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Article

Asymmetric Prefrontal Cortex Activation Associated with Mutual Gaze of Mothers and Children during Shared Play

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Abstract: Mother–child shared play provides rich opportunities for mutual symmetrical interactions that serve to foster bond formation in dyads. Mutual gaze, a symmetrical behaviour that occurs during direct eye contact between two partners, conveys important cues of social engagement, affect and attention. However, it is not known whether the prefrontal cortical areas responsible for higher-order social cognition of mothers and children likewise exhibit neural symmetry; that is, similarity in direction of neural activation in mothers and children. This study used functional Near-infrared Spectroscopy (fNIRS) hyperscanning on 22 pairs of mothers and their preschool-aged children as they engaged in a 10-min free-play session together. The play interaction was video recorded and instances of mutual gaze were coded for after the experiment. Multivariate linear regression analyses revealed that neural asymmetry occurred during mother–child mutual gaze, where mothers showed a deactivation of prefrontal activity whereas children showed an activation instead. Findings suggest that mothers and children may employ divergent prefrontal mechanisms when engaged in symmetrical behaviours such as mutual gaze. Future studies could ascertain whether the asymmetric nature of a parent–child relationship, or potential neurodevelopmental differences in social processing between adults and children, significantly contribute to this observation.

Keywords: mother–child; parent–child relationship; parenting; mutual gaze; prefrontal cortex; brain; fNIRS

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1. Introduction

Mutual interactions between parent and child lay the foundation for bond formation in these dyads [1,2]. Through these interactions, dyads can exchange information on emotional states [3] and over time, form long-lasting attachments (e.g., [4,5]). It is worth noting that these dyadic exchanges are critical to the child's early social development [6–9] and thus present an important and dynamic area of interest among developmental researchers. parent–child dyads exhibit rhythmic changes in interpersonal interactions across the child's development, as can be seen when looking at temporal variations of behavioural and biological signals [10,11]. These temporally matched behavioural and physiological signals are consonant with the biobehavioural model of synchrony [12], which asserts that observed concerted behaviours in parent–child dyads, such as mutual gazes, correspond to coordinated patterns of brain activity [13].

One such context in which behavioural signals of parent–child symmetry manifests is in shared play. In particular, shared unstructured play can reveal naturalistic symmetrical behaviours (i.e., joint mutual gaze) as well as asymmetrical behaviours (e.g., turn-taking vocalisations) that may reflect real-life interactions outside the laboratory [14]. Numerous studies have shown that symmetrical behaviours, extremely important at the individual level [15], are often underpinned by the temporal matching of brain signals between two partners, known as inter-brain synchrony [16]. Our previous research has similarly demonstrated that instances of symmetrical behaviours in parent–child dyads engaging in unstructured play entrain inter-brain synchrony, with differential effects on dyads varying in parental stress levels [17]. Other studies have demonstrated converging findings in a variety of task paradigms in both parent–child dyads (e.g., [18–20] as well as beyond parent–child (i.e., adult-adult) dyads (see [21] for review).

Of particular interest to this paper is mutual eye gaze, whereby the parent and child establish direct eye contact with each other for a sustained period of time. This is for at least two reasons. First, mutual eye gaze is a unique case of symmetrical behaviour in that the attention is not towards an external object but instead between two social agents—that is, symmetrical social behaviour. Mutual eye gaze has also been shown to be critical in facilitating social communication and shared attention [22], both of which are prerequisites for effective parent–child interactions [23]. Second, previous research has demonstrated that mutual eye gaze underlies inter-brain synchrony [18]. One study by [18] employed an unstructured play paradigm, finding significantly greater inter-brain synchrony in parent–child dyads during instances of mutual eye gaze than instances of averted eye gaze (i.e., eye gaze of at least one social agent is away from their partner). Therefore, mutual eye gaze presents a conceptually and empirically valid measure of symmetrical social behaviour to elicit inter-brain synchrony among parent–child dyads in an unstructured play paradigm.

As far as we know, past research has predominantly examined mother–child dyadic brain responses during symmetrical behaviours by calculating inter-brain synchrony indexes of brain signals within dyads (see [10]). However, in limiting neural investigations to within-dyad computations of inter-brain synchrony, the extant literature has yet to provide a broader cross-dyadic perspective of neural symmetry of groups of mothers and children. In this paper, neural symmetry is defined as directional similarities in brain activation between two groups of dyadic partners. For example, concurrent activation of a specific region of interest between groups of mothers and children is a reflection of neural symmetry, whereas a divergent neural response, where one group exhibits an activation while the other shows a deactivation, would represent neural asymmetry. An understanding of neural symmetry of groups of mothers and children is critical in illuminating the processes that occur during symmetrical behaviours which are not specific to dyadic pairs but which are instead shared across types of dyadic partners (i.e., mothers and children). Therefore, this study aims to investigate the robustness of the association between the symmetrical social behaviour of mutual gaze and the symmetrical neural activity of groups of mothers and children. Since previous studies have shown that inter-brain synchrony during symmetrical behaviours typically emerges in the prefrontal cortex (PFC), which is responsible for higher-order social cognition [24,25], the present study hypothesises that symmetrical neural activity in the PFC, measured by separately analysing the PFC activity of mothers and children, will be associated with mutual eye gaze.

2. Materials and Methods

This study is a subset of a larger fNIRS project investigating parent–child dyads, which consists of two tasks. The co-viewing task involves dyads viewing animations together; studies have found that dyadic neural activities are associated with psychological variables including parenting stress, attachment, and gender differences [17,26–28]. The second task is a play activity, where a behavioural paper on the correlation between dyadic emotional availability, past interactions, and parenting stress [29], as well as a technical study on optimising parameters and strategies during the computation of inter-brain synchrony [30] have been published. The current study investigates prefrontal neural symmetry during mutual gaze in mother–child dyads during play.

2.1. Participants

This study and all its procedures were conducted in accordance with the regulations of the Declaration of Helsinki. The protocol was approved by the Institutional Review Board of Nanyang Technological University (IRB-2018-06-016). A total of 22 mother–child pairs where the children consisted of 13 boys and 9 girls (Mean Mothers' Age = 35.7 years, SD = 4.3; Mean Child's Age = 42.6 months, SD = 6.0) participated in this study. These dyads were recruited via social media (e.g., Facebook groups and forums). All potential participants were screened for eligibility, and those with any cognitive, medical, or physiological conditions that might impede their understanding or ability to perform empirical tasks were excluded. Mother–child dyads were included in the study if they fulfilled the following criteria: (1) mothers must be aged at least 21 years; (2) children must be aged 2–4 years; (3) dyads must be biologically related; (4) dyads must be staying in the same household. Each dyad is considered an independent data point. Prior to the study, informed consent was obtained from the parents, who also provided consent on their children's behalf. All participants were remunerated upon completion of the study. Data for this study are available at https://doi.org/10.21979/N9/R7D1UP (accessed on 21 October 2020).

2.2. Procedure

The demographic information of mother–child dyads and questionnaire data on parenting stress were collected online, after which mother–child dyads visited a child-friendly laboratory where the mother was briefed about the study. After informed consent procedures were carried out, the mother and child were seated side-by-side while they were fitted with a NIRSport, NIRx Medical Technologies LLC fNIRS cap of an appropriate size. The fNIRS setup operated at 760 nm and 850 nm wavelengths, with a scan rate of 7.81 Hz in hyperscanning mode using NIRStar version 14.2. Eight sources and seven detectors were used for this study, arranged in accordance with the international 10–20 prefrontal cortex montage to form 20 channels.

Typical preschool-aged toys [31] were placed in front of the participants; these included a doll, a cash register and grocery set, a tea-party set, a toy car, two plush balls, three preschool-aged children's books, and building blocks. For a total of 10 min, parents were asked to play with their child. The experiment was recorded in .MOV format using a Sony Handycam camcorder mounted on a tripod about 2 meters away from the dyads. Participants were debriefed and remunerated at the end of the experiment.

2.3. Behavioural Coding of Mutual Gaze

Different target behaviours were annotated during the experiment, focusing on joint actions (see [32] (preprint)). To annotate the behaviours, Solomon Coder software (Version: 22 March 2017; [33]) was utilised at a rate of 5 Hz or every 0.2 s. The presence of target behaviours was annotated as "1" while their absence was annotated with a "0", following which the annotations were exported as .csv files. Only joint behaviours of a minimum of 0.5 s were included in subsequent analyses. Two research assistants proceeded with microanalytic coding of the videos after obtaining 80% of inter-rater agreement score on a sample video, after which at least 80% of inter-rater agreement score was achieved across all videos. The "irr" package from RStudio was used to compute the inter-rater agreement scores [34].

In this study, we focused on the "Mutual Gaze" behaviour, indicating whether the mother and the child were looking at each other. Due to the temporal delay in the evoked haemodynamic response captured by fNIRS [35], which lasts for several seconds, a 5-s interval flanking a mutual gaze event was used to account for neural activity that occurred immediately before and after mutual gaze. In particular, we considered the interval from 5 s before to 5 s after each annotated Mutual Gaze event; consecutive events with a distance lower than 10 s were therefore considered as a unique event.

2.4. fNIRS Data Preprocessing

fNIRS Signals

The raw fNIRS signals were preprocessed using a semi-automatic procedure. Signals with high levels of noise ($CV < 5\%$, $0.7 < SCI \leq 1$) were determined and removed from further analyses using Coefficient of Variation (CV) and Scalp Coupling Index (SCI) as quality indicators [36,37]. The SCI is an index that reflects the quality of contact between each optode to the scalp of the participant. Segments which contained spike artefacts were detected and corrected [38], and the output was inspected for further noise artefacts. An Infinite Impulse Response band-pass filter from 0.01 to 0.2 Hz was applied to the optical data, in order to remove low- and high-frequency noise. The optical data were then converted into haemodynamic states using the modified Beer–Lambert Law. The oxygenated haemoglobin (HbO) and deoxygenated haemoglobin (Hb) concentration values for adult and child signals were obtained using specific differential pathlength factors [39]. For each channel, the HbO and Hb time-series signals were inspected to ensure that the final output is in accordance with typical oxygenated and deoxygenated waveforms. Channels are defined to have acceptable signal quality after they have passed this final manual inspection of the resulting signal output.

Cleaned HbO signals were normalised and aggregated across channels underlying the following clusters in order to obtain regional activation signals: frontal left, frontal right, posterior left, and posterior right areas of the PFC Figure 1. At least 3 channels were required to have acceptable signal quality in order for regional activation for a specific cluster to be computed.

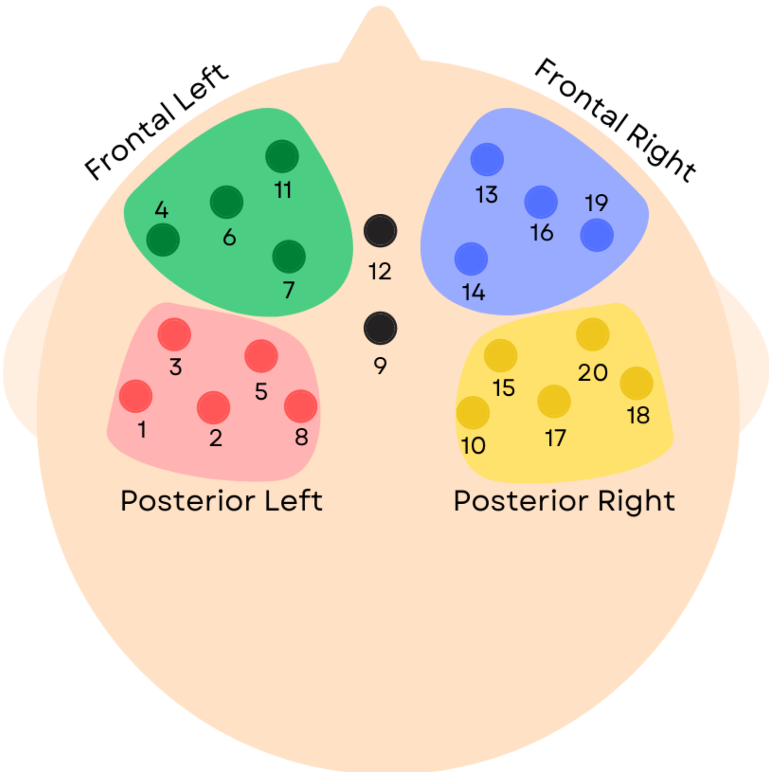

Figure 1. Schematic diagram of prefrontal clusters and their associated channels.

2.5. Analyses

Custom software based on the Python package nilearn (v.0.8.1) was used to conduct within-subject general linear model (GLM) analyses for each participant so that beta coefficients from each of the four clusters associated with mutual gaze events may be extracted. Next, a group-level analysis was conducted to investigate brain-activation patterns in groups of mothers and that of children. Multivariate regression analysis using a Ordinary

Least Squared (OLS) model was used to evaluate the difference in beta coefficients between mothers and children and between different clusters (i.e., Beta − Group (Mother/Child) + Cluster). Post hoc analysis focused on elucidating the difference between mothers and children. Then a t-test was used to assess differences between mothers and children. Following the results of the regression, where only the effect of parent, but not of clusters, was found to be significant, only one post hoc test was conducted (mothers vs. children), so the significance level would not need Bonferroni correction and should be alpha = 0.05.

3. Results

The results of the multivariate linear regression analysis ($R2 = 0.13$, $F(4, 118) = 4.29$, $p = 0.003$) showed an asymmetry between mothers and children in the values of the beta coefficients (see Table 1).

Table 1. Results of the multivariate linear regression. The intercept refers to frontal-left activation of children.

	Coefficient	**t**	***p*-Value**
Intercept	0.21	1.989	0.049
Mother	−0.39	−3.827	<0.001
Frontal Right	−0.1	−0.788	0.432
Posterior Left	−0.17	−1.128	0.262
Posterior Right	0.02	0.14	0.889

Specifically, positive beta coefficients were found for children, while negative values were found for mothers. No effect of cluster was found.

Then, beta coefficients were averaged across all clusters for all subjects (see Figure 2) and the post hoc *t*-test confirmed the difference between mothers and children ($t = -3.10$, $p = 0.004$).

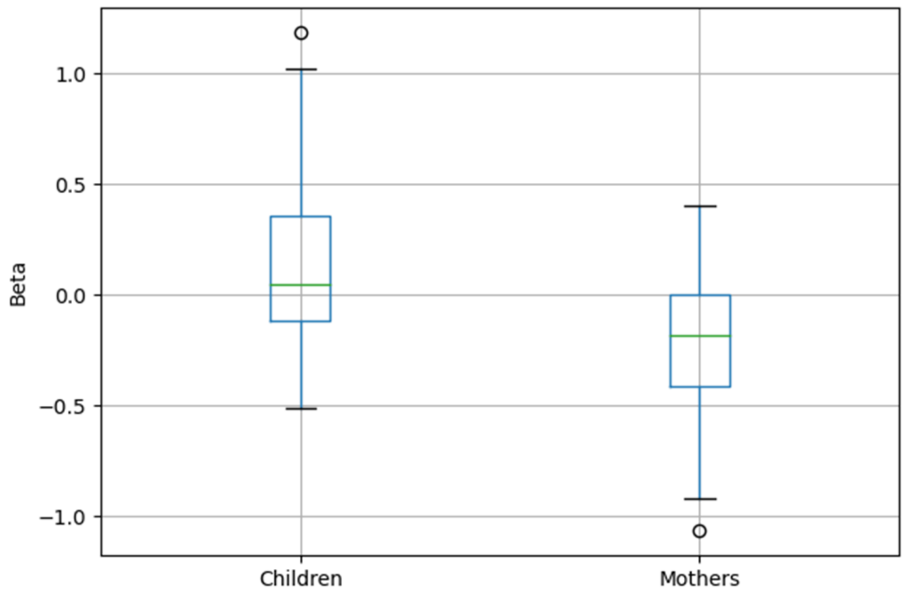

Figure 2. Distribution of the averaged beta-coefficients for Children and Mothers.

4. Discussion

Mutual gaze is a symmetrical social behaviour that fulfils an important function in facilitating emotional connection in dyadic partners. The present study sought to examine the neural activity that occurred in mother and child when dyads engaged in mutual gaze during shared play. Our central hypothesis, that we would observe symmetrical neural activity in the prefrontal cortex of groups of mothers and children during a symmetrical behaviour of mutual gaze, was not supported. Instead, this study revealed asymmetry in brain activation during mutual gaze, where one member of the dyad, the child, exhibited prefrontal activation while the other, the mother, exhibited a deactivation instead.

Findings on asymmetrical brain activity in mother–child dyads appear contrary to the prevailing literature, which largely suggests that symmetry in neural activity underpins mutual gaze in both adult–adult and adult–child pairs. For instance, several dual-fNIRS studies have shown that cross-brain coherence in the prefrontal cortex between two adults is enhanced during periods of mutual gaze [40–42]. The neural correlates of mutual gaze in adult–child pairs have also been investigated, with dual-EEG and dual-fNIRS studies likewise revealing an increase in coupling of brain signals between adult and child during mutual gaze (e.g., [18,20,43]). Notably, these studies employed computations of coherence from which a metric of similarity in the brain signals of two interacting partners was derived. In comparison, our present study investigated prefrontal activity in groups of mothers and children separately, and this difference in methodical approach could contribute to the neural asymmetry observed in mothers and children during mutual gaze in the present study.

However, our present study bears a resemblance to a recent fMRI study by [44], which used a similar approach of examining mothers' and children's brain activities as two independent groups. In their study, the researchers compared fMRI resting-state activity with frequency of mutual gaze during dyadic social interaction outside of the scanner, and observed different activation patterns in children compared to mothers. A positive association between frequency of eye contact and prefrontal activity of the middle frontal gyrus, as well as the anterior insula, was observed in children, but not in mothers. Conversely, a positive association between frequency of eye contact and maternal brain-activation was only observed in deeper structures of the anterior cingulate cortex and the precuneus of mothers. The asymmetry in findings of prefrontal activity in children and mothers in relation to frequency of mutual gaze mirrors our current observations which similarly showed prefrontal activation in children only, whereas mothers exhibited prefrontal deactivation. These observations point to potential differences in the brain mechanisms that occur in mothers compared to children during mutual gaze.

We posit two potential reasons that could explain the prefrontal asymmetry in mothers and children during a symmetrical behaviour of mutual gaze. First, the difference in prefrontal activity could have arisen due to the inherently asymmetric nature of a mother–child relationship. Compared to children, mothers have been found to more frequently initiate mutual gaze with their child during free play [45,46]. Children, however, typically attend to the toys provided during the play session and are more likely to engage in mutual gaze in response to their mother's bid for gaze. As such, the neural asymmetry in our study might be reflecting behavioural asymmetry in initiation and reciprocation of mutual gaze. Indeed, an extensive review of fNIRS studies by [47] on prefrontal cortex activity in young children has ascertained that prefrontal activation typically occurs in young children as they engage in tasks that require higher-order functions, such as inhibition and cognitive shifting. Attentional shift from the toys to engage in mutual gaze with the mother could require more cognitive control that is accompanied by prefrontal activation in children, whereas the same prefrontal cognitive processes might not be recruited in mothers, whose gaze and attention is primarily on the child.

Second, neurodevelopmental differences in the prefrontal cortex between children and mothers might also be driving the neural asymmetry observed during mutual gaze. Rapid expansion of the PFC occurs in young children under six years of age [48,49]. Compared to adults, the prefrontal cortex of young children is largely characterised by excessive neural and synaptic growth before undergoing a period of pruning and eventually reaching full maturation in adulthood. As such, prefrontal regions involved in higher-order cognitive and emotional functions may be recruited differentially in adults and children [50,51]. These neurodevelopmental differences are accompanied by striking distinctions in broader domains of social behaviours between adults and children. In a review on the maturation of sociality across the lifespan, ref. [52] posited that the central mechanisms of coordinated human interactions, namely perspective-taking, emotional encoding, and reciprocity of behaviours, are scaffolded progressively from childhood through to adulthood. From a developmental standpoint, gaze is considerably more deliberate and significant in mothers given the more developed social mechanisms in adults compared to children. Since mutual gaze requires top-down regulation [53], differences in prefrontal maturation of mothers and children could potentially contribute to the neural asymmetry observed during mutual gaze events in the dyads. Further research should be conducted to verify the plausibility of these proposed explanations.

Finally, findings from this study should be considered within the constraints of its limitations. First, this study examined only the prefrontal region of the brain, which precludes other relevant areas, such as the temporoparietal junction, which is also responsible for higher-order cognitive functions. Extending the brain region of interest beyond the prefrontal cortex could have captured neural symmetry or asymmetry which might have occurred alongside mutual gaze events. Second, this study was interested primarily in the brain responses that occurred during periods of symmetrical mutual gaze, and did not distinguish between the member of the dyad that initiated gaze and the one who reciprocated the gaze. Mutual anticipation of social behaviours such as direct eye contact has been shown to be accompanied by enhanced similarities in brain responses [20,53]. Subsequent research on this topic could explore brain responses in symmetry compared to asymmetric initiation of gaze. Third, this study did not consider other parameters of gaze, such as frequency and total duration of gaze in mother–child dyads, which could possibly influence prefrontal activity over time [44]. Finally, participants in this study did not wear eye-tracking systems, which would have provided more accurate and valuable information on gaze events, including specific directions of eye movements and computation of gaze durations to greater precision.

5. Conclusions

The present study has demonstrated that asymmetry in prefrontal neural activity occurs during the symmetrical behaviour of mutual gaze in mother–child dyads, which alludes to the possibility of mothers and children recruiting different prefrontal processes when engaging in mutual behaviours. Future research could ascertain whether this neural asymmetry is driven by the asymmetric nature of the mother–child relationship or by neurodevelopmental differences across children and adult populations. A deeper understanding of symmetry at brain and behavioural levels would add nuance to our knowledge of bio-behavioural synchrony that typically emerges in mother–child relationships.

Author Contributions: A.A. collected the data, analysed the data, and wrote the manuscript. A.B. conducted data analyses and edited the manuscript. J.P.M.B. and K.S.H.L. preprocessed behavioural data and wrote the manuscript. G.E. supervised the study and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of Nanyang Technological University (protocol code IRB-2018-06-016, 16 June 2018).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data for this study is available at https://doi.org/10.21979/N9/R7D1UP (accessed on 21 October 2020).

Conflicts of Interest: The authors declare no conflict of interest.

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