

Infants Oscillatory Frequencies change during Free-Play for Social vs Non-social Interactions.

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Abstract

The ability to investigate neural activity during infancy whilst partaking in social (and non-social) engagement with a caregiver in a naturalistic interaction is a key issue for advancing the developmental sciences. Understanding the neural basis of social interactions will allow us to explore how exposure to atypical parent-infant interactions, which serve as a model for socio-emotional development during infancy, can alter neural development. The current research aimed to observe the oscillatory activity of 6-month-old infants during spontaneous free-play interactions with their mother. A 5-minute unconstrained free-play session was recorded between infant-mother dyads with EEG recordings acquired from the 6-month-old infants ($n=64$). During the recording, social interactions and non-social behaviours were observed, with EEG assessed with these epochs.

Results showed broad increases in oscillatory activity both when an infant played independently or interacted with their mother. As hypothesised, as frequency bands approached alpha and theta, oscillatory power statistically increased. In the present 6-month-old cohort, no hemispheric differences were observed. Instead, differences appeared between electrode regions: frontal and parietal regions bihemispherically displayed similar estimates, which were larger than those observed centrally, whilst temporal estimates were larger and discrete from all other regions. The interactions observed between the behavioural events and frequency bands demonstrated a significant reduction in power comparative to the power observed in the gamma band during the baseline event. The interactions between the frequency bands and electrode locations uncover an increase in power comparative to that seen in the gamma band in the left-central region.

The present research sought to explore the obstacle of artificial play paradigms for neuroscience research, whereby researchers question how much these paradigms relate to reality outside the lab. The present work highlights the strengths and limitations of taking an unconstrained free-play approach.

Keywords: Mother-Infant Interaction, EEG, Free-play, Linear Mixed Model, Random Effect

Highlights:

- The present research took a naturalistic neurological freeplay paradigm approach.
- Increased frequency power when infants played independently or interacted with their mother.
- Increased alpha and theta oscillatory power occurred during interactions.
- Power increased in frontal and parietal regions, with larger estimates temporally.
- Naturalistic EEG induces variable data quantity by condition, and further limitations.

1.0 Introduction

Social interactions are known to be essential for different elements of infant development, for example language development (Kiselev et al., 2017) and the perception of social cues (Murray et al., 2016). In order to better understand what is termed the *social brain* (Grossman, 2015), it is important to measure electrophysiological activity as infants interact socially and thus, further our understanding of how patterns of neural activation differ across various social and non-social contexts. The neural underpinnings of social engagement during infancy, however, are not well understood in naturalistic settings and for that reason, the current research aimed to observe oscillatory electrophysiological activity of 6-month-old infants during spontaneous free-play with their mother. With this information, we can then begin to disentangle the neural bases of these engagements.

The rapid emergence of modern brain imaging techniques have enabled the literature to appreciate the remarkable plasticity of the developing brain, particularly during the first postnatal year. Experience and exposure are considered to determine, to a large degree, which synaptic connections persist and are strengthened by frequent use, or selectively eliminated as a result of inactivity (Singer, 1995; Huttenlocher, 2002). In this context, there is a substantial window for environmental input to influence the developing brain (Fox et al., 2010; Kolb et al., 2012). Observations suggest early caregiving interactions are centrally implicated in the neural development of infants and children (Nelson, 2000; Cicchetti, 2002; Belsky and de Haan, 2011; Aktar et al., 2019); making it a key developmental phase in the potential transmission of psychopathology between generations.

1.1 Parent-Child Interactions

It is agreed that one of the earliest, most intense and enduring experiences of both infancy and childhood is the parent-infant caregiving relationship, and the associated interactions that take place within it: a prime candidate to account for those individual differences in brain development driven by the environment. Decades of empirical research have provided overwhelming support for the classic notion that early parent-infant interactions

exert an exceptional influence on development; illustrated through longitudinal explorations from infancy to early adulthood (e.g., Fraley, Roisman, and Haltigan, 2013), meta-analytic reviews (e.g., Pallini et al., 2014), and experimental studies (e.g., Kochanska, Kim, Boldt, and Nordling, 2013; Guttentag et al., 2014). Psychopathology-related behaviour in early interactions may hamper the parent's ability to provide the optimal affective environment for infants' emotional development. With infants displaying high sensitivity to parental affective input in the first postnatal year, Bernier, Calkins and Bell (2016) argue that environmental factors, such as a stressful life event, or exposure to maternal mental illness, have the power to impact neural development because they are likely to influence the overall quality of parent-child interactions, which in turn are presumed to be the key factor influencing neural development.

1.2 The Neural Basis of Parent-Child Interactions

Baseline measures of neural activity are widely used with infant populations, but less research has explored the associated neural activity while infants are engaged in spontaneous free-play social interactions. The infant literature has suggested that during live interactions, fluctuations in prefrontal cortex activity (measured using functional near-infrared spectroscopy; fNIRS) in 9-15-month-old infants were observed in response to child-directed speech (Piazza et al., 2020) and neural activation in the inferior frontal, anterior temporal, and temporo-parietal regions in response to infant-directed speech and direct gaze have also been noted (Lloyd-Fox et al., 2015). These are factors known to be involved in processing auditory and visual aspects of social communication. Given the lack of directly related research in this area, adult studies can help to inform which neural correlates may be important during infant social interactions. Adult neural activation measured with EEG demonstrates the involvement of frontal, temporal, and parietal regions during joint attention (Lachat et al., 2012; Redcay et al., 2012; Williams et al., 2005). Here we define joint attention as "*the ability to coordinate attention with a social partner*" (see Mundy and Newell, 2007, page 269). Frontal regions are involved in orienting and shifts of attention (Petersen and Posner, 2012), suggesting that frontal activation may also be important for joint attention. Temporal regions are involved in facial processing, including the direction of another individual's gaze (Emery, 2000);

indicating temporal regions could be involved in face-to-face social interaction in general, and in joint attention specifically. Parietal regions are involved in orienting spatial attention and gaze following (Emery, 2000; Petersen and Posner, 2012); suggesting that parietal activation could be required for joint attention as opposed to other forms of social engagement. This prior literature suggests the likely involvement of frontal, temporal, and parietal regions in infant social engagement.

EEG recordings can be decomposed into different frequency bands, associated with different functional correlates of perception or cognition. There is evidence that both theta (~4 to ~6Hz) and alpha (~6 to ~9Hz) bands may be sensitive to aspects of the infant socially adept brain. Theta is thought to support species-relevant behaviours (Orekhova et al., 2006), whereby in human infants, greater theta power is observed during social interactions and exploratory activity (Jones et al., 2015). For example, theta power increases when 5-month-old infants look at a face with a neutral expression versus a smiling face during a period of interaction (Bazhenova et al., 2007) and in response to child-directed speech and toy play (Orekhova et al., 2006). It would therefore be hypothesised that greater theta activity would be observed during periods when the mother was speaking directly to the infant, or while the infant was playing with a toy; supported by Jones et al. (2015). Activity in the alpha band is commonly interpreted as an 'idling' cortical rhythm (Klimesch et al., 2007), with suppression equating to increased processing in specific brain regions. Klimesch et al. (2007) proposed alpha suppression may reflect the release of inhibitory mechanisms for non-essential activity. In congruence, making eye contact with an adult before jointly viewing a toy has been shown to produce alpha suppression in 9-month-old infants, whereas viewing a toy in the absence of eye contact does not (Hoehl, Michel, Reid, Parise & Striano, 2014). It would therefore be hypothesised that during social interactions, reduced alpha power would be observed. However, during independent play increased alpha may be found. Activity in the theta and alpha frequency bands are therefore sensitive to core dimensions of social processing in infancy.

1.3 Maternal Factors that may influence interactional abilities.

Previous research suggests there are emerging differences in infant EEG power across various social contexts (St John et al., 2016); however, the specific role of environmental inputs, such as face-to-face interaction and language, have not been operationalised in a fully naturalistic setting. Once we are able to understand the neural basis of social interactions and non-social behaviours, we are then able to study the influence parents have on neural development, whether this be adaptative or maladaptive.

Research exploring social-emotional development suggests that maternal sensitivity serves as a model for the child's emotional and social development (Mcelwain and Booth-LaForce, 2006). Thus, infants born to mothers with personality traits classed as a predisposition to mental illness, such as schizotypy, not only inherit a predisposing genetic vulnerability, but may also be exposed to socio-emotional environments marked by alterations in parents' emotional expressions (Eley et al., 2015; Nivard et al., 2015). Schizotypy is defined as a set of personality traits resembling the symptoms of psychosis in an attenuated, subclinical form (Ettinger et al., 2014), that represent underlying vulnerabilities to schizophrenia-spectrum psychopathology, expressed across a broad range of personality, sub-clinical, and clinical phenomenology (Kwapil and Barrantes-Vidal, 2014; Smith et al., 2019). Despite the significant hereditary predisposition surrounding mental illness, children with parents who display predispositions to mental illness do not always develop mental health issues themselves (Aktar & Bogels, 2017) as the development of said predispositions are related to the separate and joint effects of inherited genetic vulnerabilities for psychopathology and associated environmental influences (Aktar et al., 2019). Repeated exposure to a parent's 'negative mood' or reduced interactional stimulation could be described as a contributory mechanism for the development of psychopathology later in life (see Schmid et al., 2011, for example); supplying a continuous trajectory of deficient early maternal interactional behaviours on the mental health of the child (Aktar & Bogels, 2017). This poses the question as to whether parents at-risk for mental health disorders and their offspring, display altered interactional styles in comparison to the general population.

One of the social interactions examined in the present study was *mind-mindedness* (MM), defined as “*the caregiver’s ability to read the child’s behaviour with reference to the likely internal states that might be governing that specific action*” (Meins and Fernyhough, 2015, page 2). It has been operationalized in terms of the caregiver’s tendency to, (a), describe their infants with reference to mentality characteristics (Meins et al., 1998), (b) attribute meaning to infants’ early utterances (Meins, 1998), or (c) to comment appropriately on their infant’s internal states during play interactions (Meins et al., 2001). This reflects the importance of the mother responding in an appropriate manner to the child’s cues, and the caregiver’s tendency to treat the infant as an individual with their own mind, rather than an entity with means that must be satisfied (Meins, 1997). Its inclusion in the present research sought to explore the influence of schizotypic maternal traits on naturalistic interactions; whereby these abilities may be altered as a result of atypical maternal interactions.

1.4 Implications of the Present Research

Despite the importance of social interaction, to our knowledge the present study is the first to observe EEG oscillations during spontaneous, unconstrained free-play interactions between a mother-infant dyad. Recently, a publication by Nguyen and colleagues (2020a) voiced the shared concern regarding how naturalistic interactions should be in a laboratory setting. The existing literature is largely composed of constrained ‘free-play’ paradigms, that question the realism of the scenarios. These controlled-interaction paradigms offer advantages in terms of reduced movement artefacts and balanced behavioural events, but a series of recent experiments take a more naturalistic approach (see Nguyen et al., 2020b for a puzzle-based task, and Leong & Schilbach, 2019, for a novel object exploratory task). It is important for the advancement of the field of developmental cognitive neuroscience to determine the efficacy of whether wholly naturalistically EEG can be used to explore infant social interactions and non-social behaviours; allowing greater variance in parent-infant interactions on the behavioural level, and electrophysiological characteristics of the interaction on a neural level (Markova et al., 2019; Nguyen et al., 2020a). This would begin to elucidate the neural bases of social engagement during infancy. The present research asks the question of how

much insight are we able to gain by taking an utterly unconstrained interaction approach? The current research therefore aimed to address two main questions, the first of which asks: what neural oscillatory patterns are observed in 6-month-old infants during social interactions vs. non-social behaviours?

The second aim poses the question: do infants of mothers with schizotypy display altered neural frequencies when compared to infants of mothers without schizotypy (which we will define as controls for the remaining manuscript)? A naturalistic approach allows the examination of neural activity in response to interactions and developmental environments spontaneously created by atypical parenting styles; exposure to which has the potential to result in long-term effects on neural development (Bick et al., 2019; Smith et al. 2020).

2.0 Method

2.1 Participants

101 infants aged 6-months-old (M age =5.80 months; SD =9.23 days; Range=5.42-6.50 months; 47 female; all white-Caucasian) participated in the study. 65 infants (M age= 5.97 months, SD = 8.71 days; 21 female) were included in the final analysis following data editing, with participants excluded due to technical difficulties (n =6), the use of a foreign language during interactions (n =2), interactions with a second parent during the 5-minute session (n =4), less than 5-minutes of EEG recorded (n =5), no data collected due to infant fussiness (n =4), and infants who provided significant amounts of motion-artifact-filled data (n =15); for example, blink, jaw and movement artifacts. This level of participant exclusion is not atypical for naturalistic EEG paradigms with young infant participants (see Jones et al., 2015 and Stets et al., 2012). The present research focused on 6-month-old infants based on research by de Haan et al. (2004), which concluded that variations in maternal disposition altered the emotional environment experienced by infants. This, in turn, contributed to an altered event-related potential response to facial expressions in their study. Differences in EEG activation were also observed between 3-6 months old by Diego et al. (2006) as a consequence of maternal interaction styles (intrusive/withdrawn).

Recruitment was carried out using the Lancaster University Department of Infant and Child Development infant database. Ethical approval for this research was obtained and complied with Lancaster University's Ethics Board Guidelines and the North West – Lancaster Research Ethics Committee for the NHS.

2.2 Procedure

Prior to participation, the caregiver completed a questionnaire measuring their schizotypy dimensionality: the sO-LIFE (Mason, Linney and Claridge, 2005), which was used to divide the cohort (see Section 2.3 for more details). The EGI EEG cap was soaked in a warm water, sodium chloride solution with baby shampoo before fitting to the infant's head. Once fitted and following confirmation that each electrode responded to electrical

activity with all electrodes displaying less than $1k\Omega$ impedance, suggesting the electrodes were showing sufficient performance - the caregiver and infant were given a number of age-appropriate toys and were left to play for a 5-minute period. The caregiver-infant dyad was located on a playmat on the floor, with the infant either sat on the floor or in a supportive ring. They were asked to play in a way that would not produce excessive motion, but they were still allowed to move in order to maintain the infant's attention throughout. The caregiver was given the instruction to '*Please play with your baby as you would if you had some free-time together at home*'. During this time, the mother-infant dyad's status was video and voice-recorded, and the infant's EEG activity recorded, allowing for the video and EEG data to be synchronised and time-coded offline. The current EGI system was on wheels, enabling it to be moved to a central location in the testing room behind the infant. The EEG lab, in which the paradigm took place, incorporates a partially shielded environment.

Prior to data analysis, the video recordings were time-coded for the content of each second of behaviour. The behaviours coded for were divided into social and non-social components, with social behaviours including (a) a mind-related comment made by the parent (*MM*), (b) the mother speaking directly to the infant (*SPOK*), and (c) a dyadic interaction between the mother and the infant (*DYD*), defined as clear eye-to-eye contact. Non-social behaviour included, (a) the infant playing independently with a toy (*PLAY*), with no presence of the mother or the mother's hands, with only the toy within the infant's immediate gaze, or (b) the infant independently looking at objects in the room (*BASE*). These behavioural events, and the way in which they were coded are outlined in the Supplementary Materials (Smith & Elliott, 2020). The 5-minute audio and visual recording was taken during the testing period and transcribed into written form so observations could be made after the testing session was completed. The recordings were behaviourally coded second-by-second for the full 5-minute EEG recording. Each event type was identified using both the visual and auditory behaviours transcribed and observed. For example, the mother-infant dyads making direct eye-contact for the majority of the coding second would have been transcribed as a *DYADIC* interaction, whereas the infant playing with a toy independently of their mother would have been

identified as infant *PLAY*. The EEG data was epoched based on the behavioural event coding, with events added to the data using NetStation (4.5.4). 20% of video recordings were coded by a second independent coder to assess the inter-rater reliability, with a simplified coding scheme that included “SPOK”, “PLAY”, and those events that were not analogous with the above mentioned behavioural events (labelled as “NONE”), producing a mean Cohen Kappa of 0.67 ($SD=0.23$) across the subsample. When looking at the categories individually, by repeatedly recoding the categories in a one-against-all approach; comparing one label against the remaining two grouped together, the labelling of the *PLAY* event had the lowest average inter-rater reliability across participants ($M=0.42$; $SD=0.33$), with *SPOK* ($M=0.65$; $SD=0.29$) and *NONE* ($M=0.62$; $SD=0.22$) having similar Cohen Kappa scores. This highlights the comparative difficulty of defining an epoch as containing play.

2.3 Questionnaires

The sO-LIFE (Mason, Linney & Claridge, 2005) assessed schizotypy dimensionality and divided the participant cohort into infants of schizotypic mothers (iSZTm) and infants of control mothers (iCONm). The mean across the population was calculated (total $M=8.15$, total $SD=6.26$). The iSZTm condition was determined by the $M+.5SD$ (sO-LIFE Scores >11.28) and the iCONm condition by the $M-.5SD$ (sO-LIFE Scores <5.02). 19 infants were identified as infants of schizotypic mothers (iSZTm; $M\ age= 5.88$ months, $SD= 9.53$ days; 6 female) and 31 as infants of control mothers (iCONm; $M\ age= 5.89$ months, $SD= 8.03$ days; 21 female). The remaining 15 infants were categorized as not having a group as their Oxford-Liverpool Inventory of Feelings and Experiences – Short Form (sO-LIFE) scores failed to identify with either of the iSZTm or iCONm. This criterion was used as a result of its previous use in the schizotypy literature (for example, in Park, Lim, Kirk & Waldie, 2015; Smith et al., 2020).

The sO-LIFE was chosen as the measure of schizotypy dimensionality due to its fully dimensional approach. The reliability of the sO-LIFE, estimated with ordinal alpha, was disclosed to be above 0.78 (Fonseca-Pedrero et al., 2014). The Cronbach’s alpha in the present cohort was 0.79, demonstrating the consistent reliability measure of the sO-LIFE.

These levels of internal consistency are in line with the internal consistency values reported in previous studies (Lin et al., 2013a, 2013b).

2.4 EEG Analysis

EEG data was recorded with 124 Ag–AgCl electrodes in a HydroCel EGI Geodesic Sensor Net, referenced to the vertex (Cz) and arranged in the 10-20 layout, and an EGI GES 300 amplifier with an online 500Hz Butterworth software filter applied. Raw txt files were extracted from NetStation (4.5.4); with data preparation conducted using Google Colab running Python (3.6.9). To see the scripts used for all elements of analysis, see Smith & Elliott (2020). The event codes were synchronized to the EEG data, to the nearest second, with analysis only focusing on portions of the data coded for its content. MNE-Python (0.20.5; Gramfort et al., 2014) was firstly used to visualise the data to manually identify ‘bad’ channels, which produced drifts in the raw signal and high, variable decibel values across the frequency range in power spectral density plots. This variability describes substantial changes in power across the frequency ranges, which are differentiated from the other channels, indicating ill-fitting electrodes or high degree of artefact. These channels were identified as ‘bad’ by manually observing large quantities of blink, jaw, or motion artifacts. One-second epochs of behaviourally coded EEG data were rejected if the root mean square of the EEG voltage exceeded $175\mu\text{V}$ in more than 20 channels (John et al., 2016). In each participant, data associated with a behavioural code that had less than 3 occurrences were removed. These procedures lead to 7188 seconds (36.87%) of epoched data being coded as artefactual and 50 seconds (0.26%) being removed due to being under the occurrence threshold. 7312 seconds (37.50%) were coded as *SPOK*, 1839 seconds (9.43%) as *PLAY*, 471 seconds (2.42%) as *DYADIC*, 267 seconds (1.37%) as *BASE*, 206 seconds (1.06%) as *MM*, and 2165 seconds were not given a behavioural code (*NONE*; 11.10%).

Data was down sampled to 125Hz to allow for a continuous wavelet transformation, using a Daubechies 4 (db4) wavelet family, to decompose the spectral components of the entire EEG signal into the frequency bands, described in Table 1. These bands were chosen to reflect typical frequencies of interest in EEG, with down-sampling ensuring the

lower bands had less boundary coefficients at the start and end of the signal. Wavelets decompose data on a multi-scale basis (frequency and time) by projecting multiple oscillatory kernel-based waves and enable frequency components to be analysed in respect to their scale (Kiyimik et al., 2005; Sakkalis et al., 2008; Sakkalis, Zervakis, and Micheloyannis, 2006). Wavelets give accurate results with data containing discontinuities and sharp spikes (Kiyimik et al., 2005) and can be used to analyse time series with non-stationary power at different frequency bands (Sakkalis et al., 2006). The db4 wavelet is specifically used to smooth the frequency, filtering enough to characterise EEG data well, but is also computationally efficient (Kjær et al., 2017; Subasi, 2007). The resulting detail coefficients from the wavelet transform were squared to give an estimate of the periodogram/spectrum.

A Tukey Fence (Tukey, 1977) threshold with parameter 1.5 was applied to the spectral data in each frequency band for each participant to remove outlier values resulting from artefacts (see Tukey, 1977 or Quitadamo et al., 2018, for example). The channels on the edges of the cap were most commonly rejected across participants for containing artefacts. These were consequently removed from all participants. See Supplementary Figure 1 for topographical plots showing the influence channel removal had on the frequencies observed across the entire scalp. Remaining channels were assigned a hemispheric channel region depending on the location on the scalp; these being frontal, central, temporal, or parietal (See Figure 1). Attempts were made to ensure each group had a similar number of channels, whilst still reflecting the scalp topography.

Linear Mixed Models (LMMs; Gałecki and Burzykowski, 2013) were used to model the average spectral power over epochs as a linear combination of fixed and random effects. A linear mixed model (or random effect model) is a combination of a linear regression model with random effects. The linear model predicts the i^{th} participants' power at electrode j using explanatory variables e.g., Frequency. As we have several epochs for each participant and several participants, we need to account for the fact that different participants may have different baseline EEG. Thus, we introduced a 'random effect'

term to give separate intercepts for each participant. This helps to account for the inherent differences between individuals.

Table 1. Frequency Bands used in the analysis.

Decomposition level	Frequency Range (Hz)	Associated Frequency Band
D1	31.25 - 62.5	Gamma
D2	15.63 - 31.25	Beta
D3	7.81 - 15.63	Alpha
D4	3.91 - 7.81	Theta
A4	<3.91	Delta/DC

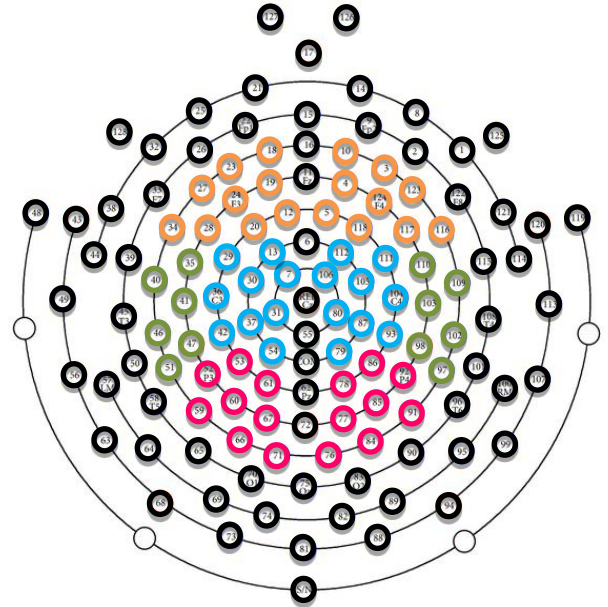


Figure 1. Channel locations used in the analysis. Black: Excluded; Orange: Frontal; Blue: Central; Green: Temporal; Pink: Parietal

A model including Frequency as a covariate would be:

$$\text{Power}_{ij} = (b_0 + u_i) + b_1 \text{Frequency}_{ij} + \epsilon_{ij}$$

Here the component u_i is a participant specific component of the intercept, with $(b_0 + u_{0j})$ therefore the overall intercept for each person.

This model can be extended to include further explanatory variables. In the present study, we consider the following explanatory variables: frequency band, electrode location, the behavioural event, schizotypy maternal group, and gender. The order of the levels within a variable, as well as the type of variable, affects the outcome of a model. Frequency band was treated as a categorical variable representing the Gamma (Baseline), Beta, Alpha and Theta bands. Similarly, electrodes were categorized as left and right, central, frontal, parietal and temporal with left central used as the baseline. Behavioural events were categorical with *BASE* (baseline), *NONE*, *PLAY*, *SPOK*, and *MM*. Group was also

categorical with levels iCONm (baseline), iSZTm, and no group. Different methods can be used to find the variables that contribute to the most statistically appropriate model. We used stepwise backward elimination of predictors based on AIC (Hayashi et al., 2019). Higher-order interaction effects are then considered, again with inclusion based on stepwise AIC.

3.0 Results

All data analysis was conducted using R (3.6.3; R Core Team, 2020), with the lme4 (1.1-21; Bates, Mächler, Bolker, and Walker, 2015) statistical package. We first selected the best model for the fixed effects and then tested for significance of our random effect for participants. Due to the heterogeneity in the variance of the residuals in our first model, we log-transformed the spectral power to ensure that subsequent models were appropriate. We observed the residuals from one participant – P49 - were clear outliers and their epochs had very high leverage, thus, data from this participant was removed from further analysis (see Figure S2). Both the Gender and Group variables were not found to be significant and were removed from the model. All other fixed effects were found to significantly improve the model. The two-way interactions between Behavioural events and Frequency band, as well as between Frequency band and Channel location also significantly improved the model. Models with random slopes did not significantly improve the fit of the model and hampered its interpretability, so these were not included in the final model. The final model for log-spectral power, including the fixed effects, interactions, and a random intercept by participants, was then fit with Restricted Maximum Likelihood Estimation to estimate variance components and confidence intervals (Fahoum et al., 2012).

The values of the fitted model are described in Table 2 and show a significant relationship between the log spectral power and the Event indicating that when all events (*DYADIC*, *NONE*, *PLAY*, *SPOK*, *MM*) are observed, the log spectral power is likely to be higher than *BASE*; *DYADIC* and *NONE* showing the greatest difference from baseline (0.08) and *PLAY* the lowest (0.05), all else held constant. However, as demonstrated in the confidence intervals (see Table 2), all events apart from *BASE* overlap. The

confidence intervals for the parameter estimates represent the standard linear model confidence intervals (as given by `confint()` in R), and are calculated using a Normal distribution assumption. For the frequency band covariate, the difference from Gamma in log spectral power for each frequency band increases as the frequency bands decrease from Beta (0.06) to Alpha (1.16) and Theta (2.84). For the Electrode Location coefficients, we observe that all locations are different from Left-Central channels apart from the Right-Central location. There is a symmetry in the coefficients for the left and right electrode regions, indicating that oscillatory activity is occurring bihemispherically, but differences are observed between the different regions [0.0] central → frontal → parietal → [0.0] we see an increase in log spectral power. It is unclear whether there is a clear distinction between the activation of frontal and parietal regions from each other, but both the central and temporal regions display distinct differences; less oscillatory activity observed centrally whilst greater power is observed temporally.

The interactions between the behavioural events and frequency bands all significantly decrease in their log power estimates comparative to the intercept (gamma band at baseline), except during the Mind-Minded events where significance is not reached. It is worth noting that although significant, this decrease is only comparatively small. Furthermore, this particular condition had very few datapoints when contrasted with the other events. Generally, the significant deviations of the frequency band*electrode location interactions increase in log spectral power comparative to the intercept (gamma band*left-central location); bar the alpha (-0.09) and theta (-0.14) band in the right-frontal locations, as well as the theta (-0.06) band in the right-temporal locations, where they decrease in log spectral power. Of those that do not significantly change, unsurprisingly this includes all frequencies in the right-central regions, but also in the alpha and theta bands in the left-frontal and left-temporal regions, and exclusively in the alpha band in the right-temporal location.

For data of this scale (47,808 datapoints) a p-value test is not appropriate as almost any effect is significant. To gauge an idea as to whether the variables were significant as an independent consequence of the sample size, the data was randomly sampled in sizes

from 1,000 to 47,000 each time fitting the final model and considering the confidence interval for each variable (Van der Leeden, Meijer, and Busing, 2008). Plots are available in the Supplementary Material and demonstrate that the effects seen here are not due to the large sample size.

In summary, the primary finding of the present research illustrated firstly that there is a broad increase in oscillatory activity both when an infant played independently (*PLAY*) or interacted with their maternal figure (*DYADIC*, *SPOK*, *MM*) comparative to when the infant was not exposed to any form of interaction (*BASE*). Whilst not reaching statistical significance, due to overlapping confidence intervals (see Table 2), the *PLAY* event implied a reduced increase in oscillatory activity when contrasted with events that contained social interactions. As hypothesised, as frequency bands approached alpha and theta, oscillatory power statistically increased. In the present 6-month-old cohort, no hemispheric power differences were observed. Instead, differences appear between the different neural regions: frontal and parietal regions bihemispherically displayed similar estimates, which were larger than those observed centrally, whilst temporal estimates were larger and discrete from all regions. As the regions of interest move out from the vertex of the head, power generally appears to significantly increase.

The interactions observed between the behavioural events and frequency bands demonstrate a significant reduction in power, albeit a small change, comparative to the power observed in the gamma band during the baseline event. Lastly, the interactions between the frequency bands and electrode locations uncover an increase in power comparative to that seen in the gamma band in the left-central region (employed as the Intercept), but not with significance throughout. See Figure 2 for a graphical representation of these effects.

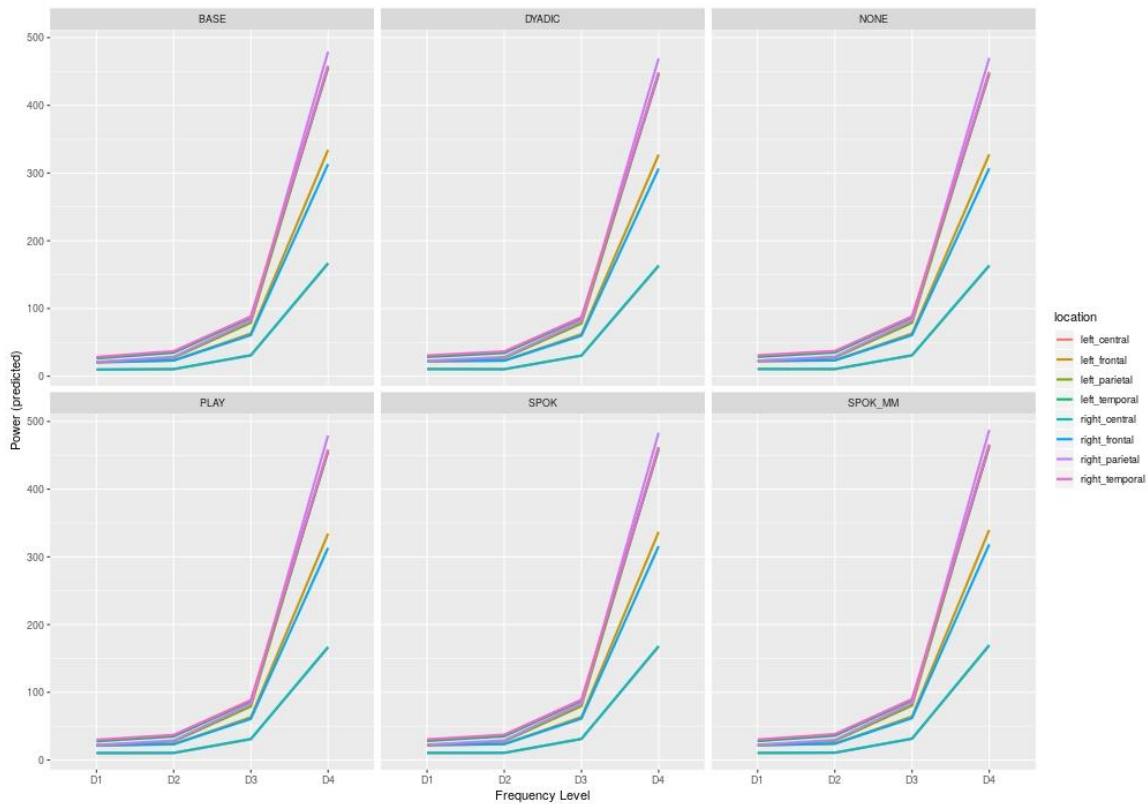


Figure 2. Power estimates for different events, in different frequency bands, at different electrode locations. D1= Gamma (31.25-62.5); D2=Beta (15.63-31.25); D3=Alpha (7.81-15.63); D4=Theta (3.91-7.81). Note. The differences can be clearly seen between different channel locations across frequency. Differences between events although significant are more subtle. There were no differences found between left and right hemispheric activity.

Table 2. Values of the Linear Mixed Model. Bold and * indicates significance to the 0.05 level.

	2.5% CI		97.5% CI	Estimate	Standard Error	t value
	(Intercept)	2.15	2.39	2.27	0.06	36.13*
Event	DYADIC	0.05	0.11	0.08	0.02	4.83*
	NONE	0.05	0.12	0.08	0.02	5.30*
	PLAY	0.02	0.08	0.05	0.02	3.24*
	SPOK	0.04	0.10	0.07	0.02	4.48*
	MM	0.03	0.10	0.06	0.02	3.69*
Frequency Band	Beta	0.01	0.10	0.06	0.02	2.41*
	Alpha	1.11	1.20	1.16	0.02	50.18*
	Theta	2.80	2.89	2.84	0.02	123.29*
Electrode Location	Left-Frontal	0.70	0.76	0.73	0.02	42.76*
	Left-Parietal	0.72	0.79	0.76	0.02	42.76*

	Left-Temporal	0.96	1.04	1.00	0.02	52.43*
	Right-Central	-0.02	0.05	0.01	0.02	0.77
	Right-Frontal	0.74	0.81	0.77	0.02	44.85*
	Right-Parietal	0.74	0.81	0.78	0.02	43.85*
	Right-Temporal	1.04	1.11	1.08	0.02	56.13*
	DYADIC*Beta	-0.13	-0.05	-0.09	0.02	-3.97*
	NONE*Beta	-0.12	-0.03	-0.08	0.02	-3.44*
	PLAY* Beta	-0.09	0.00	-0.05	0.02	-2.15*
	SPOK*Beta	-0.10	-0.02	-0.06	0.02	-2.69*
	MM*Beta	-0.08	0.02	-0.03	0.02	-1.21
	DYADIC*Alpha	-0.14	-0.05	-0.09	0.02	-4.05*
	NONE* Alpha	-0.13	-0.04	-0.08	0.02	-3.79*
	PLAY* Alpha	-0.09	-0.01	-0.05	0.02	-2.19*
	SPOK* Alpha	-0.11	-0.02	-0.06	0.02	-2.77*
	MM* Alpha	-0.09	0.00	-0.05	0.02	-1.85
	DYADIC*Theta	-0.14	-0.05	-0.10	0.02	-4.36*
	NONE* Theta	-0.15	-0.06	-0.10	0.02	-4.64*
	PLAY* Theta	-0.10	-0.01	-0.05	0.02	-2.29*
	SPOK* Theta	-0.11	-0.02	-0.06	0.02	-2.81*
	MM* Theta	-0.10	0.00	-0.05	0.02	-1.94
	Beta*Left-Frontal	0.04	0.13	0.09	0.02	3.61*
	Alpha*Left-Frontal	-0.06	0.03	-0.01	0.02	-0.59
	Theta*Left-Frontal	-0.08	0.02	-0.03	0.02	-1.33
	Beta*Left-Parietal	0.17	0.27	0.22	0.03	8.82*
	Alpha*Left-Parietal	0.13	0.23	0.18	0.03	7.30*
	Theta*Left-Parietal	0.21	0.30	0.26	0.03	10.19*
	Beta*Left-Temporal	0.17	0.27	0.22	0.03	8.25*
	Alpha*Left-Temporal	-0.02	0.09	0.03	0.03	1.26
	Theta*Left-Temporal	-0.04	0.06	0.01	0.03	0.32
	Beta*Right-Central	-0.03	0.07	0.02	0.02	0.81
	Alpha*Right-Central	-0.06	0.04	-0.01	0.02	-0.32
	Theta*Right-Central	-0.06	0.04	-0.01	0.02	-0.36
	Beta*Right-Frontal	0.00	0.10	0.05	0.02	2.06*
	Alpha*Right-Frontal	-0.14	-0.05	-0.09	0.02	-3.87*
	Theta*Right-Frontal	-0.19	-0.09	-0.14	0.02	-5.71*
	Beta*Right-Parietal	0.20	0.30	0.25	0.03	9.99*
	Alpha*Right-Parietal	0.16	0.26	0.21	0.03	8.29*
	Theta*Right-Parietal	0.23	0.33	0.28	0.03	11.14*
	Beta*Right-Temporal	0.16	0.26	0.21	0.03	7.69*
	Alpha*Right-Temporal	-0.08	0.03	-0.02	0.03	-0.83
	Theta*Right-Temporal	-0.12	-0.01	-0.06	0.03	-2.31*

4.0 Discussion

The present research sought to explore the inverse obstacle of artificial play paradigms whereby researchers question how much these paradigms relate to reality; causing us to ask the question of how much insight are we able to gain by taking an unconstrained interaction approach? The limitations surrounding spontaneous EEG are outlined across the literature (Georgieva et al., 2020; Nguyen et al., 2020a, for example). Perhaps, resulting from these limitations, it is possible to conclude that despite the aim of comprehending parent-infant interactions in naturalistic settings, some constraints are beneficial from an analysis point of view. Thus, a compromise – allowing the parent-infant dyad to interact freely, but constrained within a task (for example, Nguyen et al., 2020b; Quiñones-Camacho et al., 2019) – may be a preferable and more advantageous method of naturalistically observing dyad interactions.

The present research aimed to address two main questions: 1) What neural oscillatory patterns are observed in 6-month-old infants during social interactions vs. non-social behaviours? 2) Do infants of mothers with schizotypy display altered neural frequencies when compared to controls? In response to the primary objective, an increase in oscillatory activity was observed when an infant interacted with their maternal figure: during speech interactions, dyadic eye gaze, through mind-minded comments made by the mother (*DYADIC*, *SPOK*, *MM*), or when the infant played independently (*PLAY*), in contrast to the baseline measure. As the interaction between frequency bands and activity approached the Alpha and Theta bands, oscillatory power statistically increased, which supports prior literature indicating that these frequency bands play a role in attention and social coordination during interactions (Crespo-Llado et al., 2018; Meyer et al., 2019). No hemispheric power differences were observed as oscillatory power in the corresponding neural regions (i.e. left and right temporal regions) appeared to mirror each other. Instead, we observed that temporal estimates were larger and discrete from all regions, and that frontal and parietal regions bihemispherically displayed similar estimates, which were larger than those observed centrally. This should be viewed in context that the EEG was collected using a vertex recording reference with no averaging re-referencing applied. Indeed, amplitudes of recordings are expected to be attenuated

according to distance from the reference site (Dien, 1998). With respect to the secondary aim of the present research, the model did not observe significant differences between those infants of a schizotypic mother and those infants of a mother without schizotypy, thus no further discussion of this aim will be provided, but why this lack of significance was observed will be explored in Section 4.3.

To our knowledge, no research has taken a completely naturalistically derived approach to comparing EEG power for social interactive elements vs. non-social behaviours. A major limitation of much of the literature are the experimental constraints put on parent-infant dyads during ‘free-play’ paradigms; thus, the present research aimed to wholly remove these constraints, but in doing so encountered its own series of limitations. Before we discuss the limitations of spontaneous EEG, a strength of the present study, and a strength that should be carried forward in this field, is the use of multiple electrode channel groupings, such as the 32-electrode montage used by Georgieva et al. (2020). This approach contrasts the most similar methodological research (interpersonal neural synchronisation; for example, Leong et al., 2017) who previously predominantly focused on two EEG channels in central locations (for example, C3 and C4 in Leong et al., 2017), whereby it is difficult to make inferences about the topographical generalisability of effects. Although the present research should be interpreted with caution, from a methodological standpoint, the use of electrode channel grouping that are relatively balanced in number on both the left and right hemispheres forms a good basis from which future free-play paradigms can be developed.

4.1 Limitations of Spontaneous EEG

A recent publication by Nguyen and colleagues (2020a) voices the shared concern among all those who explore parent-infant interactions: “*to what degree should the observed interaction be naturalistic and unconstrained versus controlled?*” (Nguyen et al., 2020a, page 13). It is clear that highly controlled interactions offer advantages in terms of reduced movement artefacts, which are particularly important when exploring electrophysiological activity. Conversely, unconstrained and naturally/spontaneously derived interactions visibly generate greater ecological validity but allow for more

variance in the parent-infant interactions on the behavioural level, which can yield incomparable information regarding the behavioural and electrophysiological characteristics of the interaction (Markova et al., 2019; Nguyen et al., 2020a), but with numerous complexities in terms of the associated analyses. In the present naturalistic interaction setting, it is plausible to suggest that the social behaviours would involve more movement than the given baseline condition – generating more broadband oscillatory activity. This is a large disadvantage of spontaneous EEG; however, the present research does support prior literature and hypotheses – relating to both increased and decreased oscillatory activity. This provides support for the differences in the present dataset being due to underlying oscillatory brain activity rather than artefactual noise.

With reference to these complexities experienced in the current research, a series of artificial constraints were met, which resulted from a relatively restricted *baseline* period used comparatively with the categorised behavioural events. The current paradigm was recorded live with no constraints in the behavioural variance exhibited by each dyad; thus, the *baseline* period was identified when the infant sat independently with no interaction with their mother or toys in the room. This was experienced in the smallest quantity of seconds of all the coded behaviours; only being identified 0.54% of the time. With hindsight, and for future research, ensuring an adequate baseline period would be crucial to balance the number of behavioural classifications and comparisons made. Perhaps future unconstrained free-play explorations could incorporate an extended baseline period, whether this is defined as having the infant play independently for a period of time, a period of time where the mother is not playing in the same room as their infant or include a more constrained period of stable play to use as a comparative baseline. As stated previously, the present research found differences between the behavioural events explored and the existing baseline, but for future developments, a superior experimental design should incorporate the opportunity to increase the baseline number of epochs.

In addition to the restricted baseline period, post hoc it was acknowledged that the infants were exposed to some behavioural events in vastly larger quantities than others. For example, 37.5% of the overall data collected were coded as the mother speaking to the

infant, whereas only 1.06% as the mother speaking in a mind-minded way toward the child. As a consequence, it is difficult to make direct comparisons when the relative epochs available differ so largely. Similar to the concerns highlighted regarding the baseline period, future naturalistic free play paradigms would benefit from design elements that would increase the opportunity to initiate these less frequent behavioural events. As such, the data presented focuses primarily on those recurrent behavioural epochs.

The estimates shown in Table 2 display how as frequency moves down from the Gamma to Theta range, and channel region moves outward from the center of the head, power appears to significantly increase: there are a few prospective explanations of why this may be the case. From a wavelet perspective, assuming measurement error is equally distributed across frequency bands and locations, we would not see such a power increase. Estimates of power are generally less certain as frequency band reduces, due to there being naturally less data available to estimate power from slower frequencies comparative to faster frequency ranges. But as the confidence intervals reported in Table 2 are similar across each frequency band, it is unlikely the effects observed are merely due to error. Alternatively, we can ask how much of the differences observed between the frequency bands are cognitively driven, rather than being generated by the recording methodology themselves? If it were as simple as being a function of the quality of EEG cap fit, for example with this being poorer in the outermost electrodes, then we would expect there to be large artefacts observed across the entire montage. During the pre-processing stages, however, we meticulously removed data containing artefacts. Consequently, the results of the present study support prior literature, demonstrating that increased power in the alpha and theta frequency bands is frequently associated with social interactions (Bazhenova et al., 2007; Orekhova et al., 2006).

4.2 Limitations of Spontaneous EEG Analysis

EEG data collected from infants in the first instance is noisy in nature (see Georgieva et al., 2020, for details on infant movement artefacts). It is well known that during naturalistic interactions, movement generates a variety of different types of muscular and

movement-related artefacts, including gross motor movements and eye blinks (Bell and Cuevas, 2012), in EEG data. Previous research (for example, Georgieva et al., 2018) suggests that these artefacts, in combination, manifest broadband across the scalp; constraining the techniques available to reduce this noise. The difficulty in removing the effects of noise from the data is, in part, due to a lack of standardised specifications in the literature. There are no current norms for a reasonable quantity of data required for infancy frequency analysis, or how many epochs of “artefact free” data would be viewed as reasonable per event category. Infancy work in general encounters greater issues with noisy data when contrasted with adult EEG data (Georgieva et al., 2020) although it is difficult to contrast infant and adult EEG given how the fundamentally different the neurophysiological basis of EEG is between these populations. Infants produce larger amplitude data as a consequence of greater postsynaptic neurophysiology (see e.g., Thierry, 2005) with the consequence that the number of trials for reasonable data is not comparable with adult datasets. A technique often used to reduce the effects of recording/artefact noise on adult data is Independent Components Analysis (see Pontifex et al., 2017 for a discussion on how ICA can affect EEG data), but this often relies on having additional electrodes (e.g. EOG), which are not typically used with infants. ICA also alters the data when decomposing it into a smaller subspace; for which, again the number of components required to carry out this process is lacking reasonable guidelines for infancy research. Further, replication of brain derived data with such methods, where data is convolved in multiple ways, is potentially problematic. There are however methods for future research, such as Icasto (Himberg and Hyvarinen, 2003), which may provide more guidance for dimensionality reduction in neuroimaging research techniques, and ICA classification algorithms (e.g. ICLabel; Pion-Tonachini et al., 2019), which provide automated classification of IC categories and may be suitable for application to infant EEG in the future.

In this work we chose to use mixed models to identify the significant factors that affected average power variations. We chose this approach firstly as there are many possible variables in an unconstrained ‘free-play’ paradigm comparative to experimentally derived paradigms. This therefore presents more complicated clusters of measures that are not as

interpretable in other methods (e.g. ANOVA). Furthermore, these models also allow for intercepts to vary across subjects, with it being a reasonable assumption that different infants have different baseline power values. However, mixed models have assumptions alike to standard regression models, in that the variability of the data should be approximately equal to the deviation of the model's predicated values. In this case, for the lower log power values, the model appears to fit the central values well with more error in the upper and lower tails of the power values observed (see supplementary figures S2 & S3); this suggests the model violates the assumption of normality. However, in general, these models are relatively robust against this violation (Winter, 2013), and we observed that the effects observed in this analysis did not change when varying the large sample size. This repeated observation over different sample sizes also suggests that another limitation to the present research, namely the variability in behavioural condition occurrence (see Section 2.4 for a breakdown of the classifications), has most likely not skewed the outcome of the findings. Behavioural conditions explored were variable in number, as they were coded following the testing session with no control given over the quantity of each behavioural classification for each child. Never-the-less, the average over epochs in each of these behavioural conditions, used for analysis, had to be log-transformed due to the large differences in scale for values causing non-constant variance in the residuals. The variability in behavioural condition still suggests future developments in this field could require bootstrapping and resampling to balance out the classifications more equally. Perhaps upon replication of the current paradigm, the free-play recording could also be lengthened. Rather than 5-minutes long, 10- or 15-minutes would allow for a greater number of behaviours to be coded; which could allow for the repeated bootstrapping of random subsamples of the data to equalise class distributions, whilst still allowing a suitable sample size to endure. Given the unconstrained nature of the social interaction, infants may be capable of complying with a longer session of data acquisition. Furthermore, we believe that the results of the present research should be interpreted carefully and should provide indications for future directions in research rather than provide a clear-cut finding in isolation.

4.3 Reflections on the Primary Results

Advancing from the discussion of the primary results, further issues remain which warrant discussion. Why is it that we observe an increased oscillatory activity when the infant is playing independently or is interacting with their mother in comparison to baseline, where they are not exposed to a behavioural form of interaction? Perhaps this can be answered in accordance with the large behavioural variance described as a strength of naturalistic interactions earlier in the manuscript. Although this can be seen as a strength, when categorising behaviours into events, not one type of behaviour is captured by the said event, instead a large variety of behaviours may be encompassed within that one event. For example, *SPOK* was defined as the mother speaking directly to their infant. This introduces a large quantity of variance into the model as dull tones as well as exciting infant-directed speech will be enveloped under the same behavioural category, which may also provide reason for the overlapping confidence intervals observed in Table 2. Furthermore, why do we observe greater activity in the '*NONE*' category than during baseline? To take this second question into account, *NONE* is the event marker given to all other interactions that did not conform to the specific behavioural events explored; thus, it includes all kinds of interactions, which, in comparison with baseline, exhibits greater oscillatory activity. This is therefore not surprising.

Both the Gender and Group (Maternal schizotypy) variables were not found to be significant and were thus removed from the model. Despite not expecting to observe a gender difference during free play interactions, this did prompt the query of why maternal schizotypy did not influence the infants' oscillatory activity during social interactions and non-social behaviours when prior work has indicated some influence of maternal schizotypy on infant development (Smith et al., 2019, 2020). It may well be that this is tied to the point already addressed, in that the model is not able to capture the variance of behaviour due to the less constrained research environment. Previous literature has proposed the influence of maternal schizotypy to be too subtle to be expressed through group differences (defined through the mean sO-LIFE score $\pm 0.5SD$), but rather rely on dimensional analyses to observe these continuous differences (Smith et al., 2019; Smith et al., 2020). In sum, taking the idea that schizotypic differences are subtle, then it is difficult to capture these developmental differences with this method due to the large

variability, both in terms of the behavioural data and the model. Interpreting this lack of significance in a more developmental manner, Kaitz et al. (2010) argued that increased negative emotional interactions among anxious parents and those with a predisposition to mental illness may not be perceptible during the first 6 postnatal months. Instead, they begin to emerge in the second half of the first postnatal year during triadic interactions; hence, these subtle differences in behaviour may not be visible during everyday mother-infant interactions (Kaitz et al, 2010). Perhaps later in development, an altered oscillatory effect may be observed in response to maternal schizotypy. This is a subject matter that should receive continued interest. Exposure to divergent developmental environments, whether this be resultant from severe mental illness, predisposition to mental illness, or atypical personality traits, and its influence on socio-cognitive neural development, is an area of paramount importance considering its potential termination in atypical neural developmental end-states (Bick et al., 2019; Smith et al. 2020). Nonetheless, future research should consider employing parallel EEG recording from the infant-mother dyad (hyperscanning: see Quiñones-Camacho et al., 2019; Nguyen et al., 2020a; Santamaria et al., 2020 for reference) in order to determine the interpersonal neural network between the dyads and to provide a more sensitive measure of individual differences.

There are multiple effects of note highlighted by the model. For example, why is it that when the frequency bands decrease from Gamma through to Theta, power significantly increases? When exploring the hyperscanning literature it is logical that we see a power increase in Theta and Alpha oscillatory power as these have previously been implicated in attention and social coordination during dyad interactions (Crespo-Llado et al., 2018; Meyer et al., 2019), visual attention, and anticipatory and sustained attention during semi-naturalistic interactions (Wass et al., 2018). We also found that no hemispheric power differences were observed in the infant cohort. Instead, distinctions were observed between the different brain regions; thus, why would we expect to see similar estimates bihemispherically in the frontal and parietal regions, lower estimates in the central region, and higher temporally? In adults, it has been illustrated that in tasks requiring the processing of information involved in social cognition, the temporo-parietal junction is consistently activated during goal-directed interactions (Babiloni and Astolfi et al., 2014),

but also during face-to-face social communication, explored using a hyperscanning EEG system, Dumas et al. (2010) found alpha inter-brain synchronisation in the centroparietal cortex. This was described as a “*neuromarker of social coordination*” (Tognoli et al., 2007). We would expect that when the auditory cortex is stimulated by speech, as in the *SPOK* event in the present research, oscillatory power should increase in the temporal regions (Giraud and Poeppel, 2012). In direct relation to the infant literature, during live interactions, fluctuations in prefrontal cortex activity in 9-15-month-old infants were observed in response to child-directed speech (Piazza et al., 2020), whilst Lloyd-Fox et al. (2015) explored neural activation, measured using functional near-infrared spectroscopy, in response to infant-directed speech and direct gaze. They reported brain activation in inferior frontal, anterior temporal, and temporo-parietal regions; all of which are known to be involved in processing the auditory and visual aspects of social communication. Despite these findings, one should be cautious in interpreting significant increases in infant EEG power, without an entrenched literature with respect to perceptual or cognitive meaning (see Saby and Marshall, 2012, for a discussion on EEG band analyses and how they have been applied to specific lines of developmental research). Future work is therefore required to assist interpretation of infant EEG based on what constitutes a meaningful increase of power according to frequency band.

5.0 Conclusions

The present research aimed to observe the oscillatory activity of 6-month-old infants during free-play social interactions and non-social behaviours with their mother. The primary findings indicated an increase in oscillatory activity occurred both when an infant played independently or interacted with their maternal figure in comparison to the infant independently looking at objects in the room. Greater oscillatory power was observed in the alpha and theta frequencies, and whilst no hemispheric power differences were observed, differences appeared between the different neural regions, with greatest activation observed temporally. Previous literature (Smith et al., 2019; Smith et al., 2020) drove a secondary hypothesis asking whether interactions between mothers exhibiting high-schizotypic traits and their offspring differed in comparison to those with low-schizotypy. In the current study, no such effect was found.

An important element of the current study was to consider the methodological approach and the analytical exploration of the dataset. The present research sought to explore the obstacle of artificial play paradigms whereby researchers question how much these paradigms relate to data from the real world; causing us to ask the question of how much insight are we able to gain by taking an unconstrained interaction approach? Fundamental to this challenge is the fact it is difficult to employ the level of experimental and temporal precision required for exploration at the electrophysiological level, whilst also maintaining the diverse quality which many consider to be a defining feature of play (Neale et al., 2018). Perhaps following the limitations of the unconstrained spontaneous approach taken here, it is possible to conclude that despite the aim of comprehending parent-infant interactions in naturalistic settings, some constraints are beneficial. Thus, a compromise – allowing the parent-infant dyad to interact freely but constrained within a task – may be a preferable and more advantageous method of naturalistically observing dyad interactions in the future.

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Author contributions.

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