

Parental frontal brain activity tracks infants' attention during shared play

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Abstract

Previous research has suggested that similar patterns of neural activity occur between watching someone else perform an action and performing it oneself. Here, we demonstrate a comparable phenomenon: that, while engaged in free-flowing naturalistic parent-child play, parents' oscillatory activity recorded over frontal areas co-varies with their infants' attention patterns, independent of their own attention patterns. We also found weaker evidence for the opposite relationship: that infants' brain activity tracks adults' attention. We demonstrate this by recording dual EEG in 12-month-old infants and their parents while they were engaged in joint and solo tabletop play with toys, and analysing the time-lagged temporal associations between infants' attention towards play objects and adults' neural activity, and *vice versa*. We discuss how these inter-dyadic brain-behaviour correspondences relate to actor-observer relationships previously been documented, and consider their role as drivers of inter-personal neural synchrony.

Keywords: infant, attention, social attention, synchrony

Introduction

Recent animal research has built on previous research with humans, including both adults (Hasson & Frith, 2016; Redcay & Schilbach, 2019) and infants (Leong et al., 2017; Leong et al., 2019; Nguyen, in press; Piazza, Hasenfratz, Hasson, & Lew-Williams, in press; Santamaria et al., 2020; Wass, Whitehorn, Haresign, Phillips, & Leong, 2020), to investigate whether synchronous patterns of neural activity are observed between socially interacting animals (Kingsbury et al., 2019). Their results suggest that inter-individual neural synchrony is observed even under conditions where behavioural synchrony and shared entrainment to external sensory input are tightly controlled (Kingsbury et al., 2019). By taking *in vivo* recordings from populations of cells in the dorsomedial prefrontal cortex, they also investigated the causes of neural synchrony; they concluded that synchrony was driven by behaviour-encoding neurons that show overlapping activity when an action is performed by themselves, and when the same action is performed by a social partner (Kingsbury et al., 2019).

In humans, it has been well documented that watching someone else perform an action involves neural activity in the ‘observer’ becoming more like neural activity in the person performing the action (the ‘actor’) (Catmur & Heyes, 2019). Previous research has demonstrated these actor-observer correspondences while watching and performing actions, such as imitable physical movements (Meltzoff & Marshall, 2018). In adult-adult dyads, there is also evidence that similar processes apply across different domains, such as the neural systems that subserve pain, anger and reward (Bernhardt & Singer, 2012; Singer et al., 2004). Actor-observer correspondences have also been shown to affect autonomic activity in

the context both of adult-adult interactions (Levenson & Ruef, 1992) and adult-child (Wass. et al., in press).

During joint play, the attention patterns of parents and infants are fast-changing. Both partners direct and respond to each other's communicative cues, creating moments of shared attention towards objects, and moments of desynchronisation (Yu & Smith, 2016; 2017). Something about these processes has the effect of increasing childrens' attentiveness: we know that infants are more attentive towards play objects during joint play with an adult, compared to when playing alone (Wass et al., 2018; Yu & Smith, 2017). To understand these influences, recent research has begun to investigate actor-observer correspondences during joint play, to investigate how shared attention affects early interactions from the perspective of not one, but both members of the dyad (Hoehl, Fairhurst, & Schirmer, 2020; Mayo & Gordon, 2020; Wass et al., 2020).

Any potential actor-observer correspondences in attention were, we reasoned, most likely to occur in the theta and alpha ranges of brain activity. In adults, activity in the theta and alpha bands has been associated with attentional engagement. Whilst increased frontal theta activity is associated with sustained attention, and information processing (Gruber, Watrous, Ekstrom, Ranganath, & Otten, 2013; Sauseng, Hoppe, Klimesch, Gerloff, & Hummel, 2007), alpha often shows the opposite pattern, with decreased activity at this frequency band predicting better task-related attention (Ergenoglu et al., 2004). Similar patterns have been observed in infants, with consistent associations between internally driven attention and theta synchronisation over frontal regions (Begus, Southgate, & Gliga, 2015; Hoehl, Michel, Reid, Parise, & Striano, 2014; Jones, Venema, Lowy, Earl, & Webb, 2015; Orekhova, Stroganova, & Posikera, 1999; Orekhova, Stroganova, Posikera, & Elam, 2006); findings related to alpha

desynchronization are more mixed, where varied topographically specific patterns have been noted, depending on the type of attention task used (Bell, 2002; Orekhova, Stroganova, & Posikera, 2001; Stroganova, Orekhova, & Posikera, 1999; Xie, Mallin, & Richards, 2018).

To investigate this, in a recent study we recorded attention and neural activity in infant-parent dyads using dual EEG at the vertex only in two contexts (Wass, Noreika, et al., 2018). The first was joint play, where infants and parents played together across a tabletop. The second was solo play, where a barrier was added across the table so that parents and their infants played separately but in parallel with two identical sets of toys. Overall, we found that infants were more attentive towards the play objects during joint play (Wass, Clackson, et al., 2018; Yu & Smith, 2016). However, whereas infants' theta brain activity strongly forward-predicted their attention patterns during solo play, the same forwards-predictive relationship between brain activity and attention was *weaker* during joint play (Wass, Noreika, et al., 2018). This suggests that infants' endogenous attention control is *lower* during joint play than solo play – despite that infants were, overall, more attentive in this condition (Wass, Clackson, et al., 2018; Wass, Noreika, et al., 2018).

One possibility is that variance in infants' increased attention could be driven not by *intra*-individual differences (i.e., differences in each individual, considered separately), but by *inter*-individual differences (i.e., differences across the dyad) (Bolis, Balsters, Wenderoth, Becchio, & Schilbach, 2017; Wass et al., 2020). To investigate this, we examined how adults' brain activity (at the vertex only) entrained to the infants' attention. We found entrainment between adults' brain activity and infants' attention that was relatively specific to the theta band. These relationships were independent of the adult's own attention. We also found that, whereas the relationship between infants' brain activity and their own attention

was forwards-predictive, the relationship between adults' attention and infants' brain activity was reactive. In other words, the strongest associations were observed between infants' brain activity at time t and their attention patterns 750ms *after* time t ; whereas the strongest associations were observed between adults' brain activity at time t and infants attention patterns 750ms *before* time t (Wass, Noreika, et al., 2018).

These results suggest that the adult brain entrains to infant attention during shared play. This pattern is, we believe, comparable to the actor-observer correspondences outlined above, where neural activity in the person observing an action becomes more like neural activity in the person performing it (Catmur & Heyes, 2019; Hasson & Frith, 2016; Meltzoff & Marshall, 2018). In the context of shared naturalistic play, however, rather than resulting from direct observation of the social partner's action, these actor-observer correspondences reflect neural tracking of the infants' attention at the sub-second scale, independent of the adults' own looking behavior.

The present study builds on and extends these findings in two ways. First, we examine how these relationships vary as a function of scalp topography. Second, we examine whether similar relationships between adults' attention and infants' brain activity can be observed to those already shown between infants' attention and adults' brain activity.

The neural sources of EEG signals recorded at the scalp cannot be conclusively inferred without source localization (Cohen, 2014). Nevertheless, the first question, of how associations between brain activity and attention vary as a function of scalp topography, is an important next question in helping understand what causes these effects. The animal research described above recorded from the dorsomedial prefrontal cortex (Kingsbury et al., 2019).

Previous research examining neural synchrony in adult-child dyads using fNIRS (which has a higher spatial precision than EEG) has often found that synchrony is stronger across optodes positioned over frontal brain areas (Nguyen, in press; Piazza et al., in press). Other research has shown that ostensive cues (such as eye gaze and vocalisations) evoke different activation in low-level processing regions, but overlapping patterns of activation in frontal areas (Parise & Csibra, 2013) (see also (Grossmann et al., 2008; Imafuku, Hakuno, Uchida-Ota, Yamamoto, & Minagawa, 2014; Redcay & Warnell, 2018; Urakawa, Takamoto, Ishikawa, Ono, & Nishijo, 2015). A recent review suggested that early frontal network involvement in the complexities of real-time social interaction may help shape the system over time to be sensitive to explicit mental state representation, contributing to the role that areas such as the dorsal medial prefrontal cortex and ventral medial prefrontal cortex play in mentalising networks in adults (Redcay & Warnell, 2018). Prior infant EEG research, however, has not focused on how inter-dyadic social influences vary as a function of scalp topography.

Understanding the second question, of whether infants also show neural sensitivity to adult looking behaviour, is equally important to furthering our understanding. Previous research has suggested that infants' tendency to imitate specific adult behaviours develops early in life (Meltzoff & Moore, 1977), although this remains controversial (Oostenbroek et al., 2016). Other research into neural actor-observer correspondences has also suggested that they develop early, during infancy (Meltzoff & Marshall, 2018) – although again it remains controversial whether this is an inbuilt tendency or a learnt consequence of perceptual-motor coupling (Catmur & Heyes, 2019; de Klerk, Johnson, Heyes, & Southgate, 2015; van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008). These considerations suggest that infant neural activity might also track adult attention during shared play.

To investigate this, we recorded dual EEG during naturalistic parent-child play in the same two settings as used before. The first was joint play, where dyads played freely with toys across a tabletop; the second was solo play, where a divider was introduced and dyads played separately but in parallel with two identical sets of toys. Our analyses examined the temporal associations between visual attention and neural activity. First, as a preliminary analysis, we examined intra-individual relationships (i.e., infant attention to infant neural activity, and adult attention to adult neural activity, considered separately). Second, in our main analysis we examined inter-individual associations (i.e., infant attention to adult neural activity, and adult attention to infant neural activity). For each relationship, we assessed how it varied: i) in topographical space across all scalp electrodes for a given time window and frequency of neural activity; and ii) across time/frequency space (i.e. across all time windows and frequencies of neural activity) for a selection of individual electrodes. We predicted that: i) stronger cross-dyad associations between attention and the partner's brain activity in the theta band would be observed over anterior than posterior areas (consistent with previous fMRI and fNIRS research); and ii) similar relationships between adult attention and infant neural activity would be observed to those already documented between infant attention and adult neural activity.

Methods

Ethics Statement. The study was approved by the Psychology Research Ethics Committee at the University of Cambridge (Number PRE.2016.029). The only financial inducements were that travel expenses were reimbursed and that participating infants were given the gift of a T-shirt.

Participants. 24 and 25 parents contributed usable data for the Joint Play (JP) and Solo Play (SP) conditions respectively; for infants, the numbers were 21 and 25 for JP/SP respectively. Paired caregiver -child data were available for 22 dyads for Solo Play (12M/10F infants; mean (S.E.) infant age 339.2 (10.3) days; caregiver age 34.1 (1.0) years); and for 20 dyads for Joint Play (10M/10F infants; mean (S.E.) infant age 345.1 (12.1) days; caregiver age 34.7 (0.8) years). All participating parents were female. The recruitment area for this study, Cambridge, UK, is a wealthy university town and participants do not represent an accurate demographic sample (Henrich, Heine, & Norenzayan, 2010). Of note, a different analysis based on these data has already been published separately (Wass, Noreika, et al., 2018).

Experimental set-up. Infants were positioned immediately in front of a table in a high chair (see Figure 1c). Parents were positioned on the opposite side of the 65cm-wide table, facing the infant. The toys on the table were within easy reach. In the Joint Play condition, caregiver and child played together with a single toy at a time. In the Solo Play condition, a barrier (40cm high) was positioned across the middle of the table, and caregivers and children played in parallel with two identical but separate sets of toys. The toys were randomized between conditions. The height of the barrier was set so that parent and child still had line of sight to one another when it was in place (to avoid the possibility of infant distress). But, when it was

in place, neither could see the objects with which the other was playing. Presentation order of the Joint Play and Solo Play conditions was randomised between participants, but the two conditions were presented consecutively, with a short break in between. Parents were informed that the aim of the study was to compare behaviour while they were attending to objects separately from each other, and when they were attending to the same object. Both conditions were conducted in silence.

INSERT FIGURE 1 HERE

The mean (S.E.) duration of data collected in each condition was 10.80 (0.46) minutes for Joint Play and 10.35 (0.33) minutes for Solo Play. When the infant became fussy during testing, data collection was stopped immediately; however, this occurred fairly rarely: the number of infants contributing sessions that lasted less than 8 minutes was 2/3 for the Joint/Solo Play conditions.

Video coding. Play sessions were videoed using two camcorders positioned next to the child and parent respectively, in order to obtain a frontal head-and-shoulders view of each. Synchronisation of the two camcorders was achieved by placing radio-frequency (RF) receiver LED boxes behind the child's and parent's chairs, within view of the camcorders. These RF boxes simultaneously received trigger signals from a single source (a laptop running Matlab) at the start of the testing session, and concurrently emitted light pulses that were visible on parents' and infants' camcorders. Two categories of gaze were coded: attending towards play object, or not. Transitions between these categories were manually coded by reviewing their respective video recordings on a frame-by-frame basis (30 frames per second, 33.3 ms temporal acuity) using video editing software (Windows Movie Maker) (see Fig 1a, 1b). In order to assess inter-rater reliability, a 20% proportion of our data were double coded by a second,

blinded coder. Cohen's kappa was calculated to assess inter-rater reliability. This was found to be high for both the SP (mean (*std*)) 0.98 (0.01)) and JP (0.97 (0.003)) conditions.

EEG Data Acquisition. EEG signals were obtained using a 32-channel wireless Biopac Mobita Acquisition System and 32-channel Easycap, using a mastoid reference. EEG signals were acquired using wireless amplifiers to reduce distraction for the infant during testing. EEG was recorded at 500 Hz with no online filtering using AcqKnowledge software (Biopac Systems Inc). Conductive electrode gel SuperVisc (EasyCap, GmbH, Germany) was used to affix the electrodes/cap to the scalp and the electrode impedance was kept below 10 k Ω for infants and 20 k Ω for mothers. The ground electrode was placed on the nape.

EEG Artifact rejection and pre-processing. Automatic artifact rejection followed by manual cleaning using ICAs was performed. In brief, this consisted of: i) applying high (<1Hz) and low (>16Hz) pass filters; ii) removing noisy channels; iii) excluding egregious noisy segments; iv) ICA; v) interpolating channels excluded at ii; vi) excluding noisy segments (second stage). Full descriptions are given in the Supplementary Methods section 1.i. In our analyses only frequencies between 2 and 16Hz were examined, because our previous research has suggested that this frequency range shows least EEG signal distortion due to sweating, movement or muscle artefact in infant data (Georgieva, Lester, Yilmaz, Wass, & Leong, in press). Analyses presented in the Supplementary Methods section 1.ii Figure S1 suggest that these frequencies are not affected by filtering edge effects. Prior literature (e.g. (Orehova et al., 1999, 2001)) suggests that these frequencies were also most likely to show associations with visual attention.

Laplacian filter. A surface Laplacian filter was applied to the data in order to increase topographical selectivity by filtering out spatially broad features of the data. This filter is

thought to improve topographical localization and to minimize volume-conduction effects (Cohen, 2014; Kayser & Tenke, 2006; Perrin, Pernier, Bertnard, Giard, & Echallier, 1987). Further details, and visual outputs showing the effects of the filter, are given in the SM section 1.ii Figure S1.

Power analysis. To calculate EEG spectral power, the data were first epoched into 2000ms epochs using a moving window that moved in increments of 250ms. A linear de-trend was first applied using the Matlab function `detrend.m`, for each channel and for each epoch, and then a Fourier Fast Transform (FFT) was carried out using the Matlab function `fft.m`. For each epoch, the FFT was calculated in 1Hz frequency bins, examining frequencies between 2 and 16 Hz, and the power at that bin was expressed as relative power – i.e. the total power at that frequency divided by the total power across all frequencies (2-16 Hz) at that epoch. Thus, power estimates of the EEG signal were obtained with a temporal resolution of 4 Hz and a frequency resolution of 1 Hz.

Calculation of time-lagged temporal association. The attention data was re-sampled as continuous and time-synchronised data-streams at 4Hz (to match that of the EEG power estimate). Attention data were coded as 1 and 0 (either attentive towards the play object, or not). Synchronisation of the attention data (derived from camcorders) with the EEG data was ensured using LED boxes as described above (see Video coding section). The calculations were performed separately for each frequency band (in 1Hz bins). Only segments with usable EEG data were included in the analysis; when an EEG epoch was removed, its corresponding section of attentional data was also removed.

For each computation, the zero-lag association was first calculated across all pairs of time-locked (i.e. simultaneously occurring) epochs, comparing the EEG power profile with the binary attention data using a Mann-Whitney U test. In addition, since our use of the Mann-Whitney U test in this way violates the assumption of independence of samples which is inherent in the test, which can affect its accuracy (McKnight & Najab, 2010), we also repeated (in the SM section 1.iv) our main analyses using a point bi-serial correlation, which yielded highly similar results. See Supplementary Materials Section 1.iv Figure S3. It is also important to note that the use of the point bi-serial test for this measure also has limitations, as we also describe further in the Supplementary Materials.

The mean zero-lag association value obtained was then plotted as time “0” ($t=0$). Next, time-lagged associations were computed at all lags from -10 to +10 seconds in lags of ± 250 ms (corresponding to one data point at 4 Hz). For example, at lag-time $t=-250$ ms, the EEG power profile was shifted one data point backwards relative to the attention data, and the mean association between all lagged pairs of data was calculated. The individual time-lagged data were then averaged across participants. This analysis therefore assesses how the association between EEG power and attention varies across different frequency bands of EEG and when a time-lag is introduced between EEG and attention.

In order to ensure that the inter-individual relationships observed were not merely due to the behaviour of one partner imitating that of the other, we excluded instances in which an attention shift from the infant was immediately followed by an attention shift from the parent. Based on an average of 10.5 minutes’ data per condition, sampled at 4Hz, and allowing for some attrition at artefact rejection due to the max-min thresholding criteria, the mean number of samples

entered into the analysis was c.2300 for the zero-lag analysis. For the most extreme time lags (+/- 10 seconds), 40 fewer samples were available.

Statistical tests. To compare the distribution of time x frequency data between any single condition and a null distribution, a cluster-based permutation test was conducted across time x frequency data, using the FieldTrip function `ft_freqstatistics` (Maris & Oostenveld, 2007). In comparison to other approaches to solving the family-wise error rate, this approach identifies clusters of neighbouring responses in time/frequency space (Maris, 2012). In particular, corresponding time x frequency points were compared between contrast condition and null distribution with a paired samples t-test, and t values of adjacent spatiotemporal points with $p < 0.05$ were clustered together with a weighted cluster mass statistic that combines cluster size and intensity (Hayasaka & Nichols, 2004). Afterwards, the whole procedure, i.e., calculation of t values at each spatiotemporal point followed by clustering of adjacent t values, was repeated 1000 times, with recombination and randomized resampling of the subject-wise averages before each repetition (see Maris & Oostenveld, 2007 for further details). This Monte Carlo method thus generated an estimate of the p value representing the statistical significance of the originally identified cluster compared to results obtained from a chance distribution. Significant positive and negative clusters were identified using an alpha level of $p=.05$.

This analysis, which corrects for multiple comparisons in time-frequency space, was applied to data from individual electrode clusters that were selected in a hypothesis-driven manner (as described below). Of note, we have not also corrected for multiple comparisons across electrodes where data from these other electrodes has not been presented in the manuscript (see (Bevilacqua et al., 2018; Dikker et al., 2017; Leong et al., 2017; Wass, Noreika, et al., 2018) for similar approaches). We have, however, also provided topoplots for the exploratory purpose

of showing how our focal effects vary in topographical space, to allow the reader to judge how the effects that we were examining vary between the specific electrodes that we reported and neighbouring ones.

Results

Our results section is in two parts. In Analysis 1, we consider *intra*-individual associations, namely the association between adult attention and adult neural activity and infant attention and infant neural activity, considered separately. We examine how these relationships vary topographically, and across different frequencies of brain activity, in order to examine how they differ from the infant-parent and parent-infant relationships that we examine in Analysis 2.

In Analysis 2, we consider *inter*-individual associations, namely the association between infant attention and adult neural activity, and that between adult attention and infant neural activity. Again, we consider how these relationships vary topographically, and across different frequencies.

Analysis 1 – intra-individual association

First, we examined the relationship between adult attention and adult neural activity (Figure 2) and between infant attention and infant neural activity (Figure 3). To do this, we calculated the time-lagged association between adults' and infants' attention towards the objects (treated as a series of 1s and 0s for attending/not attending), and their own neural activity at different frequency bands.

Previously, using a similar analysis but examining the vertex location only, we had identified associations between brain activity and attention that peaked at 8Hz/4Hz for adults/infants respectively and at -750ms (brain activity preceding attention by 750ms) (Wass, Noreika, et

al., 2018). Here, we examine how these relationships vary topographically. First, we present topographical plots showing how the relationship varies across all electrodes for a given area of time/frequency space (Figure 2a/3a). Second, we present plots showing how the relationship varies across time/frequency space for a selection of individual electrodes (Figure 2b/3b). Third, we present the results of cluster-based permutation tests conducted on the time/frequency space plots (Figure 2c/3c). Finally, we present a direct anterior/posterior comparison (Figure 2d/3d).

For the first analysis (Figure 2a/3a), in order to examine how the effect varied topographically, we selected the time/frequency cluster that had showed the strongest association at the vertex location in previous research (Wass, Noreika, et al., 2018). This was 6-10Hz /3-6Hz for adults/infants, and with brain activity preceding attention by -1000 to 0 ms. For the second analysis (Figure 2b), the electrodes selected were: frontal (AFz), occipital (POz), left temporal (T7) and right temporal (T8), which are located on the anterior-posterior and transverse midlines.

Figure 2 shows the time-lagged associations between adult attention and adult brain activity. Figure 2b shows the time/frequency plot and 2c shows the significant clusters when comparing the observed values to a chance value of 0. Figure 2d shows a direct anterior-posterior comparison (only solo play is shown; the same comparison for joint play identified no significant clusters). Note that previous research has also shown that the whole-brain relationship between EEG activity and attention is stronger during solo play than joint play (Figure 2) - see (Wass, Clackson, et al., 2018; Wass, Noreika, et al., 2018). Mainly positive significant associations were observed between activity in the 5-10Hz range and attention (Figure 2b/2c). These were temporally specific – i.e. they disappeared when a lag of more

than c.5 seconds was introduced between the attention and EEG time-series. For solo play, a significant anterior>posterior difference was observed in the 5-9Hz range (Figure 2d).

Figure 3 shows the time lagged associations between infant attention and infant brain activity. As with the adults, positive associations between EEG activity and attention were observed, albeit at the 3-6Hz range for infants (Figure 3c). In contrast to the adults, significant negative associations were also observed between EEG activity and attention in the low (2-3Hz) and higher (>10Hz) frequencies. For solo play, a significant anterior>posterior difference was observed in the 3-5Hz range, and an anterior<posterior difference was observed at >7Hz (Figure 3d).

We have not statistically compared the patterns of association between infants and adults, as we considered it more meaningful to concentrate on the anterior-posterior comparison, which is our main hypothesis, as well as to compare the observed distributions with 0. Nevertheless, it can be noted that significant differences from 0 were observed across a relatively narrow frequency range in adults (5-10Hz), but across a wide range in infants (2-16Hz, including both positive and negative differences). Similarly, in the time dimension, significant differences from 0 were generally observed only from time lags from -5 to +5 seconds in the adult data, whereas they were observed across a wide range in infants (-10 to +10 seconds). These findings may all be attributable to the fact that the recording quality of the infant EEG data was, inevitably, lower than for adults.

Overall, these results suggest that: i) temporally specific associations between brain activity and attention are observed in infants, and adults, considered separately; ii) these relationships are observed at slightly different frequency ranges in infants compared to adults, involving

negative associations in infants but not adults; iii) for solo play (but not joint play) significant anterior>posterior differences were noted for both adults and infants.

INSERT FIGURE 2 HERE

INSERT FIGURE 3 HERE

Analysis 2 – inter-individual

In Analysis 2 we examine inter-individual associations: between infant attention and adult neural activity, and between adult attention and infant neural activity. These were calculated using the same approach as described for Analysis 1, above. Since this analyses examines cross-dyadic relationships, they were conducted based on the Joint Play data.

First, we present topographical plots showing how the relationship varies across all electrodes for a given area of time/frequency space (Analysis 2.1). Second, we present comparison plots showing how the relationship varies across time/frequency space for a selection of individual electrodes (Analysis 2.2).

2.1 – topographical plots

For this, our primary analysis, we have shown not just the time window of peak association (as we did for Analysis 1); rather, we have presented the full series of topographical plots for different frequency bands and different time windows. Results for infant attention to adult

neural activity are given in Figure 4. In the SM, we present identical analyses examining the relationship between adult attention and infant neural activity (Figure S4). Time data were binned into: -10 to -6.7 secs (i.e., brain activity preceding attention by 10 to 6.7 secs); -6.6 to -3.3 secs; -3.3 to 0 secs; 0 to 3.3 secs; 3.3 to 6.7 secs; 6.7 to 10 secs. For Figure 4, frequency data were binned using the conventional adult bins into: Delta (2-3Hz), Theta (4-7Hz), Alpha (8-12Hz) and Beta (13-16Hz) (only frequencies up to 16Hz were considered in this study). For Figure S4, frequency data were binned using the conventional infant bins into: Delta (2-3Hz), Theta (3-6Hz), Alpha (6-9Hz) and Beta (9-16Hz).

To examine whether observed relationships were stronger across anterior than posterior locations, results were binned into anterior and posterior electrodes, split evenly across the midline (see Figure 4b/S4b for electrode groupings). Two sets of t-tests were then conducted: first results in each bin (anterior and posterior, considered separately) were compared to a chance value of 0. Second, anterior and posterior were directly compared. In each case, multiple comparisons (multiple time windows and frequency bands) were corrected for using the Benjamini-Hochberg FDR procedure (Benjamini & Hochberg, 1995). Significant results are indicated in Figure 4b/S4b.

For Figure 4, results indicate that all four frequency bands show time-locked associations between the infant's attention and the adult's neural activity. These were positive in the theta/alpha range, negative in the delta range, and mixed in the beta range. In the theta band only, and in the time windows from -3.3 to 0 and 0 to +3.3, significant anterior>posterior differences were observed, as predicted. Of note, although other frequency bands (particularly beta) consistently showed the opposite relationship (anterior<posterior), no

significant anterior-posterior differences were observed after correcting for multiple comparisons.

INSERT FIGURE 4 HERE

In the Supplementary Materials section 2.iv Figure S4 we show an identical series of plots examining the time-lagged associations between adult attention and infant brain activity. Again, temporally specific relationships were observed between adult attention and infant neural activity. Positive relationships were observed in the theta and alpha bands. Contrary to our predictions, however, stronger relationships were not observed across anterior relative to posterior electrodes; indeed, the significant anterior-posterior differences showed the opposite pattern – posterior>anterior, in the beta band (Figure S4).

2.2 – time/frequency space plots

In order to examine how inter-individual relationships varied across time/frequency space, a subset of electrodes was selected based on the regions that showed the strongest intra-individual association between infant attention and infant brain activity in Figure 3a, along with a comparison posterior sample that was equivalently positioned, relative to the midline. These were anterior FC5 and FC6 and posterior CP5 and CP6. Of note, however, the topoplots presented in Figure 4/S4 indicate that patterns observed across neighbouring electrodes were highly similar, and not stronger at the specific electrodes selected for analysis.

Figure 5 shows a comparison of all four relationships in time/frequency space: intra-individual (infant attention-infant brain and adult attention-adult brain) and inter-individual (infant attention-adult brain and adult attention-infant brain). Fig 5a/5d show the time-lagged associations between infant attention and infant brain activity for anterior/posterior electrodes (these are similar to Figure 3, but included here for comparison); Fig 5b/5f show the associations between adult attention and adult brain activity (these are similar to Figure 2); Fig 5c/5g show the association between infant attention and adult brain activity; Fig 5d/5h show the association between adult attention and infant brain activity.

Two sets of cluster-based permutation tests were conducted based on these results (see Figure 6). First, we examined whether each dataset differed significantly from 0 (i.e., whether a significant cluster in time/frequency space was observed at that electrode, considered independently). These results are shown in Figure 6a-h. Second, we directly compared the anterior and posterior electrode groupings, to examine whether stronger relationships were observed across anterior relative to posterior electrodes. These results are shown in Figure 6i-l.

When we examined the relationship between infant attention and adult brain activity, we identified significant patterns of difference from 0 across both anterior ($p < .001$ – see Fig 5c and Fig 6c) and posterior ($p = .006$ – see Fig 5g and Fig 6g) electrodes. For the anterior grouping, relationships were stronger during the time window where infant attention preceded adult brain activity. A direct comparison of the anterior and posterior relationships indicated that results were significantly greater over anterior compared to posterior groups ($p = .01$ – see Fig 6k).

When examining the relationship of adult attention to infant brain activity, we identified significant patterns of difference from 0 across anterior ($p=.003$ – see Fig 5d and Fig 6d) but not posterior electrodes ($p=.096$ – see Figure 5h and Fig 5h). A direct comparison of the anterior and posterior relationships indicated no significant difference ($p=.21$).

Overall, these results suggest that: i) temporally specific correspondences are observed between infant attention and adult brain activity; ii) these relationships are stronger across anterior than posterior electrodes; iii) temporally specific correspondences are also observed between adult attention and infant brain activity, but these are weaker and are not stronger across anterior than posterior electrodes.

INSERT FIGURE 5 HERE

INSERT FIGURE 6 HERE

Discussion

First, we examined *intra*-individual brain-behaviour relationships by measuring the relationship of infant attention to infant neural activity, and adult attention to adult neural activity, considered separately. Second, we examined *inter*-individual brain-behaviour relationships by measuring the relationship of infant attention to adult neural activity, and adult attention to infant neural activity. Our aims were two-fold: question one was to examine how the inter-dyadic associations previously documented varied as a function of scalp topography; question two was to examine whether similar correspondences could be observed between adult attention and infant brain activity to those already documented between infant attention and adult brain activity.

Despite that we applied a Laplacian filter to counteract volume condition effects, EEG nevertheless has poor topographical specificity and strong inferences about the neural sources of signals recorded at the scalp cannot be drawn (Wolters & de Munck, 2007). However, the high temporal resolution it offers compared to other methods such as fNIRS is advantageous in two ways: first, it allows us to decompose oscillatory activity into different frequency bands, separating out low- (<3Hz), intermediate (~3Hz-12Hz) and higher-frequency (>12Hz) neural activity. Second, it allows us to examine (with high temporal specificity) how changes in brain activity associate with particular behaviours.

In our preliminary Analysis 1, we examined intra-dyadic relationships - i.e. adult brain to adult attention, and infant brain to infant attention, during solo play. Although we used the Mann-Whitney U test in a way which violates the assumption of independence of samples, which in some cases can affect the accuracy of the test (McKnight & Najab, 2010), we also

presented (in the SM section 1.iv) supplementary analyses using the point biserial correlation (see Supplementary Materials Section 1.iv Figure S3), which showed results that were highly similar, indicating that this was not the case in our data. We identified temporal associations between brain activity and attention that were consistent for adults (Figure 2) and infants (Figure 3). For adults, associations were positive and highly temporally specific (disappearing at lags of >5 seconds between the brain activity and attention). Although associations were significant across both theta and alpha ranges, the anterior>posterior differences were strongest in the theta range (Fig 2d).

For infants, the peak positive association was strongest in the theta band, but negative associations were also observed in the delta (2-3Hz) and beta (>10Hz) bands. These may reflect attention-related decreases in neural motor signalling originating from M1 and pre-motor cortices – an explanation that would match with the topographical effects of negative beta clustered located in frontal and central but not parietal-occipital regions (Cuevas, Cannon, Yoo, & Fox, 2014; Marshall & Meltzoff, 2011; van Elk et al., 2008).

In our primary Analysis 2, we examined inter-dyadic relationships - i.e. adult brain to infant attention, and infant brain to adult attention, during joint play. Our analyses indicated a range of associations between both infant attention and adult brain activity, and adult attention and infant brain activity. Our previous research suggests that the possibility that our data are contaminated by muscle or movement artifact cannot be eliminated (Georgieva et al., in press). However, the scalp topography of the associations we found suggests that they are unlikely to be attributable to muscular (e.g. oculomotor) or movement artifacts (e.g., jaw muscles in the case of the bilateral temporal Delta/Alpha relationships). We would contend, therefore, that our results show infant actor- parent observer neural entrainment during

naturalistic play. This pattern was not caused by the behaviour of one partner imitating that of the other, as direct instances of gaze-following were excluded from our analysis.

Our aim for question one was to examine whether adult brain-infant attention relationships were observed more strongly across anterior than posterior electrodes. To examine this, we conducted two analyses: first, we compared the time-lagged associations across all anterior and posterior electrodes (Fig 4); second, we compared the relationships observed in time/frequency space for a selection of anterior and posterior electrodes (Fig 5c/5g/6c/6g/6k). Both analyses suggested that significantly stronger associations were observed for anterior than posterior electrodes, but that this finding was limited to the theta/alpha range (although the exact values differ slightly between Figure 4 and Figure 6). Strikingly, the strongest anterior-posterior neural differences were observed at negative time-lags (i.e. where the adult's neural activity preceded the child's attention) (see Figure 6k). This point is discussed further below. Overall, then, these results were consistent with our prediction, that adult brain-infant attention relationships would be stronger across anterior than posterior electrodes.

Although the observed relationships were strongest in the theta band, one aspect of our results that was unexpected is that positive adult brain-infant attention relationships were also observed in the alpha band. These associations appear to be at odds with previous literature that has shown adult attentional engagement to correlate with *decreased* activity in the alpha band (Sauseng et al., 2007). One possible interpretation of this finding is that, rather than reflecting adult attentional engagement processes during joint play, alpha band activity indexes internal thought processes important to monitoring and updating information related to ongoing changes in infant attention (Knyazev, Slobodskoj-Plusnin, Bocharov, & Pylkova,

2011). For example, increased alpha band activity has been associated with storing and updating information in short term memory (Klimesch, Doppelmayr, Schwaiger, Auinger, & Winkler, 1999), performance on mental imagery tasks (Cooper, Croft, Dominey, Burgess, & Gruzelier, 2003), as well as internally directed attention (Cooper, Burgess, Croft, & Gruzelier, 2006). In contrast, the positive association between adult theta activity and infant attention may be more indicative of processes related to the adult's top-down attentional control and response planning (Hirsch, Zhang, Noah, & Ono, 2017). This interpretation is supported by the stronger anterior relationship with infant attention in the theta band, as well as the association at anterior regions in the theta band only, being strongest where infant attention preceded adult brain activity (Figure 6k). These findings are discussed in more detail below.

Figure 4 also documents some significant negative adult brain-infant attention associations between delta and beta bands. This may be because periods where infants become less attentive were associated with greater muscle movement in the parent (i.e., they might exaggerate arm/head movements to regain infant attention towards a toy, or themselves). Thus, higher delta/beta activity, which is more sensitive to muscle movement (Georgieva et al., in press) associates with reduced infant attention during joint play.

Our aim for question two was to examine whether similar inter-dyadic relationships were observed when examining the relationship between adult attention and infant brain activity. Here, we found evidence that was more mixed. A significant relationship was observed between adult attention and infant neural activity in the theta and alpha bands (Fig 5d/6d). This relationship was observed across similar frequencies to that between infant attention and adult neural activity (Fig 5c/6c). However, the adult attention-infant brain relationship was

not also observed across posterior electrodes (Fig 5h/6h), and the topographical plots showed that adult attention-infant brain relationships (Fig S4) were markedly weaker than infant attention-adult brain relationships (Fig 4). Of note, strong intra-individual associations (between infant attention and infant neural activity) *were* observed (Fig 2/5a), suggesting that the weaker inter-dyadic associations documented were not simply a function of measurement error in the infant neural recordings.

Again, the unexpected positive infant brain-adult attention relationships in the alpha band may be interpreted in relation to updating and monitoring processes involved in tracking another partner's attention during social interaction. For example, Orekhova and colleagues have shown that, in a sample of 7-12-month-olds, alpha activity is greater over anterior regions when infants observe another person's behaviour (an experimenter blowing bubbles), compared to where they wait for an expected event to happen – an index of internally controlled attention (Orekhova et al., 2001).

Whereas infant attention-adult brain relationships were consistently stronger across anterior than posterior regions (as described above), evidence for the same pattern in adult attention-infant brain relationships was more mixed. Although significant adult attention-infant brain relationships were observed in time/frequency space for the anterior (Fig 5d/6d) but not the posterior (Fig 5h/6h) electrodes, the direct comparison of anterior and posterior electrodes was not significant (Fig 6l). The results presented in SM section 2.iv also suggest that, although anterior>posterior differences were observed consistently in the theta (but not alpha) bands, they were not significant (Fig S4). These more inconsistent results are perhaps surprising given that the neural locales for the processing of social and emotional information

are not thought to markedly change in location between infancy and adulthood (Blasi et al., 2011; Grossmann et al., 2008; Redcay & Warnell, 2018).

One possibility is that the inter-individual associations we observed reflect, at least partially, one partner's anticipation of future movements by the other. Adult research using naturalistic, interactive paradigms has indicated activity in prefrontal regions involved in response planning, that had not previously been documented using non-interactive, screen-based paradigms (Hirsch et al., 2017; Redcay & Schilbach, 2019). One explanation for the relatively weaker patterns observed in infants is that this type of response anticipation would be less strong in infants, who show a more reactive, and less proactive, interactional style (Blackwell & Munakata, 2014; Feldman, Greenbaum, & Yirmiya, 1999).

Although we controlled for the possibility that inter-individual associations were merely due to the behaviour of one partner imitating that of the other, one further possible explanation for our findings is that they are attributable to associations in child-adult neural activity, and to the child's brain activity associating with the child's attention. Against this possibility is the fact that childrens' own brain activity was actually less predictive of their own attention patterns during joint play (Figure 2/3) – at a time when adult's brain activity is *more* predictive. Future work should, however, directly investigate how the inter-dyadic attention-brain relationships that we have investigated here relate to previous findings of brain-brain synchrony. Of note, however, whereas previous investigations into brain-brain associations have used methods such as Generalised Partial Directed Coherence (Leong et al., 2017) and Phase Locking Value (Covarrubias et al., in press), no previous research has measured amplitude-amplitude correlations, which would be the most analogous approach to that we used here.

Future work should build on our present findings by further investigating whether interpersonal synchrony is similarly stronger in anterior than posterior regions, and how this differentially affects later or earlier stages of information processing (Hasson & Frith, 2016; Konvalinka & Roepstorff, 2012). Future work should also investigate whether the degree to which parents show neural reactivity to their child's attention is consistent as a measure of individual differences, and if so how this relates to individual differences, and psychopathology. Finally, future work should also investigate the role of shared understanding in driving synchrony (Nummenmaa et al., 2012).

Figures

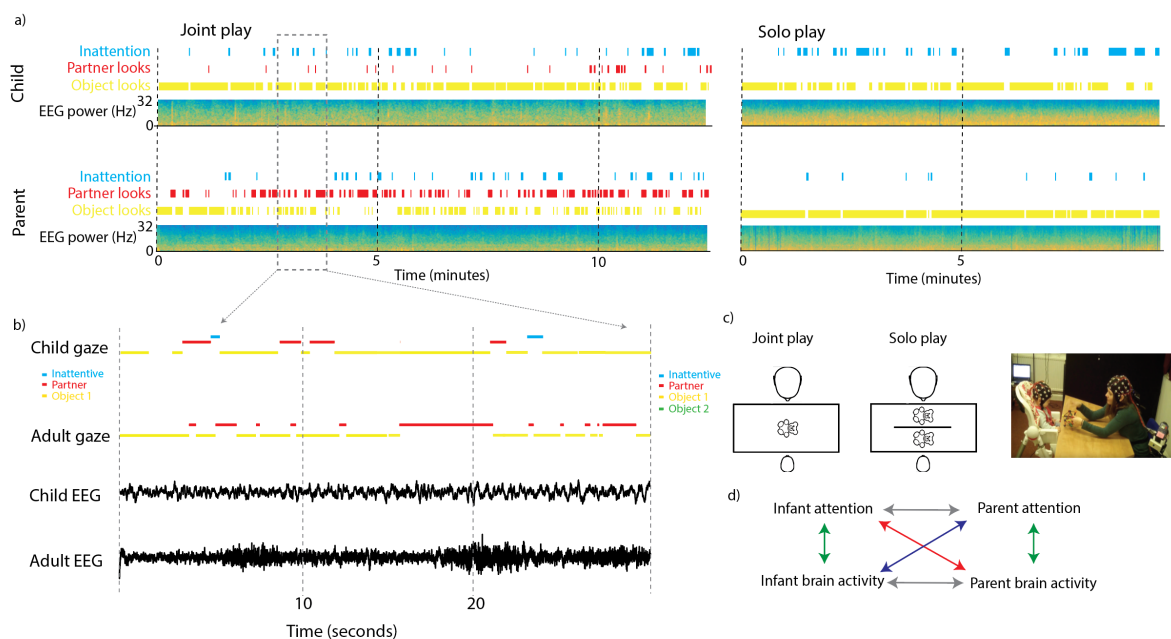


Figure 1: a) examples of raw data; even from this raw data sample some significant patterns previously noted during shared naturalistic play can be seen – such as that parents pay more attention to infants during joint play than vice versa (Yu & Smith, 2013), and that infants are more inattentive during solo play than joint play (Wass, Clackson, et al., 2018). b) close-up example of a 30-second segment of data. c) schematic and photograph illustrating the experimental set-up. d) Illustration of the different types of relationship that can be studied across dyads. Rather than directly examining synchrony between infant brain activity and adult brain activity, here we examine the relationship between infant attention and adult brain activity (drawn red) and between adult attention and infant brain activity (drawn blue).

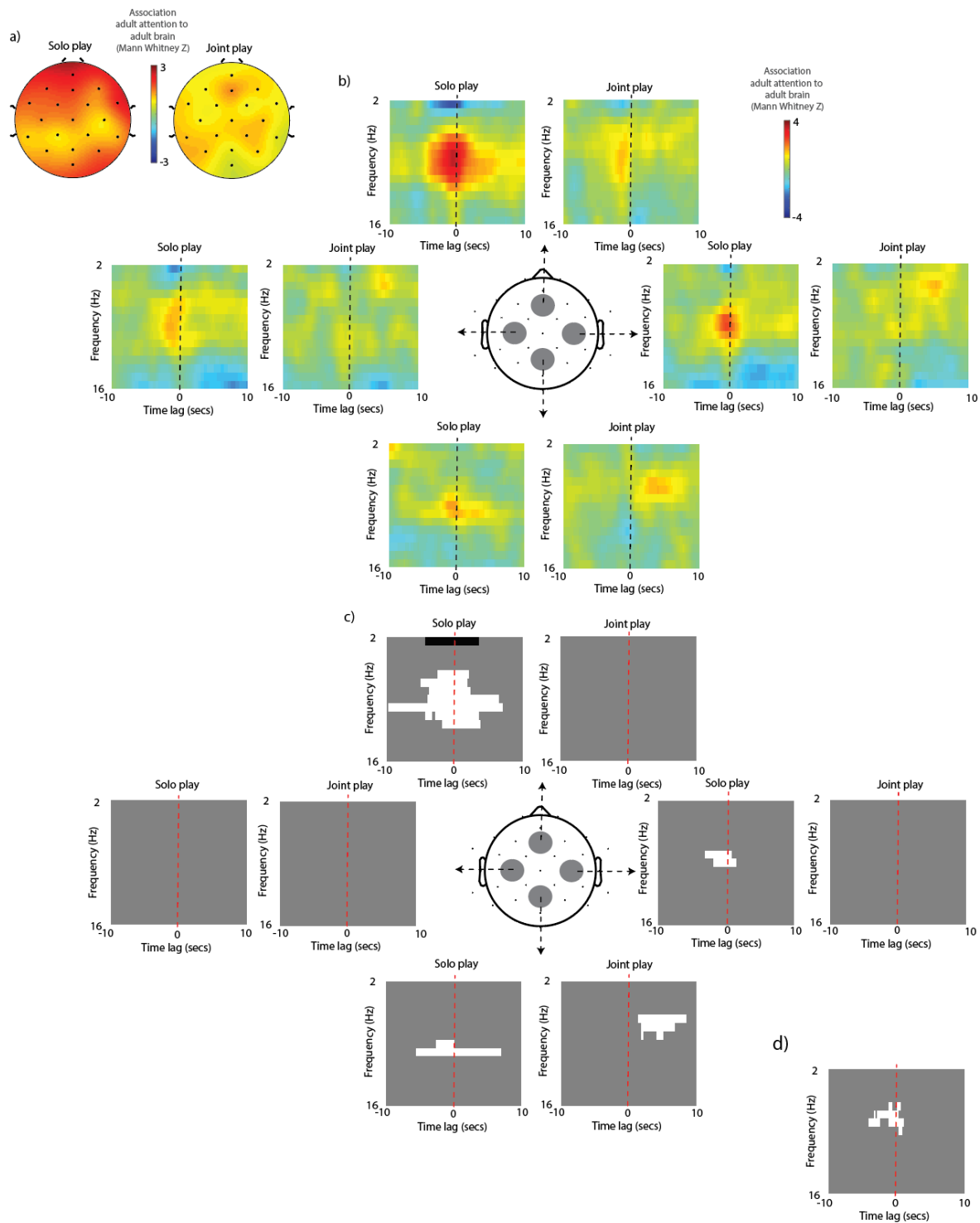


Figure 2: a) Topoplot showing the cross-correlation between adult attention and adult brain activity in the 6-10Hz frequency range and in the time window from -1 to 0 seconds (brain activity preceding attention) for solo play (left) and joint play (right). This frequency and time range were chosen because previous research using the vertex location only identified them as showing the strongest association between adult attention and adult brain activity

(Wass, Noreika, et al., 2018). Colour bar shows the strength of the association between attention and neural activity, indexed as a Mann Whitney Z value. b) Time-lagged associations between adult attention and adult brain activity for the four different locations shown as grey circles in the central image. For each location, the same plot has been shown for Solo play (left) and Joint play (right). In each case, the x-axis indicates the variable time lags used to calculate the relationship between attention and brain activity, from -10 (brain activity preceding attention by 10 seconds) to +10 (brain activity post attention by 10 seconds). The y-axis indicates the different frequencies of brain activity, from 2 to 16Hz. Colour bar shows the strength of the association between attention and neural activity, indexed as a Mann Whitney Z value. c) Results of cluster-based permutation tests run on the data shown in Figure b. Areas shaded white indicate significant positive clusters; areas shaded black indicate significant negative clusters, $p < .05$. d) Results of cluster-based permutation tests to directly compare the strength of the associations between anterior and posterior electrodes. White indicates anterior > posterior, $p < .05$. Only Solo Play is shown; the equivalent comparison for joint play was not significant ($p = .17$).

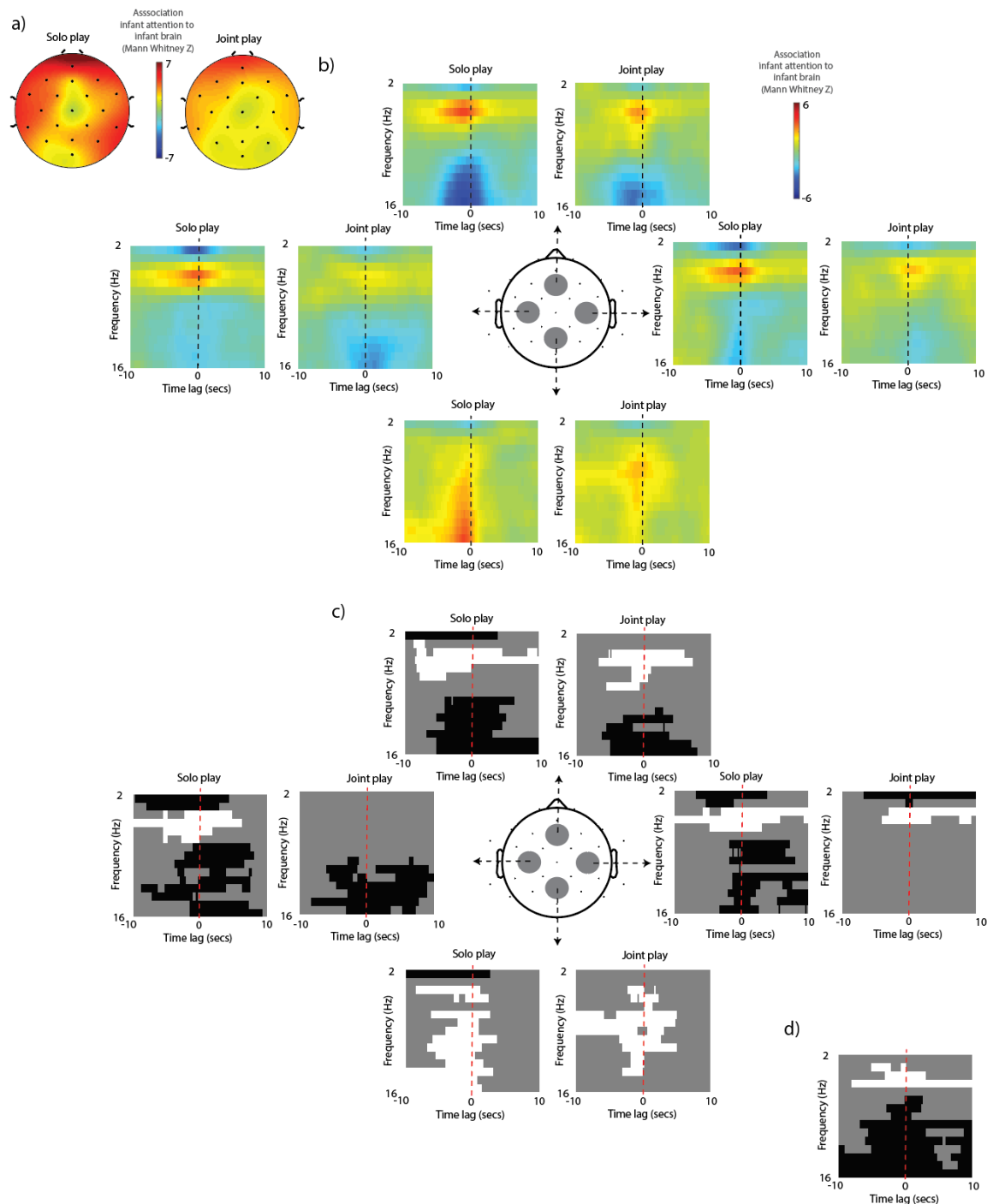


Figure 3: a) Topoplot showing the time-lagged associations between infant attention and infant brain activity in the 3-6Hz frequency range and in the time window from -1 to 0 seconds (brain activity preceding attention) for solo play (left) and joint play (right). Colour

bar shows the strength of the association between attention and neural activity, indexed as a Mann Whitney Z value. b) Time-lagged associations between infant attention and infant brain activity for the four different locations shown as grey circles in the central image. For each location, the same plot has been shown for Solo play (left) and Joint play (right). In each case, the x-axis indicates the variable time lags used to calculate the relationship between attention and brain activity, from -10 (brain activity preceding attention by 10 seconds) to +10 (brain activity post attention by 10 seconds). The y-axis indicates the different frequencies of brain activity, from 2 to 16Hz. Colour bar shows the strength of the association between attention and neural activity, indexed as a Mann Whitney Z value. c) Results of cluster-based permutation tests run on the data shown in Figure b. Areas shaded white indicate significant positive clusters; areas shaded black indicate significant negative clusters. $p < .05$. d) Results of cluster-based permutation tests to directly compare the strength of the associations noted between anterior and posterior electrodes. White indicates anterior > posterior, black indicates posterior > anterior, $p < .05$. Only Solo Play is shown; the equivalent comparison for joint play was not significant ($p = .10$).

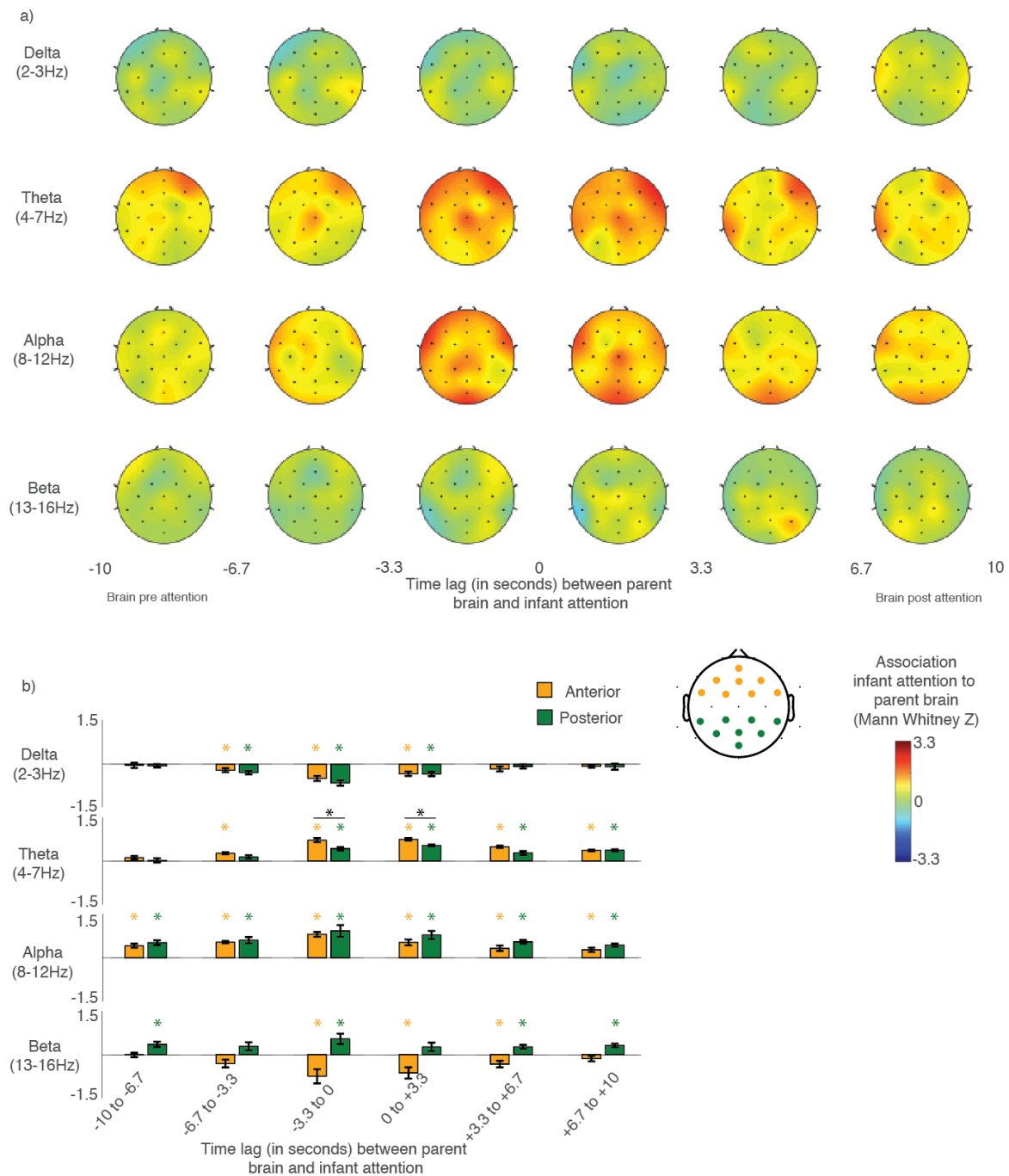


Figure 4: a) Time-lagged associations between infant attention and adult brain activity. Frequency data were binned using the standard adult bins into: Delta (2-3Hz), Theta (4-7Hz), Alpha (8-12Hz) and Beta (13-16Hz), which are shown in separate rows. Time data were binned into different time windows from -10 to -6.7 secs (i.e., brain activity preceding attention by 10 to 6.7 secs) to +6.7 to +10 secs (i.e. brain activity 6.7 to 10 seconds after

attention), which are shown in separate columns. Colour bar shows the strength of the association between attention and neural activity, indexed as a Mann Whitney Z value. b) Bar-charts showing the same data as above, but binned into anterior and posterior electrodes using the electrode grouping shown in the legend. Coloured stars indicate that the result for that electrode grouping (anterior or posterior) differed significantly from 0, $p < .05$. Black stars indicate that the anterior vs posterior comparison differed significantly from zero.

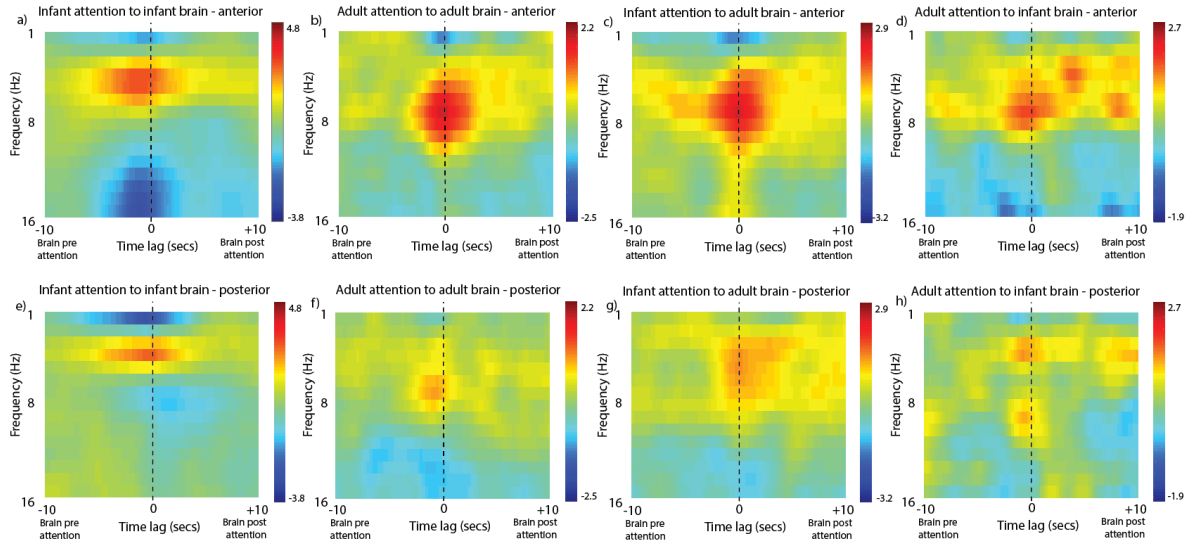


Figure 5: Time-lagged associations between attention and brain activity. a-d show results at anterior locations (see text); e-h show the posterior locations. a & e show infant attention to infant brain (these are similar to those shown in Figure 2, but included here for comparison); b & f show adult attention to adult brain activity; c & g show infant attention to adult brain activity; d & h show adult attention to infant brain activity. In each case, the x-axis indicates the variable time delays used to calculate the time-lagged relationship between attention and brain activity, from -10 (brain activity preceding attention by 10 seconds) to +10 (brain activity post attention by 10 seconds). The y-axis indicates the different frequencies of brain activity, from 2 to 16Hz. Colour bar shows the strength of the association between attention and neural activity, indexed as a Mann Whitney Z value.

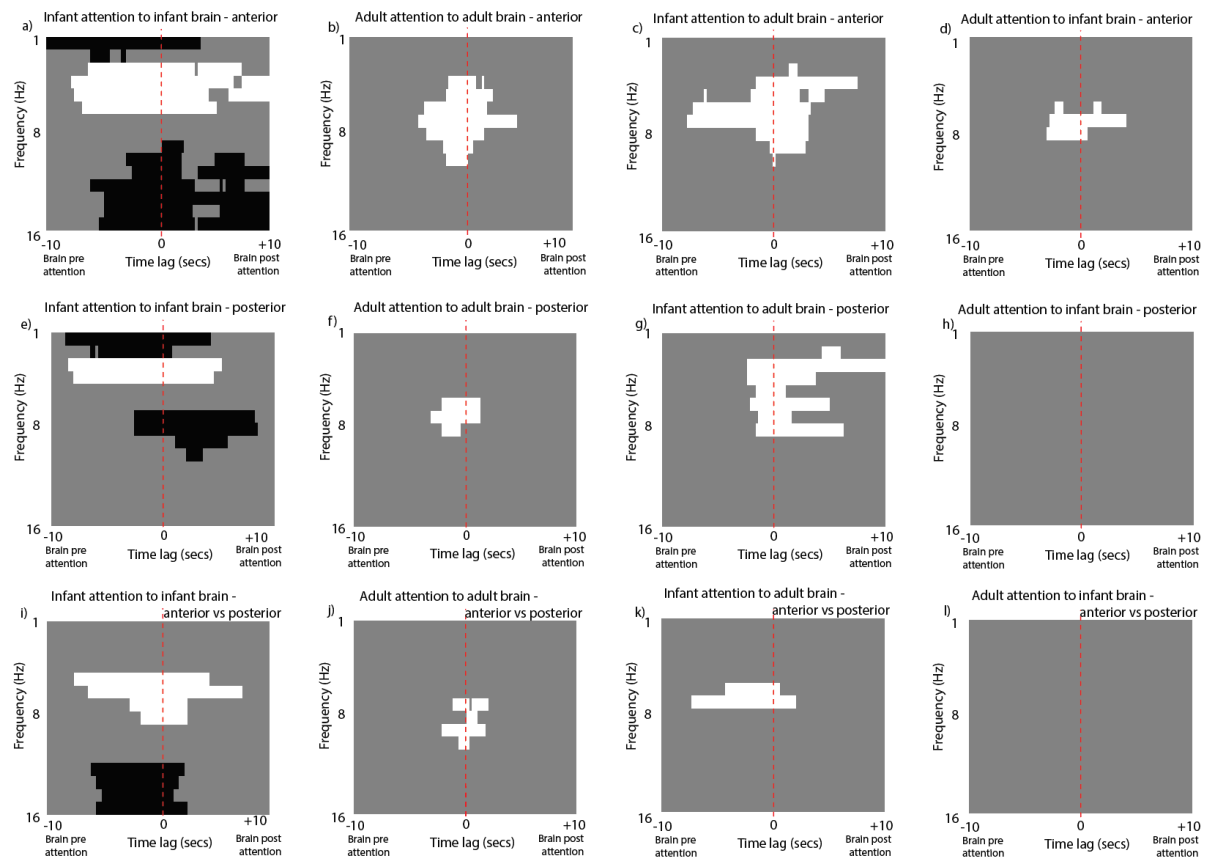


Figure 6: Results of cluster-based permutation tests for analyses in Figure 5. Figures a-h show the results of tests conducted to assess whether the relationships shown in Figure 5a-5h differ significantly from chance. Figures i-l show the results of tests conducted to assess whether anterior relationships were stronger than posterior ones (so Figure i shows a vs e, and so on). Areas shaded white indicate significant positive clusters, and areas shaded black indicate negative clusters ($p < .05$).

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Supplementary Methods

1.i EEG pre-processing and artefact rejection

Prior to artefact rejection data were concatenated across the Solo Play and Joint Play conditions for each participant, in order to ensure that all artefact rejection procedures were applied identically across conditions. First, low- and high-pass filters were applied using a third-order Butterworth filter to exclude activity below 1Hz and above 16Hz (see section 1.ii, below). Second, noisy channels were identified by calculating the power spectrum with Fast Fourier Transform (FFT) and summing the total power across the frequency spectrum. Channels for which the total power was greater than two inter-quartile ranges above the mean total power for all channels were excluded. The mean (*S.E.*) (range) of electrodes removed was 3.41 (*0.31*) (0-8) for infants and 2.00 (*0.21*) (0-5) for adults. In addition, the total power across the entire frequency spectrum was visually inspected for each channel at this stage, and data from a further 3 infants were excluded because the total power for all channels was markedly above the average total across all infants, and because visual inspection of the data confirmed that this was not due to factors such as sporadic noisy segments, or to ground noise that could be removed via ICA. (These 3 infants were already excluded prior to calculating the final participant numbers reported in the main Methods section.) Third, continuous data were segmented into two-second epochs, and the most egregious sections of noisy data were excluded prior to running the ICA. In order to ensure that comparable amounts of data were retained at this stage for infant and adult participants, this was done by calculating the max-min change on a per-channel, per-epoch basis, across all channels and epochs, and determining what level of this threshold would mean that 6% of data were excluded, separately for infants and parents. This threshold was set, for this coarse, initial rejection stage, at $\pm 181\mu\text{V}$ for adults, and $\pm 617\mu\text{V}$ for infants, reflecting a naturally higher amplitude of EEG oscillations in infants (de Haan, 2008). Visual inspection of the data confirmed that this stage exclusively eliminated gross motor artifacts due to head movements etc, which are commonly observed in infant EEG data (Georgieva, Lester, Yilmaz, Wass, & Leong, in press), and which if too prevalent can affect the accuracy of an ICA decomposition.

Fourth, an extended ICA algorithm was then run on the data using the runica algorithm implemented within EEGLAB in Matlab (Delorme, Sejnowski, & Makeig, 2007). The time-courses and spatial distributions of the ICs were visually inspected and the components accounting for ground noise, eye blinks, eye movements and other muscular and movement artifacts were then manually marked and removed (Jung et al., 2000). Fifth, channels that had been excluded at stage two were interpolated using the spherical interpolation function from EEGLAB (Delorme & Makeig, 2004). Sixth, a second max-min criterion was applied, identical to that applied at stage three but with more stringent criteria. For each epoch and for each channel, the max-min value was calculated. Epochs showing a difference $>\pm 80\mu\text{V}$ were excluded from the adult data. The percentage of epochs excluded at this stage was calculated for the adult data, and the threshold determined such that an identical proportion of samples from the infant dataset were excluded. For the infant data, this threshold value was $\pm 196\mu\text{V}$. The mean (*std*) proportion of epochs excluded at artefact rejection was 0.088 (*0.083*) for Infant JP; 0.064 (*0.075*) for Infant SP; 0.16 (*0.16*) for Parent JP; 0.033 (*0.050*) for Parent SP.

1.ii Test of filter edge effects

Following a request from the reviewers, we conducted an additional analysis to verify how far the Butterworth filters applied at step 1 of the artefact rejection procedure had edge effects within the 1-16Hz range. These analyses were applied to a subset of 16 datasets. The high- and

low-pass filtered data were compared with two comparison datasets: first, the same data but unfiltered; second the same data but applied with a different filter: symmetric high and low pass (1 and 20 respectively) FIR filters with a hamming window applied: order 3381 and transition slope was 0.25 (25%). The same process as described in the main text for a power analysis was then applied, and the results of the original filtered data were compared epoch-wise with the two comparison datasets. Results (see Figure S1a) suggest that relative power in the 1Hz bin is substantially lower for both the Butterworth and the comparison filter, indicating edge effects affecting this frequency bin. Epoch-wise correlations between the Butterworth filter and both the unfiltered and alternative filtered data are also relatively low for the 1Hz bin (~ 0.4) (Figure S1b). Relative power at other frequency bins is lower in the unfiltered data as a consequence of the filtering effect for the 1Hz bin, but the epoch-wise comparisons show high associations ($r > .8$) between the results of the Butterworth filter and both the raw data and alternative filter. As a result of this, the 1-2Hz bin was dropped from subsequent analyses but all other bins were retained.

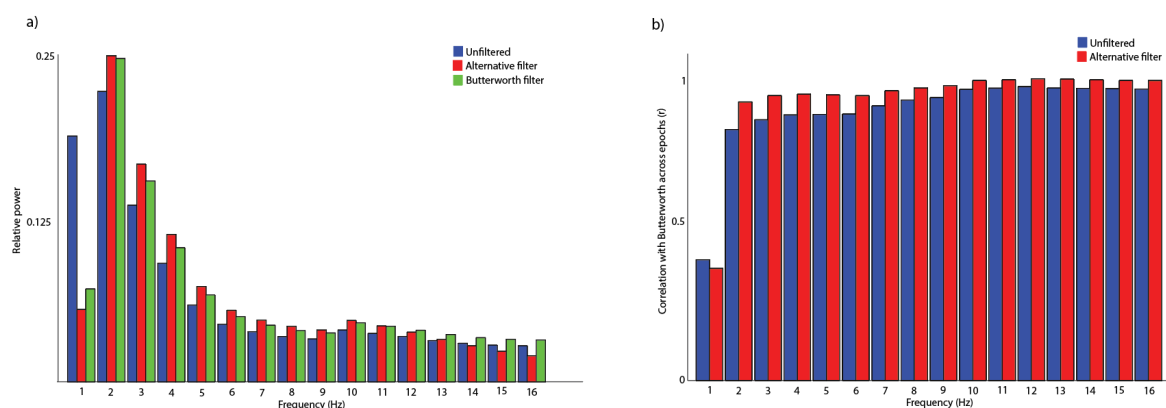


Figure S1: Comparison of high-and low-pass filtered data with two comparison datasets. Comparison conducted as described in the SM section 1.ii. a) Comparison of relative power; b) Correlation between Butterworth and comparison datasets.

1.iii Laplacian filter

The surface Laplacian filter was applied using the Matlab function `laplacian_perrinX.m`, supplied with the Current Source Density Toolbox (Cohen, 2014; Kayser & Tenke, 2006a). The Legendre polynomial was set at 7 and the smoothing parameter at 10^{-5} . Although the number of channels in the present study, 32, is below the normal suggested minimum of 64 channels (Cohen, 2014), this is not without precedent (Perrin, Pernier, Bertrand, Giard, & Echallier, 1987), and an evaluation of the performance of the algorithm with low-density recordings suggested that it provides accurate approximations of high-density recordings (Kayser & Tenke, 2006b). Figure S2 shows an illustration of absolute power from a sample infant participant before and after the application of the Laplacian filter.

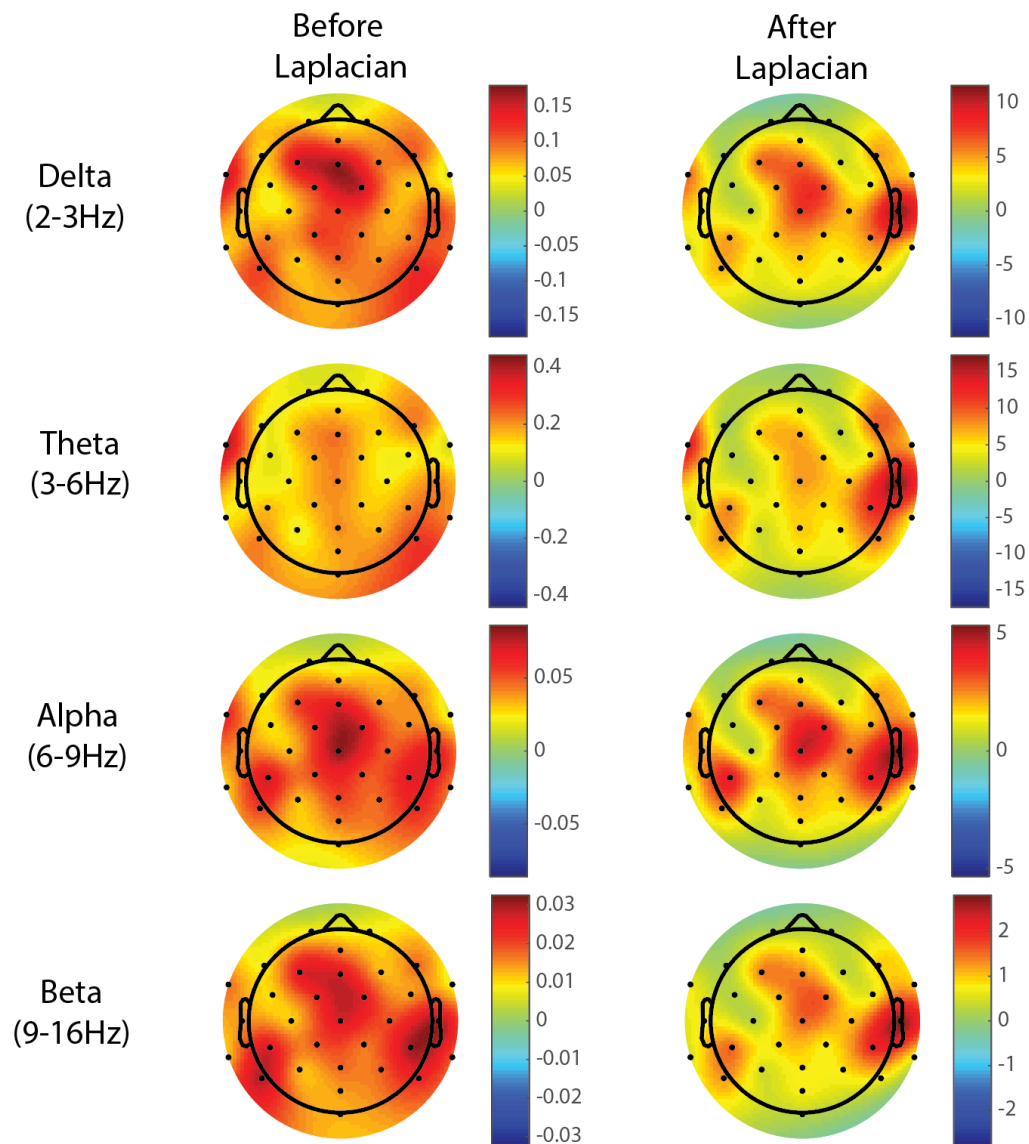


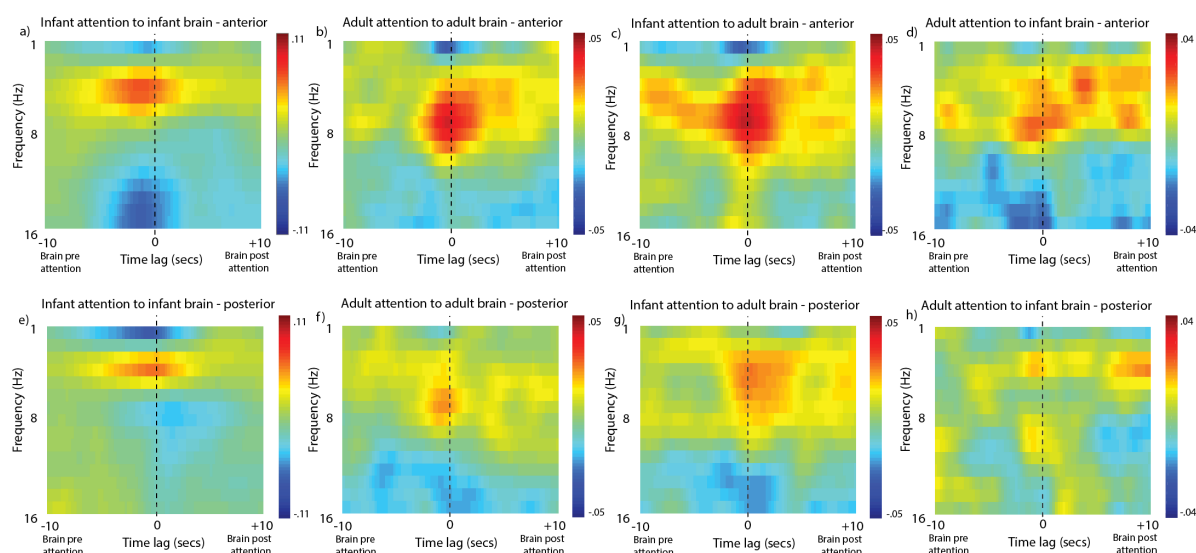
Figure S2: Absolute power from a sample infant participant before and after application of the Laplacian filter. Left: before filter; right: after filter. Top to bottom: frequency bands, from Delta to Beta.

1.iv Comparison analysis with point-biserial correlation instead of Mann Whitney U

For the analyses presented in the main text, we use a Mann Whitney U test to examine the time-lagged association between a continuous variable (EEG power) and a binary attention variable (attending/not attending). Since our use of the Mann Whitney U test in this way violates the assumption of independence of samples which is inherent in this test, which in some cases can severely affect its accuracy (McKnight & Najab, 2010), we also repeated our analyses using a point bi-serial correlation, in order to assess whether this was the case with the present dataset.

Whereas the Mann Whitney U test assesses how the association between EEG power and attention changes across different frequency bands of EEG activity and when a time-lag is introduced between the EEG and the attention variables, the point-biserial test assesses the correlation between EEG and attention. The point-biserial test is considered the appropriate test for assessing the correlation between a continuous variable (in our case, EEG power) and a binary variable (in our case, attention)¹. Note, however, that our use of the point-biserial test in this way also technically has shortcomings, insofar as it does not account for the dependence of data points within one variable (e.g., EEG power at point n is not independent from power at point n-1) (Tate, 1954).

Nevertheless, and in order to assess the similarity between these two tests when applied to our data, we repeated the analyses presented in Figure 5 (the primary results figure in the manuscript) using the point-biserial correlation test instead of the Mann Whitney U test. Our analyses were calculated using the Matlab function `pointbiserial.m`². In all other respects the analyses presented here are identical to those shown in Figure 5 in the main text. Although the units differ markedly, the results of the two tests are, for this measure, virtually identical.



¹ <https://stats.stackexchange.com/questions/342205/correlation-metric-for-0-1-vector-and-real-values-vector>
<https://medium.com/@outside2SDs/an-overview-of-correlation-measures-between-categorical-and-continuous-variables-4c7f85610365>

² <https://uk.mathworks.com/matlabcentral/fileexchange/11222-point-biserial-correlation>

Figure S3: Identical tests to those shown in Figure 5 of the main manuscript, but using the point-biserial correlation test instead of the Mann Whitney U test.

Supplementary Results

2.i – Supplementary Results for Analysis 2.1 – relationship of adult attention to infant brain activity

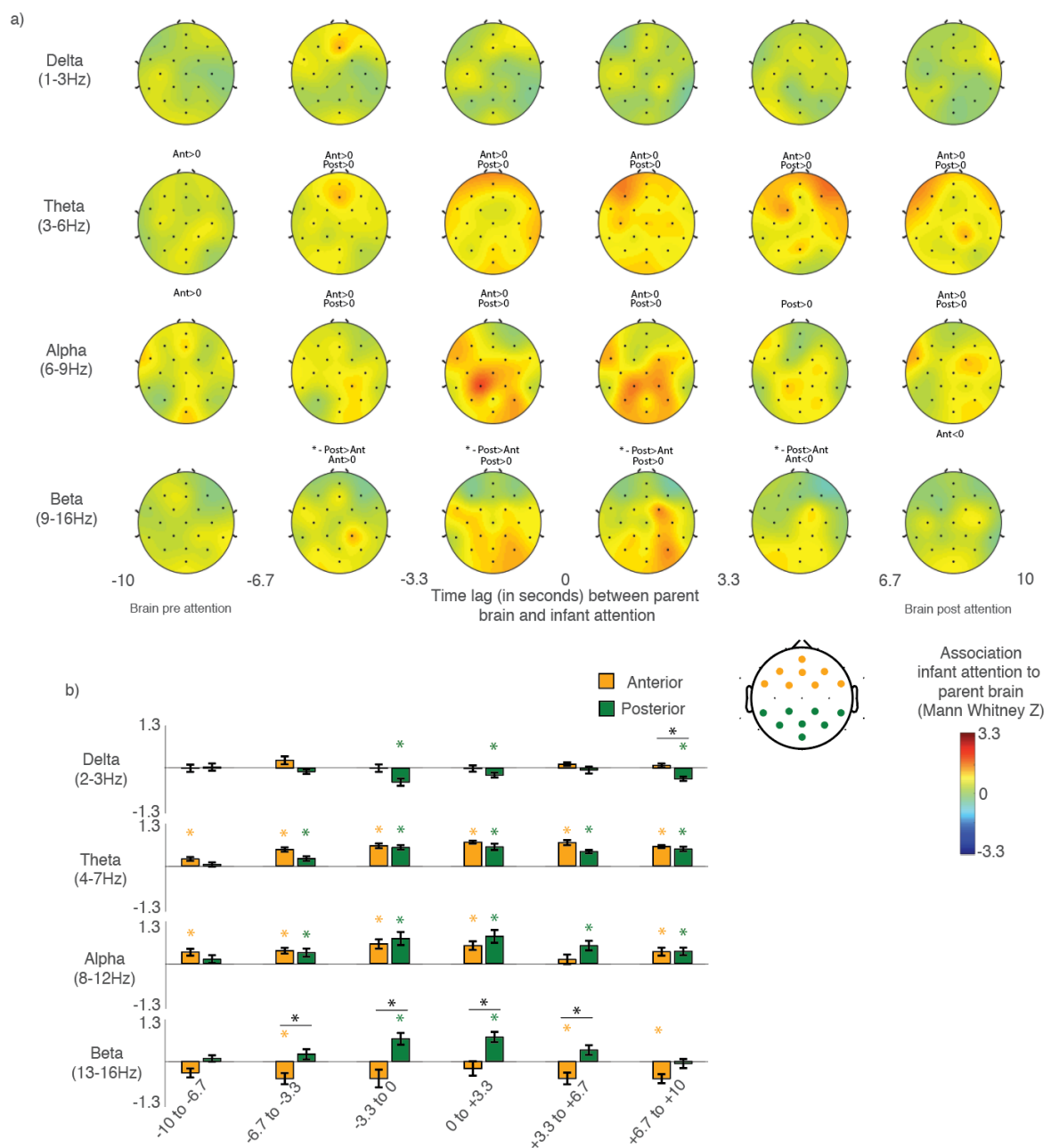


Figure S4: Cross-correlations between adult attention and infant brain activity. Frequency data were binned using the standard infant bins into: Delta (2-3Hz), Theta (3-6Hz), Alpha (6-9Hz) and Beta (9-15Hz), which are shown in separate rows. Time data were binned into different time windows from -10 to -6.7 secs (i.e., brain activity preceding attention by 10 to 6.7 secs) to +6.7 to +10 secs (i.e. brain activity 6.7 to 10 seconds after attention), which are shown in separate columns. Colour bar shows the strength of the cross-correlation between attention and neural activity, indexed as a Mann Whitney Z value. Text above the topoplots indicates the significant ($p < .05$) results from tests conducted to assess whether average anterior or posterior electrodes were higher. b) Bar-charts showing the same data as above, but binned into anterior and posterior electrodes using the electrode grouping shown in the legend. Coloured stars indicate that the result for that electrode grouping (anterior or posterior) differed significantly from 0, $p < .05$. Black stars indicate that the anterior vs posterior comparison differed significantly from zero.

Supplementary References

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