growing up (Gao et al., 2017).

Suboptimal or lacking social interaction with both primary caregivers and peers during this period was found to have long-lasting negative effects on neural development (Perry, 2002). Thus, scientists have argued that the episode of extreme dependency on the social environment during infancy could play a fundamental role in the development of important neural structures (Atzil et al., 2018; Atzil & Barrett, 2017; Fotopoulou & Tsakiris, 2017). Fotopoulou and Tsakiris hypothesize that the essential aspects of neural processing within the so called minimal self (i.e. interoception, exteroception and primary affective states) are shaped by early social input instead of being biologically predetermined (Fotopoulou & Tsakiris, 2017). This adds an interesting perspective to the fundamental debate of nature vs. nurture and emphasizes the importance of early social interaction for the development of the neural architecture observed in adults.

Developmental Role of Mutual Gaze

Gaze in Early Communication

As a result of the dependency on their caregivers to support allostatic regulation (Atzil & Barrett, 2017) and their initially limited possibilities to actively interfere with their environment through e.g. grasping or crawling, infants rely heavily on social communication during the first year of life (Feldman, 2016). Gaze, specifically mutual eye contact, is one of the first and essential forms of social communication (Redcay & Saxe, 2013). Infants show a bias towards face-like stimuli as early as the first hour of life (Johnson et al., 1991) and develop a sensitivity to mutual gaze within few days after birth (Farroni et al., 2002). In this early period, eye contact is believed to play a critical role in social and fundamental cognitive development. It serves as one of the primary cues to detect self-relevance, i.e. the infant's ability to perceive that an interaction partner's action and communicative intent is directed at the infant (Grossmann, 2015). While the infant's self-relevance in early social interactions does not require an explicit concept of the self, it is believed to be the implicit foundation for the subsequent development of more complex and explicit levels of self-awareness in adults (Grossmann, 2015; Rochat, 2003). Furthermore, the development of the self has been argued to be routed in early social interactions and the emergence of self-relevance (Reddy, 2003).

Mutual Gaze as an Ostensive Cue During Early Learning

According to the theory of natural pedagogy, self-relevance and the increased sensitivity to self-relevant information is an important premise for infantile learning processes (Csibra & Gergely, 2009; Grossmann, 2015). During social interaction ostensive cues, such as mutual gaze, can serve as a signal of intent to communicate (Csibra & Gergely, 2009). Infants can detect potentially important learning opportunities through these types of communicative signals (Csibra & Gergely, 2009). In a study by Urakawa and colleagues infants fixated the interaction partner's eye region longer in a direct gaze condition (Urakawa et al., 2015). Moreover, when addressed with direct eye gaze 6-month old infants were more likely to subsequently follow an experimenter's gaze towards an object (Senju & Csibra, 2008). Similarly, findings from a study with 9-month old infants suggest that infants are more sensitive to ostensive object-directed gaze when preceded by an episode of direct eye contact (Senju et al., 2008). Niedźwiecka and colleagues found that the duration spent in mutual gaze during parent-infant interaction at 5-months positively predicted infants' attention control at 11-months (Niedźwiecka et al., 2018). These findings hint towards an important role of mutual gaze in attention control development as well as in learning scenarios involving joint attention and ostensive demonstrations. Here, mutual gaze is understood to support the management and focusing of infants' limited attentional resources, shifting the infant's attention towards subsequent ostensive communication (Csibra & Gergely, 2009). The resulting improvement of cognitive performance is known as the "eye contact effect" (Niedźwiecka, 2020).

The underlying mechanisms linking social gaze and infant learning potentially have a substantial developmental impact. Infants' gaze following capacities and their ability to utilize interaction partners' communicative cues have been found to be developmental predictors of successful language acquisition (Brooks & Meltzoff, 2005; Kuhl, 2011) and the subsequent development of theory of mind (Brooks & Meltzoff, 2015). Furthermore, sustained attention and the development of attention control are considered to be precursors to several fundamental aspects of human cognition, such as self-regulatory functions, executive functioning, language development and problem solving (Johansson et al., 2015; Yu & Smith, 2016).

Recent years yielded a critical discussion on the functional role of ostensive cues. A group of researchers claims that infant gaze following could also be accounted for by attentional processes, instead of resulting from infants' sensitivity to ostensive communication (Gredebäck et al., 2018; Szufnarowska et al., 2014). This would challenge a cornerstone of natural pedagogy theory, as it is built around the concept that children are innately receptive to social cues in order to facilitate social learning (Csibra & Gergely, 2009). In response, based on a study on 9-month old infants, Okumura and colleagues argue that both attentional cues (e.g. non-communicative behavior or an acoustic marker) and ostensive cues affect infants' gaze following (Okumura et al., 2020). However, only ostensive cues were found to have an effect on referential learning (Okumura et al., 2020). Congruent findings were reported in a study specifically addressing mutual gaze as an ostensive cue (Okumura et al., 2016). In line with these findings, Wu and colleagues demonstrated that 8-month old infants learned about previously unknown attention cues and consequently cued objects, when the novel cues were initially paired with ostensive communication (Wu et al., 2014). In succeeding conditions infants were sensitive to the attention cues even when they were presented without preceding ostensive signals (Wu et al., 2014). This suggests that ostensive communication, such as mutual gaze, promotes multi-modal learning from novel attention cues (Wu et al., 2014). It can therefore be assumed that mutual gaze indeed has a distinct ostensive role in infant learning processes (Okumura et al., 2016; Okumura et al., 2020; Wu et al., 2014).

Neural Correlates of Mutual Gaze

The neuronal networks involved in social functioning and processing of social information are both functionally and anatomically connected to each other, and further domain-general networks (Barrett & Satpute, 2013; Redcay & Warnell, 2018). Across most of these functional networks, sensitivity to social information within the medial prefrontal cortex (mPFC) appears to be a common denominator and is thought to play a crucial role in various aspects of social cognition (Amodio & Frith, 2006). Increased activation of mPFC was observed in response to mutual gaze, and when subjects were addressed with their own name (Frith, 2007). These activation patterns are attributed to reading communicative intentions and several other mechanisms underlying theory of mind (Amodio & Frith, 2006; Frith, 2007).

MPFC-sensitivity to communicative cues, specifically social gaze, have also been observed in the developmental context. When 4-month old infants watched computer animated adult faces, Grossmann and colleagues observed increased activity in prefrontal and temporal regions in response to direct gaze, compared to averted gaze (Grossmann et al., 2008). While activations in the temporal lobe were attributed to right superior posterior temporal cortex, a region linked to the processing of biological motion (Grossman et al., 2000; Saxe, 2006), increased activity in prefrontal areas following direct eye contact were interpreted as mPFC-reactivity to social gaze (Grossmann et al., 2008). Similarly, Rigato et al. report larger event-related potentials (ERPs) over frontocentral electrodes linked to direct gaze, when infants of the same age observed pictures of faces with varying facial expressions (Rigato et al., 2010). When Urakawa and colleagues recorded 7-month olds' gaze direction and neural activity via fNIRS during the popular children's-play "peekaboo", infants fixated the interaction partner's eye region for a longer period of time, when the experimenter presented direct gaze, compared to averted gaze (Urakawa et al., 2015). Furthermore, the direct gaze condition resulted in an increased hemodynamic response in the infants' mPFC (Urakawa et al., 2015).

Natural pedagogy theory's assumption of infants' early sensitivity for mutual gaze is further supported by a series of experiments investigating infants' neural correlates of joint attention and learning during social interaction. Striano and colleagues found a larger negative component (Nc) in 9-month-old infant ERPs, when mutual gaze with an adult experimenter preceded the observation of a novel object (Striano et al., 2006). In a refined itineration of this live ERP paradigm, Parise et al. observed congruent Nc patterns in 5-month old infants (Parise et al., 2008). When the subjects had engaged in joint attention towards novel objects on a screen, initiated through mutual gaze with an experimenter, subsequent presentation of these objects induced a larger Nc amplitude compared to when the experimenter had merely fixated the infants' chest (Parise et al., 2008). An increased amplitude of the Nc in infant ERPs is considered to be a neural correlate of attentional processes, functioning as a supporting mechanism of visual attention control (Reynolds & Richards, 2005). Furthermore, the negative component is understood to be generated within the prefrontal cortex (PFC) (Reynolds & Richards, 2005). Taken together, these findings strengthen the assumption that joint attention initiated through direct eye-contact supports the management of infants' attentional resources during social interaction

(Parise et al., 2008; Striano et al., 2006). Furthermore, mPFC-sensitivity to direct gaze and facial communication cues is argued to be a prerequisite and basis for social interaction and learning (Grossmann et al., 2008). The mPFC is thought to be involved in the detection of self-relevant information and the representation of joint attention (Grossmann, 2013, 2015; Saxe, 2006). Similar functions have been attributed to social gaze (Csibra & Gergely, 2009; Grossmann, 2015; Senju & Csibra, 2008).

The mPFC is associated with a widespread set of cognitive functions (Grossmann, 2013) and is particularly involved in social cognition and interpersonal coordination processes during social interaction (Amodio & Frith, 2006; Schilbach et al., 2013). According to Grossmann and Johnson, the prefrontal cortex plays a crucial role in cortical and cognitive maturation processes during early development (Grossmann & Johnson, 2013). Within the developing social brain, the mPFC is thought to orchestrate activation patterns of increasingly specialized cortical regions, in response to novel social cognitive tasks (Grossmann & Johnson, 2013). This makes mPFC particularly important for the acquisition of new skills, as neural activity is believed to migrate to more posterior regions, when the appropriate activation patterns have been established (Grossmann & Johnson, 2013). Furthermore, Grossmann and Johnson theorize that top-down mPFC-feedback supports the functional specialization and localization of posterior cortical regions linked to social cognition (Grossmann & Johnson, 2013). Given the impact of social interaction on neurodevelopment (Atzil et al., 2018; Atzil & Barrett, 2017; Fotopoulou & Tsakiris, 2017) and the orchestrating role of prefrontal cortex in early learning and cortical refinement during infancy (Grossmann & Johnson, 2013), the early sensitivity of mPFC to mutual gaze could represent a fundamental developmental mechanism in the emergence of social cognition and learning, as well as in the formation of infants' first interpersonal relationships.

Second Person Neuroscience
Mutual gaze has long been recognized as an important mechanism in (early) social interaction, e.g. as a signal of communicative intent and social relatedness (Cary, 1978) or a supporting factor in cognitive growth (Kaye & Fogel, 1980). However, most neuroscientific approaches studied gaze behavior, and social interaction in general,

in controlled environments, where the subject takes the role of an observer, instead of engaging in realistic social interaction (Hasson et al., 2012; Hoehl & Markova, 2018; Schilbach et al., 2013). In recent years a growing number of scientists called for a methodological shift in social neuroscience (Hari et al., 2015; Hasson et al., 2012; Hoehl & Markova, 2018; Rice et al., 2016; Schilbach et al., 2013). This "Second Person Neuroscience"-account argues that engaging in real social interaction is qualitatively different from observing prerecorded social stimuli on many levels (Schilbach et al., 2013; Redcay & Warnell, 2018). The Interactive Brain Hypothesis (IBH) introduces the idea that dynamic social interaction and interactive experience acts as a catalyst for the emergence of social brain functions and therefore social cognition (De Jaegher et al., 2010; De Jaegher et al., 2016; Di Paolo & De Jaegher, 2012). In line with the second person neuroscience account, IBH argues that social interaction could activate neural processes distinct to interactive scenarios (De Jaegher et al., 2010).

Jones and colleagues observed that when 6 and 12 month-old infants watched live-action stimuli and prerecorded video-based stimuli, the naturalistic live experience more efficiently elicited responses in EEG theta activity, a frequency band thought to be particularly sensitive to social interaction (Jones et al., 2015). Furthermore, 9-month old infants produced a higher Nc in a live-interaction paradigm, compared to similar paradigms with prerecorded stimuli (Striano et al., 2006). Similarly, Hirsch and colleagues observed greater frontal and parietal activation during eye-to-eye gaze, compared to when subjects fixated the eyes of a photograph (Hirsch et al., 2017). In an interesting series of studies Rice and colleagues observed increased neural activity in social cognition and mentalizing areas, when subjects believed that an audio-feed was presented in real-time by a real person, compared to when they believed it was prerecorded (Rice et al., 2016; Rice & Redcay, 2016). The effect was found both in adults (Rice & Redcay, 2016) and in children between 7 and 13 years old (Rice et al., 2016), suggesting that the observed results are stable through developmental changes in the social brain. Similar paradigms revealed increased neuronal activation patterns in the reward network in response to live interaction compared to prerecorded stimuli (Pfeiffer et al., 2014; Redcay et al., 2010). Although perhaps being highly naturalistic, prerecorded social stimuli might therefore not be a valid equivalent to real-life social stimuli during observational paradigms, neither in adult, nor in infant studies.

More importantly however, the second person neuroscience approach questions the use of observational paradigms, as an approach to studying neural correlates of real-life social interaction (Schilbach et al., 2013). This claim is based on robust findings that human beings display altered behavior and employ different neural networks when observing social stimuli compared to engaging in real social interaction (see review in Redcay & Warnell, 2018 and Schilbach et al., 2013). The key aspect responsible for this difference seems to be the dynamic reciprocal character of real-life social interaction (Murray & Trevarthen, 1986; Schilbach et al., 2013). Based on a series of experiments investigating neural correlates of dynamic social interactions, Schilbach and colleagues hypothesize that areas associated with the Mentalizing and Mirror Neuron Networks, particularly mPFC, are responsible for interpersonal coordination during social interaction (Schilbach et al., 2013). Moreover, the mentalizing, reward and, to a lesser extent, mirror neuron networks show selective activation to live social contexts (Redcay & Warnell, 2018). In conclusion, it can be assumed that observational paradigms, as traditionally used in psychological methodology, might not be able to reveal the neural correlates and mechanisms of real-life social interaction. The second person neuroscience account therefore argues that social interaction must be studied in a social context with engaged participants (Hari et al., 2015; Schilbach et al., 2013; Wheatley et al., 2019).

Recent technological advances allow the implication of neuroscientific methods into more ecologically valid paradigms. Measuring the neural activity of two or more subjects simultaneously (i.e. hyperscanning) makes it possible to address the interpersonal dynamics of social interaction from a neuroscientific perspective (see review by Babiloni & Astolfi, 2014). This has the potential of making a previously unavailable dimension of social interaction accessible to research. By studying the underlying mechanisms of continuous reciprocal social interaction, future studies could gain important insights into new aspects of social cognition and how mutual understanding is achieved on a neural level (Gallotti et al., 2017; Konvalinka & Roepstorff, 2012; Wheatley et al., 2019).

The call for a methodological change in social neuroscience is also highly relevant to the developmental context (Hoehl & Markova, 2018; Nguyen, Bánki et al., 2020; Rice et al., 2016). Contrary to the common misconception that infants take the role of a passive and reflexive observer during early social interaction, infants develop a complex set of social communicative skills and are able to coordinate complex

expressive behavior with their mothers from as early as 3 months old (Yale et al., 2003). Even pre-linguistic infants use complex vocalizations in order to restore interrupted interactions with their mothers (Bourvis et al., 2018). Furthermore, in a study by Murray and Trevarthen mothers showed different communicative behavior depending on whether they watched a live video-sequence of their babies or a replayed one, the only difference being that the live condition enabled potentially responsive communication (Murray & Trevarthen, 1986). In paradigms where adults either followed the infant's gaze direction or looked at objects the infant had not looked at before, 5-, 6.5- and 9.5 month old infants showed neural sensitivity in the mPFC to when their gaze was followed (Grossmann, Lloyd-Fox, & Johnson, 2013; Rayson et al., 2019). Grossmann argues that the heavy involvement of infants' PFC, as discussed in previous chapters, indicates their active engagement during early social interactions (Grossmann, 2015).

These findings suggest that infants are sensitive to communicative cues on both neural and behavioral levels, actively engage and dynamically act and react during social interaction. Furthermore, infants' responsivity has been found to affect their mothers' communicative behavior. Thus, Cohn and Tronick conclude that mother-infant face-to-face interaction is marked by bidirectional influence and Beebe and colleagues argue that studies on early social interaction should focus on the dyadic level of analysis, as interactive processes are heavily characterized by dynamic and reciprocal interpersonal coordination (Beebe et al., 2010; Beebe et al., 2016; Cohn & Tronick, 1987, 1988).

Mother-Infant Synchrony

Investigating social interaction via the second person neuroscience approach emphasizes its bidirectional and reciprocal aspects as well as mechanisms that support the dynamic coordination between interaction partners. One of those mechanisms is interpersonal synchronization, i.e. the temporal alignment of behavioral or biological processes between interacting individuals (Hoehl et al., 2020; Leclère et al., 2014). Human beings are highly sensitive to the temporal properties of social stimuli, and the successful temporal coordination between interaction partners positively influences interaction outcomes (Schirmer et al., 2016). Live face-to-face interaction requires individuals to continuously monitor and adapt to their interaction

partners (De Jaegher et al., 2010; Shockley et al., 2009). According to the predictive coding theory, human beings create a hierarchy of internal predictive models of the world that are constantly updated and optimized, thus enabling the interpretation of and reaction to usually noisy sensory input (Friston & Kiebel, 2009). When interaction partners align during social interaction, the respective opposite's behavior and communication is more predictable and additional cognitive resources are available for other aspects of social interaction (Hoehl et al., 2020; cf. Garrod & Pickering, 2004). Interpersonal synchronization between interaction partners is therefore believed to facilitate mutual understanding (Hari et al., 2013; Hoehl et al., 2020). Furthermore, interpersonal synchrony seems to be associated with relationship quality (Gvirts & Perlmutter, 2020; Kinreich et al., 2017; Nguyen, Schleihauf et al., 2020). Reindl and colleagues observed higher neural synchrony when children between 5 and 9 years cooperated with their mother, compared to an unknown female experimenter (Reindl et al., 2018). Additionally, interpersonal synchrony increased both on the behavioral and neural level after previously unfamiliar subjects performed a collaborative task together (Yun et al., 2012). This hints towards a bidirectional relatedness between relationship quality and interpersonal synchrony (Hoehl et al., 2020).

Synchronization processes take place on various levels and although interpersonal synchrony can be achieved purposefully, for example when making music or dancing, it is created mostly automatically and without conscious effort (Hoehl et al., 2020). For instance, Feldman and colleagues found that dyads' cardiac rhythms aligned when mothers and their 3-month old infants synchronized on a behavioral level (Feldman et al., 2011). This indicates that interpersonal alignment through mutual gaze, affect or vocalizations (i.e. behavioral level) affects, and perhaps induces, synchrony on other levels, for example physiological rhythms. Within the developmental context, Feldman describes interpersonal synchronization as an "overarching process that coordinates the ongoing exchanges of sensory, hormonal, and physiological stimuli between parent and child during social interaction" (Feldman, 2007b, p. 340). Interpersonal synchrony in this period is thought to create a fundament for the development of more complex social behavior, such as the ability to form intimate relationships (Feldman, 2007c). Behavioral synchrony between 14-month-olds and an interaction partner was found to promote children's prosocial behavior and helpfulness towards the other person (Cirelli, 2018). Moreover, in a

longitudinal study on children from 3 months to 13 years old, Feldman found that higher affective synchrony between mother and child in the first year of life predicted the later development of verbal IQ and moral cognition and was directly associated with empathic capacity during adolescence (Feldman, 2007a). Thus, Feldman theorizes that early mother-infant synchrony familiarizes infants with the emotional reciprocity characterizing human relationships (Feldman, 2007a). From a broader perspective, alignment between mother and infant regulates infants' internal rhythms (e.g. sleeping, eating etc.), thus supporting allostatic regulation (Harrist & Waugh, 2002). Hence, various forms of dyadic synchrony on various interactional levels have been found to accompany and support critical developmental challenges throughout all episodes of infancy, with first signs of mother-infant alignment emerging already during pregnancy (for review see Feldman, 2007b).

Interpersonal Neural Synchrony

Interpersonal synchronization processes during social interaction have also been found on the neural level. Studies on adult dyads found increased interpersonal neural synchrony (INS) across frontocentral and centroparietal regions linked to better performance in cooperation tasks (Szymanski et al., 2017), during interactive decision making (Hu et al., 2018), as well as in imitation tasks (Dumas et al., 2010). Comparable findings have been reported for adult-child (Reindl et al., 2018) and adult-infant dyads (Miller et al., 2019; Nguyen, Schleihauf et al., 2020). Here, increased INS across similar regions was found during cooperative tasks in contrast to competitive tasks (Reindl et al., 2018), and when the task was performed independently (Miller et al., 2019; Nguyen, Schleihauf et al., 2020). Gvirts and Perlmutter argue that the level of interaction and behavioral synchrony affects interpersonal neural coupling (Gvirts & Perlmutter, 2020). Yun et al. theorize that inter-brain synchrony could be a neural correlate of implicit social interaction (Yun et al., 2012).

According to Tomasello, the emergence of social cognition is based on mutual attention (Tomasello, 1995). Establishing mutual attention is therefore crucial for social interaction (Gvirts & Perlmutter, 2020). Gvirts and Perlmutter point out that INS is mostly found in brain regions that have been linked to social cognition and attention in previous single-brain studies, namely PFC and the temporoparietal

junction (TPJ) (Gvirts & Perlmutter, 2020). INS across these regions is thought to serve as a mechanism of mutual attention, enabling interaction partners to mutually focus on important aspects of their interaction (Gvirts & Perlmutter, 2020). Gvirts and Perlmutter define a network spanning PFC and TPJ as the mutual social association system (Gvirts & Perlmutter, 2020). According to Hasson and Frith, dynamic neural coupling between interaction partners functions as a fundament for mutual understanding and makes communication possible (Hasson & Frith, 2016). Moreover, the coupling of interaction partners' mutual attention system is argued to be the basis and guidance for increasingly complex processes of social cognition, from joint attention to theory of mind and inferences about others' mental states (Gvirts & Perlmutter, 2020). Along the same lines, Stolk and colleagues argue that interpersonal neural synchrony emerges through shared conceptualization, thus enabling mutual understanding (Stolk et al., 2014). Fishburn et al. point out that INS is a supporting mechanism of shared intentionality, i.e. collaborative interaction towards a shared goal (Fishburn et al., 2018). Similarly, neural synchrony between instructor and learner predicted learning performance during an interactive social learning task (Pan et al., 2018).

Kinreich and colleagues (2017) conducted a dual EEG hyperscanning experiment where either couples or strangers engaged in a naturalistic social interaction (Kinreich et al., 2017). Their results were in line with the assumed link between neural synchrony and the level of social connectedness (Gvirts & Perlmutter, 2020). More importantly however, neural synchrony was mainly linked to moments of social gaze, in contrast to verbal aspects of communication, such as speech duration or content (Kinreich et al., 2017). Based on these findings, the authors argue that interpersonal brain coordination during social interaction could mainly rely on non-verbal forms of communication, particularly social gaze (Kinreich et al., 2017). Moreover, Jiang and colleagues found higher INS between frontal areas, when subjects sat face-to-face compared to sitting back-to-back during conversation (Jiang et al., 2012). Similarly, Hirsch and colleagues found increased interpersonal neural synchrony linked to mutual gaze, arguing that eye-contact could support cross-brain synchronization (Hirsch et al., 2017).

Links between mutual gaze and interpersonal neural synchrony have also been reported for adult-infant dyads: Leong and colleagues found increased neural synchrony across the alpha- and theta-frequency bands while infants watched an

adult singing nursery rhymes with direct relative to indirect gaze (Leong et al., 2017). Their results also showed strengthened bidirectional neural connectivity during direct gaze, which further underlines the dynamic nature of these synchronization processes, as well as the involvement of mutual gaze (Leong et al., 2017). Additionally, Piazza and colleagues found that interpersonal synchronization across the PFCs of infants and an adult experimenter was closely related to the dynamic fluctuations of mutual gaze, infant affect and joint attention (Piazza et al., 2020). Gvirts and Perlmutter argue that social cues during mutual attention could act as "synchronization triggers" and continuous salient cues by both interaction partners can strengthen interpersonal neural connectivity (Gvirts & Perlmutter, 2020).

The emergence of the second person neuroscience approach and technological progress allowing hyperscanning in ecologically valid scenarios have produced various studies on interpersonal neural synchrony in recent years (Babiloni & Astolfi, 2014; Schirmer et al., 2020). However, being a relatively novel methodological approach, literature on hyperscanning is lacking an experimental common ground (Schirmer et al., 2020). This makes interpretation and comparison of findings difficult. Furthermore, the concrete psychological meaning of INS remains poorly understood (Burgess, 2013; Hoehl & Markova, 2018; Liu et al., 2018; Schirmer et al., 2020). Schirmer and colleagues therefore call for an organized and collaborative effort in order to achieve methodological clarity and elaborate a theoretical framework guiding future studies (Schirmer et al., 2020).

Functions of Alpha- and Theta Frequency During Early Social Interaction

On a neural level social interaction and dyadic coordination seem to be closely linked to oscillations in the alpha- and theta frequency bands (e.g. Leong et al., 2017). Alpha oscillations are understood to be strongly associated with attention and memory (Foster et al., 2017; Klimesch et al., 1993; Klimesch, 2012; Payne et al., 2013). Hoehl et al. conducted wavelet analyses of infants' EEG-signal in a joint attention paradigm and found that infants' neural activity showed desynchronization in alpha frequency when jointly looking at a stimulus was preceded by an episode of direct eye contact between experimenter and infant (Hoehl et al., 2014). Alpha desynchronization is seen as a correlate of selective cortical activation and attentional mechanisms (Pfurtscheller, 2003; Ward, 2003). Klimesch theorizes that

alpha oscillations are involved in the recruitment of a semantic knowledge network, functionally and structurally overlapping with the default mode network (Binder et al., 2009; Klimesch, 2012). Both networks are associated with social functioning and introspection (Kleckner et al., 2017) as well as semantic processing (Binder et al., 2009; Klimesch, 2012). According to Klimesch's theory, alpha desynchronization and synchronization processes could function as a mechanism to selectively recruit (desynchronization) and suppress (synchronization) regions associated with the semantic knowledge network (Klimesch, 2012; Ward, 2003). Based on their results and an adult joint attention study reporting similar oscillation patterns (Lachat et al., 2012), Hoehl and colleagues argue that the observed alpha desynchronization linked to mutual gaze during joint attention could recruit the semantic knowledge network during early social learning (Hoehl et al., 2014; Michel et al., 2015). Additionally, frontocentral alpha (aka: mu-rhythm) attenuation has been linked to several other subprocesses of (early) social interaction and joint attention, such as sustained attention (Xie et al., 2018) and the detection of interaction partners' gaze following (Rayson et al., 2019). Pineda and Hecht associate mu-suppression in adults with mentalizing skills and theory of mind (Pineda & Hecht, 2009).

Increased frontal theta-power in infants is hypothesized to reflect activity of an executive attention control network involved in processing own and other's gaze direction, as well as goal-directed behavior (Bazhenova et al., 2007; Michel et al., 2015; Mundy & Newell, 2007; Petersen & Posner, 2012; Posner & Petersen, 1990). Bazhekova and colleagues argue that cortical theta synchronization could be a neural correlate of infants' social attention (Bazhenova et al., 2007). Furthermore, increased theta oscillations were observed in 9-month old infants during a violation of expectation paradigm (Köster et al., 2019). Thus, theta synchronization is thought to support the processing of unexpected stimuli, an important aspect of early learning (Köster et al., 2019).

Various adult-studies by Klimesch and colleagues associate phasic alpha desynchronization and theta synchronization with improved cognitive and memory performance (Klimesch et al., 1994; Klimesch, 1996; Klimesch et al., 1997; Klimesch, 1999). Jones and colleagues found both alpha desynchronization and theta synchronization over frontal areas when infants observed social, compared to non-social stimuli (Jones et al., 2015). Furthermore the results suggested an increased neural sensitivity to ecologically valid stimuli (i.e. live interaction) (Jones et al., 2015).

Similar oscillatory patterns were found in infants and preschoolers during social interaction and exploratory activities (Orekhova et al., 2006). Infants between 4 and 9 months showed increased alpha suppression in response to object-directed eye gaze and increased theta power for objected-averted gaze (Michel et al., 2015). These findings indicate that fundamental processes of infants' and adults' social cognition could be supported through frontal alpha- and theta-band activity. Moreover, these neural processes seem to be particularly sensitive to mutual and object-directed gaze. Alpha desynchronization and theta synchronization in frontal areas appear to reflect dynamic attentional processes during early social interaction. Mutual attention is an important basis for the emergence of social cognition, and therefore an essential supporting mechanism during social interaction (Gvirts & Perlmutter, 2020; Tomasello, 1995).

Wass and colleagues conducted a dual EEG study where mother-infant dyads either jointly or separately played with a toy (Wass et al., 2018). Although infants' overall attentiveness towards objects increased during joint play with their mothers, the predictive link between infants' theta activity and visual attention, hence their endogenous attentional control, decreased (Wass et al., 2018). Additionally, the mothers' theta fluctuations were found to be responsive to their infants' attentional behavior during joint play and greater maternal neural responsivity related to longer sustained attention by infants (Wass et al., 2018). These findings suggest that theta oscillations are involved in attention-control and -monitoring during real-life social interaction (Wass et al., 2018). More importantly however, this study allows first insights into how interpersonal coordination could be regulated on the dyadic level through the dynamic and interpersonal interaction of behavioral and neural mechanisms (Hoehl & Markova, 2018). Considering the essential role of social interaction in cognitive and neural maturation processes, these findings are highly relevant.

Research Question and Hypotheses
During social interaction individuals dynamically monitor and adapt to each other, in order to achieve successful communication (De Jaegher et al., 2010; Konvalinka et al., 2010; Konvalinka & Roepstorff, 2012; Shockley et al., 2009). Interpersonal synchronization reduces the cognitive load of these continuous adaptation processes

as interpersonal alignment makes others' communicative behavior more predictable (Garrod & Pickering, 2004; Hari et al., 2013; Hoehl et al., 2020). The first year of life is marked by a fundamental dependency on infants' social environment (Atzil & Barrett, 2017). The need for social interaction in an episode of neural plasticity and cortical maturation is believed to have an essential impact on infants' neural, cognitive and behavioral development (Atzil et al., 2018; Fotopoulou & Tsakiris, 2017). In recent years, the aspect of synchronicity on both the neural and the behavioral level was increasingly recognized as an essential aspect of dynamic coordination during social interaction (Hoehl et al., 2020; Wass et al., 2020). Interpersonal synchronization processes during infancy are thought to have a critical impact on the emergence of social cognition, learning outcomes and other important developmental challenges (Feldman, 2007a, 2007c). Mutual gaze resembles one of the most fundamental and early forms of behavioral synchrony and allows for early bidirectional interaction, as both mother and infant are sensitive to the respective other's eye-contact soon after birth (Cohn & Tronick, 1987, 1988; Csibra & Gergely, 2009; Redcay & Saxe, 2013).

Literature suggests heavy involvement of frontal areas, particularly mPFC, during social interaction (Amodio & Frith, 2006; Schilbach et al., 2013). The prefrontal cortex appears to be highly sensitive to social gaze cues (Grossmann et al., 2008; Rigato et al., 2010; Urakawa et al., 2015) and is associated with important functions during early neurodevelopment (Grossmann & Johnson, 2013). Furthermore, several EEG-studies found a decrease in frontal alpha and an increase of frontal theta oscillations in response to ostensive social stimuli, particularly to social gaze (Jones et al., 2015; Michel et al., 2015; Orekhova, 1999; Orekhova et al., 2006). These activation patterns are believed to reflect attentional processes and the recruitment of semantic knowledge networks during social interaction (Bazhenova et al., 2007; Hoehl et al., 2014; Köster et al., 2019; Michel et al., 2015). Mutual gaze is widely acknowledged as a fundamental aspect of dynamic mother-infant interaction (Hoehl & Markova, 2018). Accordingly, neural correlates of mutual gaze have been extensively studied in the past (Grossmann et al., 2008; Rigato et al., 2010; Urakawa et al., 2015). Only recently, however, as a result of the emerging second person neuroscience account, neuroscientific paradigms have begun to acknowledge the dynamic and bidirectional nature of real-life mother-infant interaction.

Hoehl and colleagues observed frontal alpha desynchronization in infants when adults engaged in eye contact with them before presenting novel objects (Hoehl et al., 2014). Based on their findings, the authors hypothesize that eye contact during live social interaction induces the recruitment of a semantic knowledge network (Hoehl et al., 2014). The activation of this network is believed to be accompanied by alpha desynchronization and is an important mechanism during social learning (Hoehl et al., 2014). Although Hoehl et al.'s experimental setup involved a real social interaction partner, the infants were merely observing the experimenter/the stimuli within a strictly timed paradigm. This resulted in a restricted one-way interaction lacking the mutual dynamic adaption processes characterizing naturalistic social interaction. Moreover, the paradigm involved a female experimenter, previously unknown to the infants. Several studies have shown that important aspects of social interaction, such as the effectiveness of social gaze cues, depend on the degree of social connectedness between the interaction partners (Hoehl et al., 2012; Hoehl et al., 2020; Minagawa-Kawai et al., 2009; Yun et al., 2012). Based on these findings it could be argued that mothers should be included as interaction partners in future studies. This would increase ecological validity as mothers are usually the primary caregiver and main source of social interaction during the first year of life.

The association between theta synchronization and mutual gaze has not been studied as thoroughly so far. However, Orekhova observed increased frontal theta in infants during a "peekaboo"-game involving mutual gaze (Orekhova, 1999). Theta synchronization over frontal areas is thought to be associated with infants' anticipatory processing and behavior during social interactions (Orekhova, 1999; Orekhova et al., 2006). Furthermore, Wass and colleagues allowed first insights into the essential role of theta frequency in dyadic attention coordination during real-life mother-infant interaction (Wass et al., 2018). As one of the primary cues in ostensive communication and the signaling of subsequent socially relevant information, mutual gaze serves a similar function on the behavioral level (Csibra & Gergely, 2009; Niedźwiecka, 2020).

In line with the second person neuroscience approach, this study aimed to gain further insight into the functions of alpha- and theta frequency bands during mother-infant interaction. Furthermore, possible links to behavioral coordination through mutual gaze were investigated. In contrast to previous experiments, this study

implemented a free-play paradigm with no major restrictions to the dyadic interaction and included mothers in the experiment for a maximal amount of ecological validity.

Based on the literature the following hypotheses were formulated:

H1: The average theta-power over frontocentral EEG-electrodes of both mothers and infants is significantly higher during free-play compared to a resting-state condition.

H2: The average alpha-power over frontocentral EEG-electrodes of both mothers and infants is significantly lower during free-play compared to a resting-state condition.

H3: Increased behavioral coordination during free-play, reflected through a longer overall duration of mutual gaze episodes, corresponds to increased average theta-power (synchronization) over frontocentral EEG-electrodes of both mothers and infants.

H4: Increased behavioral coordination during free-play, reflected through a longer overall duration of mutual gaze episodes, corresponds to decreased average alpha-power (desynchronization) over frontocentral EEG-electrodes of both mothers and infants.

Method

This master's thesis was realized within the context of a larger project, studying mother-infant synchronization during contingent live interactions (coSMIC Project). Data collection took place between April and August of 2018 at the Max Planck Institute for Human Cognitive and Brain Sciences in Leipzig, Germany.

Participants

From a provisional set of 69 dyads providing complete behavioral and neural data, 31 were selected for further analyses. This reduction was due to exceptional noisiness in the EEG-signal of the excluded dyads. Within the final sample (n=31, 16 female) infants were on average 8,24 months old (SD = 8,72 days). Mothers' mean age was 34,07 years (SD = 4,05 years). Only full-term infants with normal birthweight were selected for the experiment.

Study Design

During the experiment the infants sat on an infant-chair facing their mothers. The dyads' neural activity was measured via dual EEG hyperscanning. Prior to the start of the experiment the mothers went through a training phase in order to get accustomed to task and setting. Testing started with a resting state condition (RS), during which the dyads observed soap-bubbles blown by an experimenter for 55 seconds. Mothers were asked to passively observe the bubbles without interacting with the infant. This was followed by a "free play" condition (FP). Here, mothers were instructed to play with their infants as they would at home, without implementing toys (Beebe et al., 2010). FP lasted for a period of 2 minutes and 40 seconds. The interaction was recorded by a total of four cameras, strategically positioned in order to deliver sufficient video material for behavioral off-line coding. Figure 1 shows an example of one of the camera angles and the experimental setup during the free play condition.

The coSMIC paradigm spanned several additional conditions, however, as the RS and FP conditions where located at the very beginning of the experiment there are no suspected confounds related to fatigue or fussiness caused by the length of the experiment.
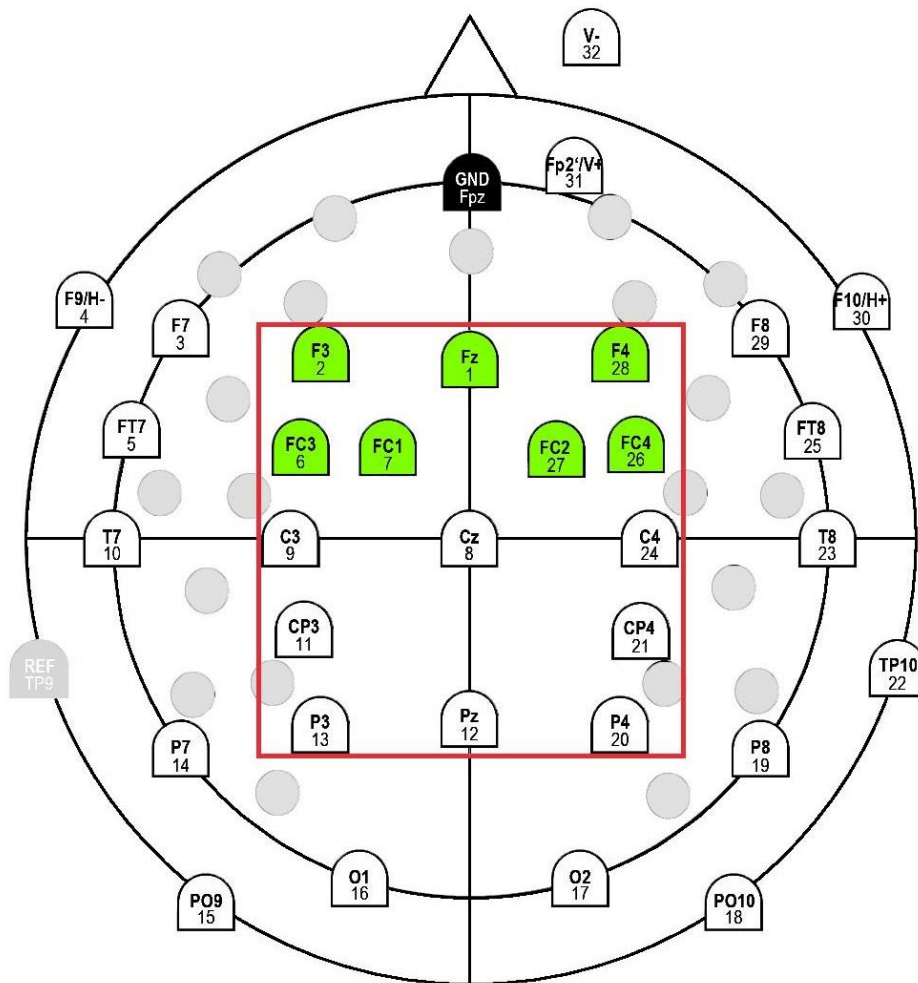
Figure 1: Experimental setup during free play (FP)

Figure 2: actiCap Channel Configuration, Channels inside the red square were included in preprocessing; ROI is highlighted in green

Behavioral Coding

Adapting coding schemes from previous studies (Cohn & Tronick, 1987; De Schuymer et al., 2012; Feldman et al., 2011; Markova & Legerstee, 2006; Pelaez-Nogueras et al., 1996) the following coding scheme was developed:

- Social gaze
    - <u>Face</u>: Gaze directed at the partner's face (even if face is covered by e.g. hands)
    - <u>Body</u>: Gaze directed at the partner's body/body parts (e.g. hands), but away from the face
- <u>Object/environment gaze</u>: gaze directed at an object (could also be own body) naturally present within the setting or environment *with clear interest* (i.e. no staring, no random gaze roaming)
- <u>Gaze aversion</u>: gaze directed away from the partner, not orienting towards something in the environment. This category includes briefly looking away during an interaction, (slightly) closing the eyes, looking away accompanied by arching of the back, turning of the body, or increased motor activity. (The focus here is not on actively observing something located away from the partner, but rather on down-regulating interaction intensity; see Field, 1981). This includes:
    - Turning away from partner without interest in object/environment
    - Empty staring
    - Actively avoiding eye-contact
- Not visible/codable

Following this scheme, the dyad's gazing behavior was micro-coded (frame per frame) off-line using the computer-software Interact (Mangold Interact, Version 18, Mangold International GmbH). A behavior had to occur for at least one second in order to be taken into account. Episodes of mutual gaze were defined as moments in which both mothers' and infants' gaze direction was coded as "gaze directed to partner's face". The coding scheme included additional categories as it was designed to be used for further analyses within the coSMIC project. These were not regarded in this thesis, however. For later analyses and comparisons to the neural data, mutual gaze was quantified through overall duration during FP (Kuzmanovic et al., 2009).

A second rater performed reliability coding on a set of 16 dyads (ca. 23%), randomly selected from the final sample. Cohen's Kappa was used as a measure of inter-rater reliability (IRR) (1=perfect agreement, 0=no agreement). Kappa values were .81 for infants' and .803 for mothers' gazing behavior ($p < .05$).

EEG Data Acquisition

Brain activity was recorded simultaneously in mothers and infants via two 32-channel BrainAmp amplifiers (Brain Products GmbH, Gilching, Germany) and two 32-electrode actiCap-systems (EASYCAP GmbH, Herrsching, Germany) with a sampling rate of 500 Hz. Electrodes were positioned according to the 10-20 international system for electrode placement (e.g. Santamaria et al., 2020; channel configuration is depicted in Figure 2).

EEG Artifact Rejection and Preprocessing

Preprocessing was implemented in MATLAB via the Fieldtrip toolbox. Raw EEG-Data was imported, and peripheral channels, irrelevant to this study, rejected, in order to reduce noise. Included channels for data cleansing were: F3, Fz, F4, FC3, FC1, FC2, FC4, C3, Cz, C4, CP3, CP4 (see Figure 2). Remaining noisy channels were detected and manually selected for interpolation with neighboring channels. In a next step, independent component analyses (ICA) were conducted to detect eye-movement artifacts. Components exceeding a correlation threshold of 0.8 with the EOG-electrodes (i.e. electro-oculogram) were rejected. The available channels were re-referenced relative to the common average. Finally, remaining artifacts were detected through a predefined amplitude threshold (50 µV) within a 200 µs sliding window and then rejected manually.

EEG Power Analysis

For power analysis of the EEG data, time frequency response was calculated, and power spectra were computed using Welch's method. This resulted in power estimates for each available channel with a frequency resolution of 1 Hz. Power estimates were then averaged within the alpha and theta frequency bands. Based on previous studies, infant theta was defined at 3-6 Hz, infant alpha at 6-9 Hz. Mother theta was defined at 4-7 Hz, mother alpha at 8-12 Hz (Jones et al., 2015; Orekhova,

1999; Orekhova et al., 2006; Wass et al., 2020). Finally, the alpha- and theta-power estimates were averaged over the frontocentral region of interest (ROI), spanning channels F3, Fz, F4, FC3, FC1, FC2 and FC4 (see Figure 2). Thus, frontocentral alpha- and theta power estimates were obtained for infant and mother in the two experimental conditions (RS, FP).

Statistical Analysis

Statistical analysis was conducted in RStudio for Windows (Version 1.9.959), an integrated development environment for the statistical computing software R (RStudio Team, 2020).

Alpha- and Theta-power differences between RS and FP were investigated by comparing their central tendency. Graphical data inspection revealed one extreme outlier (i.e. >3*IQR distance from 1st or 3rd Quartile) in mothers' average alpha power during FP, as well as in mothers' average theta power during RS (see Figure 3). Revision of the video material of the relevant dyads revealed no abnormalities explaining the extreme outlier in average mother alpha power during FP. As a result, this dyad was not excluded. In the case, responsible for the extreme outlier in mothers' average theta power during RS, the recordings showed that the mother was clearly interacting with the infant throughout the whole duration of the condition, while the baby was fixating the bubbles. The outlier was therefore excluded from further analyses. While this case does not allow for any interpretations, it is still noteworthy that it is in line with the theoretical background of this study (i.e. theta-synchronization linked to social interaction). Paired one-sided t-tests were computed, where data structure met the test-assumptions. This was the case for infant theta power. All other variables (infant alpha, mother alpha and theta) were investigated through Wilcoxon signed-rank tests. Here, the average power differences between RS and FP were not normally distributed and therefore required non-parametric testing. P-values were adjusted for multiple comparisons using the Bonferroni-Holm Correction.

Associations between mutual gaze duration and the subjects' average alpha and theta power during FP were investigated through correlation analyses. Due to the extreme outlier in mothers' average alpha power, a non-parametric Spearman's rank correlation coefficient (one-sided) was computed. All other variable-pairs met the Pearson test assumptions of linearity, absence of extreme outliers, as well as

bivariate normal distribution. The latter was tested for via the Henze-Zirkler Test for Multivariate Normality (Henze & Zirkler, 1990). These variable-relations were investigated using one-sided Pearson-Correlations.

Results

Neural and behavioral data was investigated using the appropriate descriptive measures. See table 1 for mean individual looking times to interaction partner's face, as well as mean overall duration of mutual gaze during FP. Figure 3 depicts differences in central tendency between average alpha and theta power during FP and RS.

Table 1: *Average gaze durations during FP*

Gaze Direction	Mean	SD
Mother → Infant Face	135.98s	22.04s
Infant → Mother Face	56.27s	31.86s
Mutual Gaze	51.87s	27.5s

RS vs FP

A paired one-sided t-test revealed that infants' average theta power was significantly higher during FP (M = 5.28 µV²/Hz, SD = 1.66 µV²/Hz) compared to RS (M = 4.59 µV²/Hz, SD = 1.71 µV²/Hz), $t(30)$ = 4.01, $p < .001$.

The non-parametric Wilcoxon signed-rank tests indicated the following significant median differences (median (*MED*) and interquartile range (*IQR*) are reported as measures of descriptive statistics): Mothers' average theta power was significantly higher during FP (*MED* = 0.50 µV²/Hz, *IQR* = 0.23 µV²/Hz) compared to RS (*MED* = 0.40 µV²/Hz, *IQR* = 0.161 µV²/Hz), Z = -4.404, $p < .0001$. Infants' average alpha power was significantly lower during FP (*MED* = 1.44 µV²/Hz, *IQR* = 0.89 µV²/Hz) compared to RS (*MED* = 1.71 µV²/Hz, *IQR* = 1.50 µV²/Hz), Z = -4.324, $p < .0001$.

Mothers' average alpha power did not significantly differ between conditions (FP: *MED* = 0.262 µV²/Hz, *IQR* = 0.107 µV²/Hz; RS: *MED* = 0.267 µV²/Hz, *IQR* = 0.196 µV²/Hz), Z = 0.029, $p = .512$.
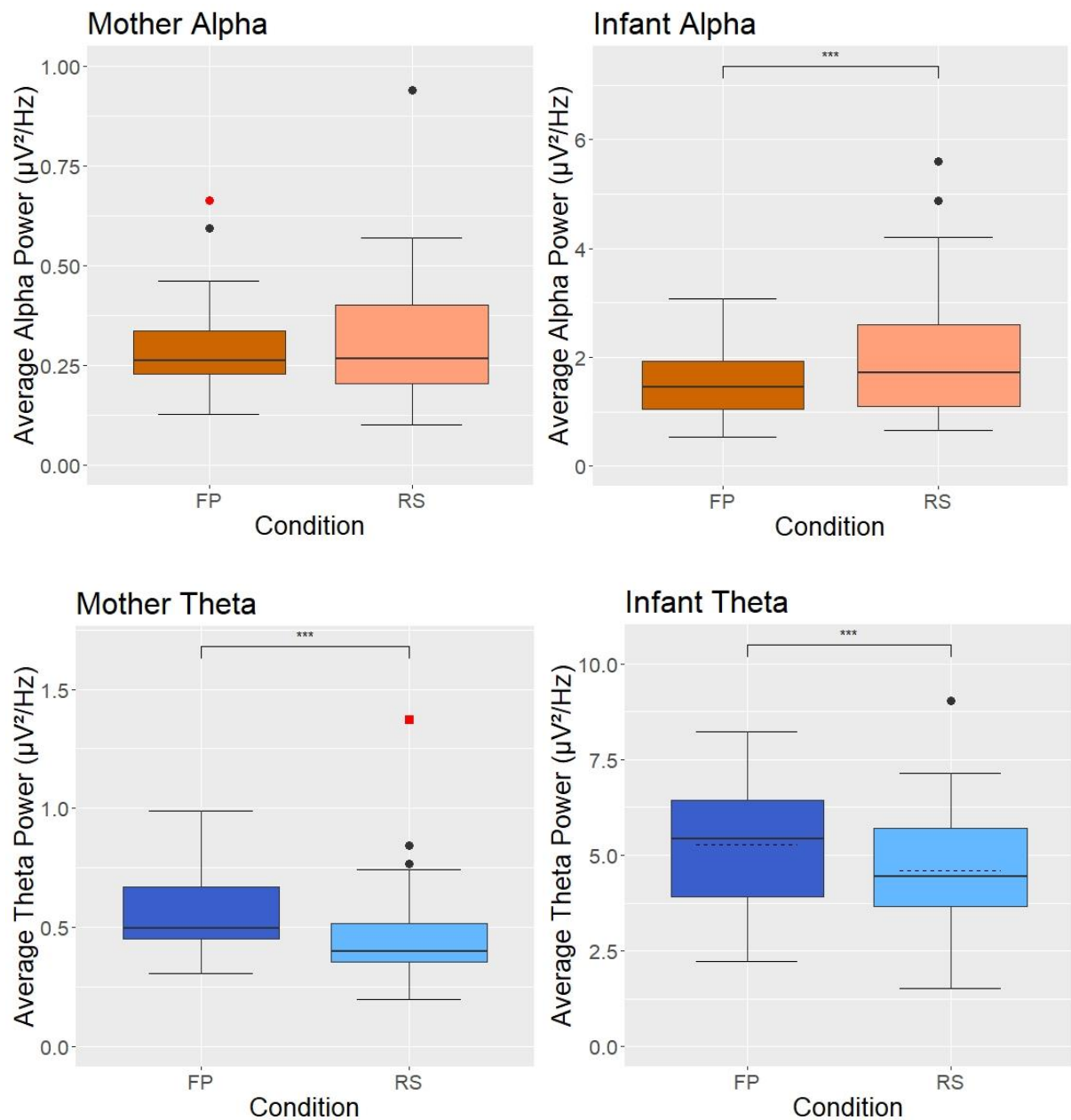
Figure 3: Boxplots of average alpha- and theta-power during FP and RS; Orange: alpha frequency, Blue: theta frequency; significant differences of central tendencies are marked with (***), (≙p<0.001). As infants' average theta power - differences were investigated with a t-test, means are indicated by dashed lines. Extreme outliers (>3*IQR distance from 1st or 3rd Quartile) are marked in red. The extreme outlier in mothers' average theta power during RS (red square) was excluded from further statistical analyses. The rest of the Mother Theta RS boxplot illustrates data distribution after exclusion.

Correlations

Correlation analyses did not reveal significant associations between the neural data and mutual gaze duration (alpha power mother (spearman): ρ = .151, p = .793; alpha power infant: r = -.082, p = .331; theta power mother: r = -.234, p = .897; theta power child: r = -.055, p = .616)(See Figure 4 for Scatterplots).
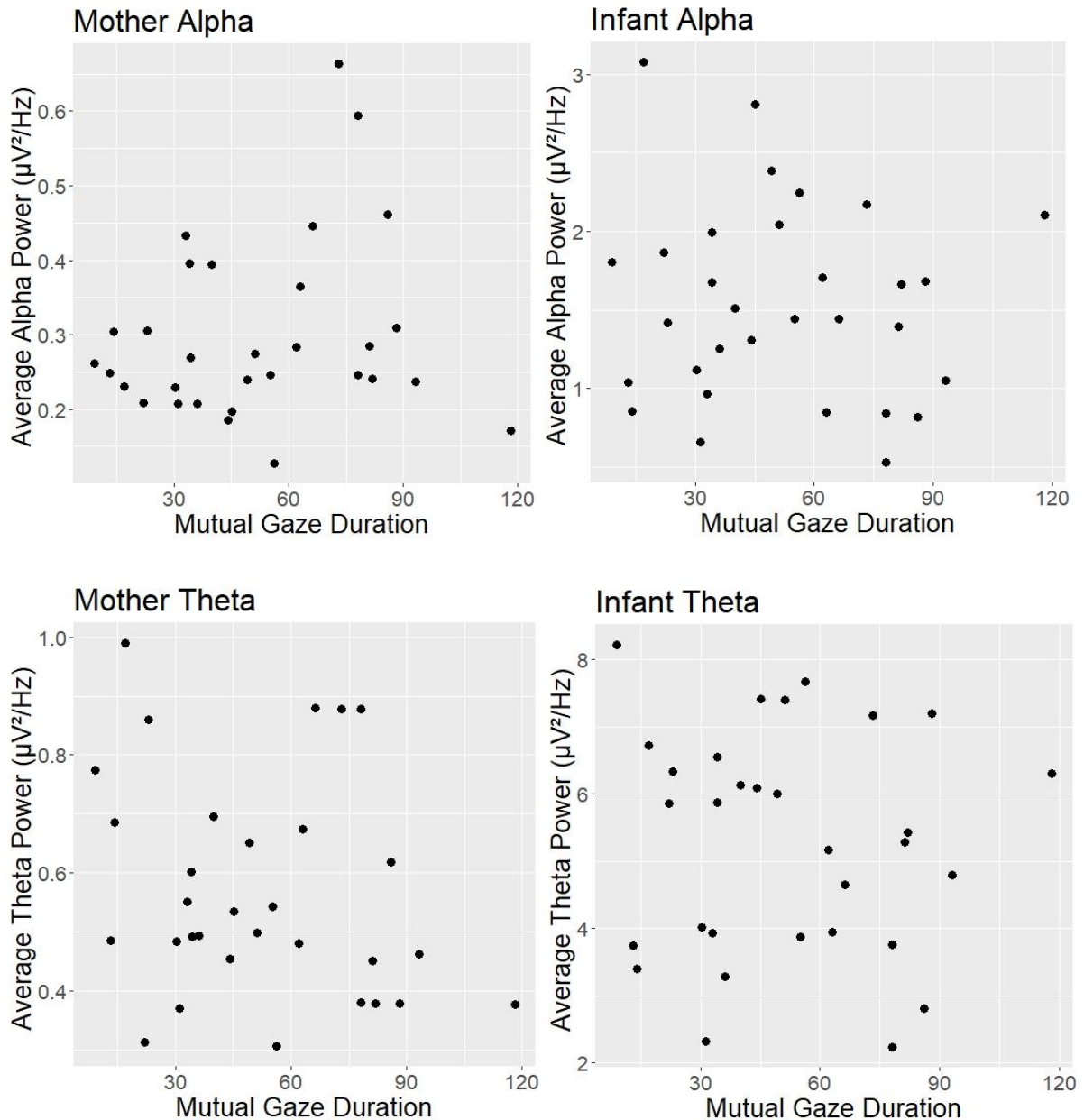

Figure 4: Scatterplots illustrating the associations between subjects' average alpha- and theta-power and mutual gaze duration during FP

Discussion

In order to investigate the neural supporting mechanisms of dyadic coordination during naturalistic and bidirectional mother-infant interaction, a dual EEG hyperscanning setup was implemented in a "free play" paradigm where mothers and infants interacted with minimal restrictions. In line with the emerging second person neuroscience approach (Hoehl & Markova, 2018; Schilbach et al., 2013), this study aimed to gain further insight into the dynamics of social interaction by emphasizing its social dimension.

Theta synchronization is widely understood as a neural correlate of executive attention control (Michel et al., 2015; Orekhova, 1999; Orekhova et al., 2006). Frontal theta, in particular, is argued to underly anticipatory processes in infants (Orekhova, 1999; Orekhova et al., 2006). A recent hyperscanning study by Wass and colleagues implies that theta activity could play an important role in the dynamic interpersonal coordination of attention (Wass et al., 2018). The present study compared average frontal theta power during free play to a resting state condition. As predicted, statistical analysis revealed increased theta synchronization during FP in both subjects. These findings are in line with previous studies and further consolidate the suspected specialized role of theta activity during mother-infant interaction due to the high ecological validity of the paradigm. Interestingly, the resting state condition also contained attention-grabbing stimuli in the form of soap bubbles. Increased theta power during FP could therefore hint towards a specific sensitivity to social interaction.

Results on alpha frequency were not as clear. While the predicted desynchronization in frontal alpha power during FP compared to RS was observed in the infants, mothers showed no significant differences. This is particularly interesting as mothers spent significantly longer looking at their infant's face (M = 135.98s, SD = 22.04s) than vice versa (M = 56.27s, SD = 31.86s), t(30) = 12.056, $p < .001$ (post-hoc paired two-sided t-test). Alpha desynchronization is understood to reflect selective cortical activation processes (Hoehl et al., 2014; Klimesch, 2012; Ward, 2003) and suppressed alpha, particularly over frontocentral regions (i.e. mu-rhythm), was linked to various fundamental aspects of social cognition and learning in several previous studies on both adults and infants (Hoehl et al., 2014; Pineda & Hecht, 2009; Xie et al., 2018). The significant tendencies in average infant alpha power observed in the

present experiment are in line with the previous findings. The lack of these tendencies in mother alpha power could have several reasons. For instance, as RS involved an experimenter blowing bubbles, this could have resembled a social situation for the mothers, resulting in alpha suppression in this condition as well. Moreover, inspection of the video material captured during RS revealed that, although instructed otherwise, mothers tended to try to direct their infants' attention towards the soap bubbles. This behavior would induce joint attention on the mothers' part, which has been linked to alpha suppression in several previous studies (Hoehl et al., 2014; Lachat et al., 2012; Michel et al., 2015). Another possible explanation could be that alpha frequency is known to show prominent interindividual differences (Klimesch, 1999). Previous studies have suggested the need for a functional differentiation of the alpha frequency band in upper and lower alpha frequency (Klimesch et al., 1993; Klimesch, 1996; Petsche et al., 1997). Thus, averaging EEG power over the whole span of the alpha frequency band (8-12Hz) could lack the precision needed for the detection of predicted tendencies. Investigating EEG-power at individual frequency peaks should be considered in future studies.

Correlation analyses between mutual gaze and the subjects' average alpha- and theta-power yielded none of the expected results. Considering that previous studies strongly associate mutual gaze with frontal alpha suppression (Hoehl et al., 2014; Prinsen & Alaerts, 2020) and to a lesser degree with theta synchronization (Orekhova, 1999), it must be investigated why these links were not observed in the present study. Apart from the previously discussed issue of averaging neural signals over the whole frequency range, the temporal imprecision of both the neural and behavioral variables could be another possible explanation. Although it can be argued that overall duration is an appropriate way of modeling social gaze in order to investigate its neural correlates (Kuzmanovic et al., 2009), this quantification is likely too reductive for this study's objective. Particularly, because the methodological strength of electroencephalography lies in its high temporal resolution. Previous studies link improved cognitive and attention performance to alpha desynchronization and theta synchronization in phasic activity (i.e. fast adaption), while observing different activation patterns in tonic activity (i.e. slow adaption) (Klimesch, 1996, 1999). Furthermore, Busch and colleagues argue that theta-oscillatory phase appears to be more sensitive to perceptive input than amplitude (Busch et al., 2009). This further emphasizes the need for a temporally sensitive methodological

approach. Thus, time-locked analysis of behavioral and neural data would be more suitable to model the dynamic properties of real-life social coordination.

Eye-contact is associated with several communicative functions, such as signaling communicative intent or initiating ostensive communication (Senju & Csibra, 2008). In early mother-infant interactions mutual gaze is argued to support infants' attention control and focus (Csibra & Gergely, 2009). The emergence and maturation of attention control mechanisms during infancy is likely to have a long-term developmental impact on fundamental aspects of adult cognition (Johansson et al., 2015; Yu & Smith, 2016). Overall, the literature supports the developmental importance of social interaction during infancy and emphasizes the role of social gaze. However, most studies on social gaze rely on findings from non-interactive experimental studies on western, middle-class, typically developing cohorts (Akhtar & Gernsbacher, 2008). Akhtar and Gernsbacher argue that methodological and cultural biases led to an overrepresentation of mutual gaze in research on infant social cognition and consequently to a simplification of its role in real life social interaction (Akhtar & Gernsbacher, 2008). In fact, findings on mutual gaze in naturalistic contexts reveal a rather complex functionality: On one hand, mutual gaze has been found to have calming effects on infants (Blass et al., 2007). On the other hand, infants tend to avoid direct gaze in order to down-regulate their affective state when over-aroused (i.e. gaze aversion)(Field, 1981). While in some social situations mutual gaze might support infants' attention allocation, other contexts, particularly situations with high cognitive demand, are understood to benefit from gaze aversion, as engaging in mutual gaze is accompanied by a higher cognitive load (Doherty-Sneddon & Phelps, 2005). Furthermore, findings from cross-cultural studies suggest a less prominent role of mutual gaze during early mother-infant interaction in non-western societies (LeVine, 1994; Richman et al., 1992). Based on these findings Akhtar and Gernsbacher conclude that early social behavior and mother-infant interaction should be approached from a cross-cultural and multimodal standpoint (Akhtar & Gernsbacher, 2008).

While the present study concentrated on behavioral coordination and its effects on the interaction partners' individual brain activity, the second person neuroscience approach also encourages the investigation of how human beings coordinate life-social interaction on an interpersonal neural level. Recent studies have strengthened the assumption that mutual understanding and dynamic interpersonal coordination is

supported by oscillatory phase synchronization between the interaction partners' brains (Gvirts & Perlmutter, 2020; Hasson & Frith, 2016). However, the concrete psychological meaning of INS remains unclear (Burgess, 2013; Liu et al., 2018; Schirmer et al., 2020). Neural alignment is thought to be closely associated to synchronization on the behavioral level (Gvirts & Perlmutter, 2020). This understanding is largely based on findings from EEG hyperscanning studies with adult subjects (Babiloni & Astolfi, 2014; Liu et al., 2018), as the methodological implementation in a developmental context comes with several difficulties (Noreika et al., 2020; Wass et al., 2020). Nonetheless, developmental social neuroscientists have called for a methodological change towards the second person neuroscience approach (Hoehl & Markova, 2018).

As social gaze plays an important role in early social communication (Csibra & Gergely, 2009; although see Akhtar & Gernsbacher, 2008) and direct eye-contact represents a form of behavioral alignment, mutual gaze could serve as a "synchronization trigger" for interpersonal neural alignment during social interaction between mother and child (Gvirts & Perlmutter, 2020; Leong et al., 2017).To date only few studies have addressed the association between behavioral coordination through mutual gaze and INS in adult-infant dyads (Leong et al., 2017; Piazza et al., 2020), while none have included infants' most important social partner, their mothers. By considering the methodological problematics discussed above, an itineration of the present study's paradigm could investigate how mutual gaze dynamically relates to neural synchronization between mother and infant, in order to gain a better insight into how dyadic coordination is facilitated through interacting processes on the behavioral and neural level.

Application of the second person approach to developmental social neuroscience allows scientists to investigate the neurobehavioral dynamics of early social interaction in ecologically valid paradigms (Hoehl & Markova, 2018). Moreover, it introduces a novel dimension to mother-infant interaction by conceptualizing it on the dyadic level, as well as emphasizing the reciprocal and dynamic aspects of early social communication and coordination. A better understanding of social interaction and the emergence of social cognition could be applied to a variety of domains. For instance, new insights into mechanisms underlying early learning, language acquisition and attachment (Hoehl & Markova, 2018) could be implemented in educational and social policies as part of an evidence driven adaptation of

educational structures as proposed by Blakemore and Frith (Blakemore & Frith, 2005). Furthermore, a neurobehavioral assessment of early social interaction has the potential to be a sensitive diagnostical tool in the clinical context (Leong & Schilbach, 2019; Redcay & Schilbach, 2019). A better understanding of links between social behavior and underlying neural processes could help in the identification of neural biomarkers of typical or atypical social development (Grossmann, 2015). For instance, neural sensitivity to dynamic social gaze could be used to differentiate between neurotypical infants and infants at risk of developing autism at an early age, when the assessment of behavioral diagnostic markers is not yet effective (Elsabbagh et al., 2012; Hoehl et al., 2009). While there is no known cure for autism, an early diagnosis is argued to significantly improve the infant's quality of life as well as parent-infant relationship (Elder et al., 2017).

In summary, second person developmental neuroscience has enormous potential for the conceptual differentiation of early social interaction, as well as the practical application in various fields, such as the clinical and educational context. However, in order to unravel its full potential this approach longs for methodological refinement towards a feasible balance of maximized ecological validity and experimental control of confounding variables. The present study should be interpreted in the context of this endeavor: Firstly, its findings are in line with the previous literature regarding frontal alpha and theta sensitivity to social interaction. Secondly, the null findings on the link between mutual gaze and alpha and theta power suggest methodological improvements for future studies, considering it plausible that they are caused by the analytical approach and not by the experimental paradigm per se. Thirdly, and most importantly, the findings resulted from a highly naturalistic experimental scenario. The implemented experimental paradigm in principle proved as capable of reproducing previous results with maximized ecological validity. The present findings can thus be understood as a proof of concept regarding the associations between frontal alpha desynchronization/frontal theta synchronization and early social interaction as established in previous studies. This implies that ecologically valid paradigms can be sensitive instruments, capable of exploiting the full potential of second person developmental neuroscience. Given its variability, the highly naturalistic free play paradigm implemented in the present study, combined with more sophisticated statistical analyses, could serve as a sand box for experimental designs in future studies.

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Appendix

Abstract

English Version

During early childhood the brain's both structural and functional architecture is highly plastic and sensitive to external input. This period is also characterized by infants' strong dependency on their social environment, especially their primary caregivers. Thus, scientists argue that early social interaction has a fundamental impact on early neurodevelopment and the emergence of social cognition. During social interaction human beings dynamically and bidirectionally monitor and adapt to each other. These coordination processes are thought to be supported by decreased alpha power (desynchronization) and increased theta power (synchronization) over frontocentral areas. Furthermore, alpha desynchronization and theta synchronization was observed in association with mutual gaze. In early mother-infant interaction mutual gaze is thought to act as an important communicative cue supporting dynamic interpersonal coordination. Although findings emphasize the dynamic and reciprocal qualities of real-life social interaction, social neuroscience is dominated by observational paradigms with participants passively observing social stimuli. This study investigated alpha and theta activity in mothers and infants through an EEG hyperscanning paradigm. This allowed the dyads to interact freely, thus ensuring maximal ecological validity. Average alpha- and theta-power values were compared between a "free-play" (FP) and a resting state (RS) condition and overall mutual gaze duration during FP was correlated with average alpha and theta power of both mothers and infants. Infants' average alpha power was significantly lower during FP. Average theta power was significantly higher during FP in mothers and infants. Correlation analyses indicated no significant associations. The results are discussed in the context of previous findings and future directions.

Deutsche Version

Die frühe Kindheit ist von existenzieller sozialer Abhängigkeit, sowie von hoher Neuroplastizität und Aufnahmefähigkeit gegenüber externen Reizen gekennzeichnet. Es wird daher angenommen, dass frühe soziale Interaktion einen wesentlichen Einfluss auf die Entwicklung neuronaler und sozial-kognitiver Strukturen hat. Erfolgreiche Interaktion setzt voraus, dass die interagierenden Personen kontinuierlich und dynamisch aufeinander reagieren. Es wird vermutet, dass sich

diese Koordinationsprozesse in erhöhter Alpha-Power (Desynchronisation) und verringerter Theta-Power (Synchronisation) im frontozentralen EEG-Signal widerspiegeln. Alpha-Desynchronisation und Theta-Synchronisation konnte ebenfalls bei gegenseitigem Blickkontakt beobachtet werden. Studienergebnisse deuten darauf hin, dass gegenseitiger Blickkontakt in der frühen Mutter-Kind-Interaktion eine grundlegende koordinative Rolle spielt. Obwohl der derzeitige Erkenntnisstand die Bedeutung der dynamischen bidirektionalen Eigenschaften von realen sozialen Interaktionen unterstreicht, kommen in der sozial-neurowissenschaftlichen Forschung bislang überwiegend Paradigmen zum Einsatz, bei denen die Versuchspersonen passiv soziale Reize beobachten. Die vorliegende Studie untersucht die Alpha- und Theta-Aktivität bei Müttern und Säuglingen unter Anwendung eines EEG-Hyperscanning-Paradigmas, das eine freie Interaktion ermöglicht und so eine maximale ökologische Validität sicherstellt. Die durchschnittlichen Alpha- und Theta-Werte wurden zwischen einer „Free-Play" (FP) und einer Resting-State Bedingung (RS) verglichen. Außerdem wurde die Beziehung der Gesamtdauer des Blickkontakts während FP mit der durchschnittlichen Alpha- und Theta-Aktivität von Müttern und Säuglingen untersucht. Die durchschnittliche Alpha-Power von Säuglingen war während FP signifikant niedriger. Die durchschnittliche Theta-Power war während FP bei Müttern und Säuglingen signifikant höher. Korrelationsanalysen der Beziehung zwischen der Dauer des Blickkontakts und Alpha- und Theta-Aktivität von Müttern und Säuglingen ergaben keine signifikanten Resultate. Die Erkenntnisse der Studie werden in Bezug auf frühere Ergebnisse und zukünftige Ansätze diskutiert.

Abbreviations

EEG	*electroencephalography*
ERP	*event-related potential*
fMRI	*functional magnetic resonance imaging*
fNIRS	*functional near-infrared spectroscopy*
FP	*free play condition*
IBH	*interactive brain hypothesis*
INS	*interpersonal neural synchrony*
mPFC	*medial prefrontal cortex*
Nc	*negative component*
PFC	*prefrontal cortex*
ROI	*region of interest*
RS	*resting state condition*
TPJ	*temporoparietal junction*

Figures

Tables