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Research paper

Social interactions between attachment partners increase inter-brain plasticity

Linoy Schwartz [a,*], Jonathan Levy [a,b], Carmel Salomonski [a], Itai Peleg [a], Olga Hayut [a], Orna Zagoory [a], Ruth Feldman [a,c]

[a] Center for Developmental Social Neuroscience, Reichman University, Herzliya, Israel
[b] Department of Criminology and Gonda Brain Research Center, Bar-Ilan University, Ramat-Gan, Israel
[c] Yale University, Child Study Center, United States

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ABSTRACT

Inter-brain synchrony between interacting partners is an important feature of social brain function, but whether neural coordination persists beyond the immediate social moment is unknown. Using hyperscanning EEG, we investigated whether a brief mother-adolescent face-to-face interaction induces sustained changes in inter-brain synchrony. We measured neural synchrony in the fronto-temporal network of 110 mothers and adolescents (55 dyads) during co-present resting-state recordings before and after a naturalistic, positively-valanced face-to-face interaction. We found enhanced inter-brain synchrony in the fronto-temporal network following the social interaction, indicating that positive social exchanges can temporarily modify patterns of neural synchrony. The magnitude of this post-interaction neural synchrony was mediated by the partners' behavioral synchrony during the interaction. Oxytocin increase from pre- to post-interaction predicted the increase in neural synchrony above and beyond behavioral synchrony, suggesting a distinct neuroendocrine path for inter-brain coordination. Results indicate that positive social interactions between attachment partners can induce short-term changes in neural synchrony that persist beyond the immediate exchange. Our findings suggest a potential mechanism by which repeated social experiences within attachment relationships may influence neural development and highlight the need to consider inter-brain dynamics in research on the social foundations of brain development.

1. Introduction

Social interactions play a critical role in shaping neural functioning throughout the lifespan, but their role in enhancing neuroplasticity through two-brain mechanisms has not yet been examined. Traditional neuroplasticity research has extensively documented experience-dependent changes within individual brains, including mechanisms such as long-term potentiation, dendritic remodeling, and the formation of new neural circuits (Citri & Malenka, 2008; Holtmaat & Svoboda, 2009; Turrigiano & Nelson, 2004; Zatorre et al., 2012). These neuroplastic processes enable learning and adaptation through Hebbian plasticity and homeostatic regulation (Bliss & Collingridge, 1993; Malenka & Bear, 2004; Turrigiano & Nelson, 2004). A growing body of evidence suggests that social interactions may specifically induce changes in neural functioning across interacting partners (Hasson et al., 2012; Hasson & Frith, 2016; Redcay & Schilbach, 2019). This phenomenon, which we refer to as "inter-brain plasticity," describes how social engagement may influence neural functioning between individuals beyond the moment-to-moment neural synchronization observed during interaction. In the current study, we examine whether such inter-brain plasticity may chart a novel pathway of experience-dependent modifications in social brain networks.

1.1. Social interactions and neural development

From infancy, humans display heightened neural sensitivity to social stimuli, with preferential responses to faces and face-like configurations (Johnson et al., 1991; Morton, 1991; Reid et al., 2017), human voices (Fifer & Moon, 1994; Vouloumanos & Werker, 2007), and biological motion (Simion et al., 2008). While these early predispositions reflect innate neural detectors for social stimuli, substantial developmental changes in face and biological motion perception occur throughout the first months and years of life that extend well beyond these initial biases (Farroni et al., 2002; Johnson, 2005; Tzourio-Mazoyer et al., 2002).

* Corresponding author at: Center for Developmental, Social, and Relationship Neuroscience, Reichman University, Herzlia 0460101, Israel.
E-mail address: linoy.schwartz@post.runi.ac.il (L. Schwartz).

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Critically, experience plays a fundamental role in sculpting these perceptual abilities through interaction with the social environment. For instance, infants develop race-specific tuning in face recognition, showing enhanced discrimination for faces from their own racial group by 6–9 months of age, a phenomenon that reflects the narrowing of perceptual categories based on the statistical regularities of faces encountered in their environment (Kelly et al., 2007; Sangrigoli et al., 2005). Similarly, voice perception becomes increasingly attuned to the phonetic categories and prosodic patterns of the infant's native language through cumulative exposure (Kuhl, 2004; Werker & Tees, 1984). This experience-dependent refinement illustrates how initial broad sensitivities become progressively specialized through neural plasticity mechanisms that optimize perception for the specific social and cultural contexts in which development occurs.

Early attachment relationships provide a critical context for social neural development (Ainsworth, 2013; Salter Ainsworth & Bell, 1981). Through repeated interactions, the infant and caregiver neurophysiological systems become aligned in ways that support optimal development, with the caregiver's mature regulatory systems scaffolding the infant's emerging neural architecture (Feldman, 2007, 2012, 2017). Measurable effects of these interactions have been documented across multiple neural systems, providing a particularly crucial context for understanding social influences on neural development. Longitudinal research has demonstrated specific pathways through which early caregiving experiences shape neural outcomes across development. One such example has been documented by Kok et al. (2015), who found that maternal sensitivity at 6 months predicted increased gray matter volume in multiple brain regions at 8 years, even after controlling for confounding variables (Kok et al., 2015). Similarly, Luby et al. (2012, 2016) reported that maternal support in early childhood predicted larger hippocampal volumes and accelerated hippocampal growth in school-age children, with effects moderated by early stress exposure (Luby et al., 2012, 2016). Conversely, Bernier et al. (2019) demonstrated that maternal sensitivity predicted decreased amygdala volume, suggesting differential effects across neural systems (Bernier et al., 2019).

At the functional level, maternal behavior marked by attunement to infant mental states at 13–15 months predicted enhanced connectivity between the default mode network and salience network by age 10 (Dégeilh et al., 2018), while mother-infant interactions characterized by positive affect and appropriate stimulation at 5 months predicted enhanced frontal resting EEG power at 10 and 15 months (Bernier et al., 2016). Whittle et al. (2014) found that positive parenting predicted attenuated volumetric growth in the amygdala and accelerated thinning of cortical regions during adolescence, reflecting more efficient neural maturation (Whittle et al., 2014).

These associations extend into adolescence and adulthood, with maternal sensitivity predicting more robust neural empathic responses to others' distress (Levy et al., 2019), enhanced neural processing of attachment cues (Moutsiana et al., 2015), and more consolidated amygdalar and insular responses to others' emotions (Morgan et al., 2023). A comprehensive 20-year longitudinal study by Ulmer-Yaniv et al. (2021) demonstrated that mother–child behavioral synchrony measured repeatedly from infancy to adulthood shaped the sensitivity of adults' neural empathic response to others' emotions, highlighting the enduring impact of early interaction patterns on neural function (Ulmer-Yaniv et al., 2023). Additionally, longitudinal studies have shown that mother–child behavioral synchrony from infancy onward predicts the magnitude of neural activation to attachment cues in adolescence (Levy et al., 2019; Pratt et al., 2019), and functionality of neuroendocrine systems involved in stress regulation, social bonding, and immunity (Feldman, 2017, 2023; Ulmer-Yaniv et al., 2023).

This dynamic neural coordination, initially established through parent–child interactions, evolves across development. By adolescence, neural systems become particularly attuned to broader social contexts, displaying heightened sensitivity to social influence and peer feedback (Berns et al., 2010; Blakemore & Mills, 2014; Sherman et al., 2016). Importantly, neural plasticity in response to social experiences does not end with childhood or adolescence; adults maintain significant capacity for neural reorganization across the lifespan (Balazova et al., 2021; Lövdén et al., 2013; May 2011; Schmidt et al., 2021; Voss et al., 2010), with continued social experiences shaping neural structures and functions (Davidson & Mcewen, 2012; Tost et al., 2015).

The social brain network, which includes regions such as the medial prefrontal cortex, superior temporal sulcus, and temporoparietal junction, specializes in processing social information and is tuned by social experiences (Adolphs, 2009; U. Frith & Frith, 2010; Redcay & Schilbach, 2019; Schurz et al., 2021; Feldman, 2021). This network exhibits substantial plasticity, as demonstrated by several longitudinal studies. For example, Valk et al. (2017) found that 3 months of socio-cognitive training focused on perspective-taking and compassion induced significant increases in cortical thickness in right inferior frontal gyrus and left anterior insula (Valk et al., 2017). In a subsequent study, Valk et al. (2023) showed that 9 months of targeted socio-cognitive training resulted in both structural and functional changes in regions associated with social cognition, including enhanced functional integration in temporal areas (Valk et al., 2023). Finally, Klimecki et al. (2014) reported that compassion training altered neural responses to others' suffering, increasing activation in medial orbitofrontal cortex, cingulate cortex, and ventral striatum. These findings collectively suggest that social brain networks remain adaptable through adulthood, responding to specific types of social learning and experience (Klimecki et al., 2014).

1.2. *Hyperscanning and Inter-Brain synchrony*

Hyperscanning methods, which allow simultaneous recording of brain activity from multiple individuals, have significantly advanced our understanding of inter-brain dynamics during social interactions (Babiloni & Astolfi, 2014; Czeszumski et al., 2020; Hari & Kujala, 2009; Konvalinka & Roepstorff, 2012). These techniques have been implemented across multiple neuroimaging modalities, including fMRI (Koike et al., 2019), EEG (Djalovski et al., 2021; Dumas et al., 2010; Endevelt-Shapira et al., 2021; Leong et al., 2017; Schwartz et al., 2022), fNIRS (Cui et al., 2012; Jiang et al., 2015; Q. Liu, Cui, et al., 2024; J. G. Miller et al., 2019), and MEG (Hirata et al., 2014), allowing for comprehensive characterization of neural synchronization at different spatial and temporal scales.

Studies using these methods have identified neural synchronization patterns across multiple brain regions during various forms of social exchange, including cooperation (Cui et al., 2012; Q. Liu, Cui, et al., 2024; J. G. Miller et al., 2019), joint attention (Koike et al., 2019), and naturalistic interaction (Dikker et al., 2017; Djalovski et al., 2021; Schwartz et al., 2022). Particularly robust synchronization has been observed between emotionally bonded individuals such as parent–child dyads (Endevelt-Shapira et al., 2021; Endevelt-Shapira & Feldman, 2023; Nguyen et al., 2020; Reindl et al., 2018) and romantic partners (Djalovski et al., 2021; Kinreich et al., 2017), suggesting that relationship quality modulates inter-brain coupling.

The biobehavioral synchrony framework (Feldman, 2012, 2015, 2017) provides a comprehensive theoretical basis for understanding these findings. This framework proposes that social interactions coordinate multiple systems—behavioral, physiological, and neural—between interacting partners in temporally precise ways. According to this model, the temporal coordination of social behaviors (e.g., shared gaze, affective expressions, vocalizations) is underpinned by synchronization of neural activity and physiological processes between interacting partners. This multi-level synchrony represents both the immediate mechanism of social interaction and a pathway through which repeated social experiences may shape neural development (Feldman, 2015, 2017, 2021).

Studies using hyperscanning have characterized fronto-temporal networks during parent–child interactions across development.

Enhanced neural synchrony has been observed during adult-infant and parent-infant social engagement (Leong et al., 2017; Nguyen et al., 2020; Piazza et al., 2020; Santamaria et al., 2020), with specific patterns of frontal-to-frontal synchrony facilitating information transfer between mature and developing brains (Leong et al., 2017). In preschool-age children, increased synchrony in frontal and temporal regions has been documented during naturalistic conversations and problem-solving with parents (Nguyen et al., 2020; Quiñones-Camacho et al., 2022) as well as cooperation and collaboration (Cui et al., 2012; Q. Liu, Cui, et al., 2024; Q. Liu, Zhu, et al., 2024; J. G. Miller et al., 2019; Wang et al., 2020).

Importantly, comparative studies have demonstrated relationship specificity in neural synchronization patterns. Reindl et al. (2022) found increased prefrontal synchrony in mother–child dyads compared to stranger-child dyads during both baseline and task conditions, independent of behavioral synchrony (Reindl et al., 2022). This suggests that enhanced neural coupling may reflect aspects of the attachment relationship rather than merely shared behavior or task engagement. Similar specificity has been observed in studies comparing parent-infant to stranger-infant (Endevelt-Shapira & Feldman, 2023).

Recent longitudinal research has demonstrated that maternal sensitivity at infancy predicts fronto-temporal neural coupling 12 years later (Schwartz, Hayut, et al., 2024), suggesting that inter-brain dynamics may serve as a mechanism through which early caregiving experiences become biologically embedded and continue to influence social neural function across development. This longitudinal perspective aligns with theoretical models suggesting that repeated experiences of interpersonal neural synchrony contribute to the development of specific neural architectures optimized for social cognition and interaction (Feldman, 2017, 2023; Wheatley et al., 2024).

Notably, while hyperscanning studies have extensively documented neural synchronization patterns during ongoing social interactions across various contexts and relationships (Djalovski et al., 2021; Endevelt-Shapira & Feldman, 2023; Leong et al., 2017; Q. Liu, Zhu, et al., 2024; J. G. Miller et al., 2019; Reindl et al., 2022; Schwartz et al., 2022; Schwartz, Hayut, et al., 2024; Schwartz, Levy, et al., 2024), a critical question remains unaddressed in the literature: does neural synchrony persist beyond the immediate interaction period? This temporal dimension is essential for understanding whether social interactions induce short-term modifications in inter-brain functional connectivity that might, through repetition, contribute to more enduring neural changes.

Limited evidence suggests that specific types of coordinated activity may temporarily enhance neural synchrony following interaction. For instance, Shamay-Tsoory et al. (2024) demonstrated that coordinated motor movements induced neural synchronization that persisted for several minutes after the activity concluded (Shamay-Tsoory et al., 2024). However, it remains unclear whether neural coupling observed during naturalistic social interactions, particularly within attachment relationships, shows post-interaction persistence. This question is particularly relevant given theoretical proposals about the role of repeated synchronous experiences in shaping developmental neural trajectories.

1.3. The Current Study

In light of the above, the goal of the current study is to address the specific gap in knowledge by examining whether positive mother–child interactions induce temporary changes in neural coupling that persist into a post-interaction resting-state. By comparing neural coupling during resting-state periods before and after a positive face-to-face interaction, we aim to investigate the short-term effects of social exchange on inter-brain dynamics. This approach allows us to distinguish between synchronization that occurs only during active interaction and potential short-term plasticity effects that persist beyond the interaction period.

We focused on mother–child dyads as a context where maternal attunement has been shown to significantly influence child neural development across multiple domains (Feldman, 2012, 2015b, 2015a; Levy et al., 2019; Pratt et al., 2017; Schwartz, Hayut, et al., 2024). Mother-child interactions represent a prototypical context for studying biobehavioral synchrony, as these relationships are characterized by well-established patterns of behavioral coordination that develop over years of interaction (Feldman, 2007, 2012, 2021) and are supported by specific neuroendocrine systems involved in affiliation and attachment (Feldman, 2017; Feldman et al., 2013).

Our study focuses on inter-brain synchrony in the beta rhythm, building upon previous research. Beta oscillations have been found to play an important role in social neural processing by modulating information flow in higher brain regions and supporting social functions such as empathy and understanding others ((Bressler & Richter, 2015; Friston et al., 2015; Levy et al., 2018; Pratt et al., 2018). Beta rhythms have also been found to facilitate key social processes including active information processing (Sedley et al., 2016), mentalization (Soto-Icaza et al., 2019), and prediction of others' actions (Koelewijn et al., 2008), functions relevant for inter-brain coordination. Hyperscanning studies have demonstrated cross-brain synchrony in the beta frequency during various social contexts, including cooperative tasks, compassionate responses, and face-to-face interactions (Ciaramidaro et al., 2018; Sinha et al., 2016; Yun et al., 2012). Individual factors such as trait empathy and joint attention predicted inter-brain beta synchrony (Dikker et al., 2021), and these rhythms have been shown to support natural communication between close relationships, including mother-adolescent dyads (Schwartz et al., 2022; Schwartz, Hayut, et al., 2024; Schwartz, Levy, et al., 2024). Given this evidence linking beta oscillations to social processing and interpersonal synchrony, we focused our analysis on inter-brain synchrony in the beta band.

Inter-brain synchrony has been quantified using the weighted phase lag index (wPLI), a connectivity measure that estimates the consistency of phase relationships between neural oscillations recorded from two different brains. The wPLI captures moments when neural activity in corresponding brain regions of two individuals becomes temporally coordinated, reflecting shared neural states that may underlie social connection and mutual understanding. Moreover, unlike simple correlation measures, wPLI specifically examines phase relationships while being robust to volume conduction and shared environmental noise that could create spurious connectivity (Vinck et al., 2011).

Inter-brain synchrony was examined within the fronto-temporal network, a system that underpins core processes of social cognition and mentalization. This network includes the lateral prefrontal cortex (LPFC), associated with executive control and goal-directed behavior (Dosenbach et al., 2008; E. K. Miller & Cohen, 2001); the medial prefrontal cortex (mPFC), implicated in self-referential processing, theory of mind, and social evaluation (Amodio & Frith, 2006a; Mitchell et al., 2005), and temporal regions such as the superior temporal sulcus (STS) and temporal-parietal junction (TPJ), which are essential for interpreting biological motion, perspective-taking, and mental state attribution (Saxe & Kanwisher, 2003; Schurz et al., 2014, 2021). Collectively, these areas constitute a distributed "social brain" network (C. D. Frith & Frith, 2007) that supports the detection, interpretation, and alignment of internal states during social interaction. Inter-brain synchrony within this network has been posited to reflect shared attention, mutual prediction, and affective resonance, and may form a neural substrate for the real-time coordination of behavior and emotion across individuals (Hasson et al., 2012; Redcay & Schilbach, 2019). Importantly, these fronto-temporal circuits have demonstrated substantial plasticity in response to various social experiences and learning paradigms (Davidson & Mcewen, 2012; Kolb & Gibb, 2011; Valk et al., 2017, 2023), making them prime candidates for examining short-term modifications following social interaction.

Two specific hypotheses were formulated: First, face-to-face interactions between mothers and their adolescent children will enhance

inter-brain synchrony within the fronto-temporal network, and this enhancement will persist into the post-interaction resting-state. This persistence would indicate short-term plasticity in inter-brain dynamics following social interaction, extending beyond the period of active engagement. We expect to observe increased synchronization when comparing post-interaction to pre-interaction resting-state measurements, reflecting temporary modifications in functional connectivity patterns induced by the social exchange.

Second, the degree of enhancement in post-interaction neural synchrony will be modulated by the amount of dyadic behavioral synchrony displayed during the face-to-face interaction. Consistent with the bio-behavioral synchrony framework (Feldman, 2012, 2017), we predict that dyads exhibiting greater behavioral coordination will show more pronounced increases in neural synchrony following the social interaction. Additionally, given Oxytocin's well-established role in promoting social bonding and affiliative behaviors (Feldman, 2015a; Feldman et al., 2013; Priel et al., 2019; Tillman et al., 2019), and emerging evidence suggesting its involvement in facilitating interpersonal neural synchrony and social coordination (Gordon et al., 2010; Levy et al., 2016; Shamay-Tsoory & Abu-Akel, 2016), we will examine whether changes in Oxytocin levels from pre- to post-interaction correlate with corresponding changes in neural synchrony. This investigation may illuminate potential mechanisms through which repeated social interactions could affect social brain development over time, while also providing a foundation for future studies examining longer-term plasticity effects across different relationship contexts and developmental periods.

2. Materials and methods

2.1. Participants

The study initially included 122 participants (61 mother–child dyads) recruited through community center advertisements and social media platforms. This dataset is part of a larger, ongoing research program examining mother–child synchrony and the effects of remote versus face-to-face interactions on inter-brain and behavioral synchrony patterns. Demographic information was collected via questionnaires. All mothers self-reported as biological mothers and primary caregivers. Mothers' mean age was 43.93 years (SD = 4.26), and children's mean age was 12.13 years (SD = 1.42). The children sample included 29 males. All participants self-reported as physically and mentally healthy, and all children were enrolled in mainstream public schools. The mothers provided written informed consent for themselves and their children. All experimental procedures were explained to participants beforehand, and they were informed of their right to withdraw at any time while retaining full compensation. Participation was compensated at a rate of $30 per hour. The study was approved by the Reichman University Institutional Ethics Committee and conducted in accordance with relevant guidelines and regulations.

The main inter-brain connectivity analysis was conducted on 55 dyads following application of exclusion criteria (detailed in section 2.4.1). The regression analysis examining associations between neural synchrony and behavioral measures was conducted on complete cases (n = 51), with four dyads excluded due to unavailable behavioral coding data.

2.2. Procedure

Participants arrived at the laboratory between 3 PM and 6 PM. This timing was chosen to minimize the effects of diurnal changes in Oxytocin (OT) reactivity, as research has shown this hormone fluctuates as a function of the time of day (Amico et al., 1981). Upon arrival, participants underwent a 10-minute familiarization period within the laboratory environment, during which no physical contact occurred between mother and child. During this period, participants received detailed information regarding the experimental procedure and were seated comfortably in the testing room. The primary objective of this familiarization phase was to ensure that participants could acclimate to the laboratory environment and that any stress related to arrival or exposure to the novel setting could dissipate, as such stressors are known to affect baseline hormonal levels (Dickerson & Kemeny, 2004). The no-contact protocol was specifically implemented to minimize the acute effects of Oxytocin release associated with physical touch between mother and child, which could confound baseline measurements and influence subsequent inter-brain synchrony patterns (Feldman et al., 2010; Uvnäs-Moberg et al., 2014). This approach allowed for the establishment of a controlled baseline state prior to the experimental manipulation, ensuring that observed neural, endocrine and behavioral synchrony patterns would reflect the specific interaction conditions rather than residual effects from pre-experimental physical contact. Following the familiarization phase, baseline saliva samples were collected from both participants. Following saliva collection, the mother and child completed the baseline resting-state paradigm, during which both participants were seated facing the wall, 50 cm apart, and were instructed to sit as still and quiet as they could.

Following baseline measurements, the mother and child were separated into different rooms where they engaged in a series of brief remote social interactions, including a phone call and text messaging exchange. All remote interactions focused on positive-valence topics to maintain consistency with the subsequent face-to-face paradigm. Following, the dyad was reunited for a 3-minute face-to-face interaction during which they were instructed to engage in a naturalistic conversation about a positive topic pre-determined by the researcher. The order and conversation topics were counterbalanced across participants and included planning a fun day together, organizing a camping trip, or planning an amusement park. These topics were selected to elicit positive emotions and natural social engagement between the mother and child.

Following these interactions, the mother–child dyads completed the post-interaction resting-state paradigm, which was identical in duration and structure to the baseline paradigm (see Fig. 1). This post-interaction period allowed for the measurement of neural activity changes resulting from the social interaction while maintaining comparable recording conditions to baseline. Upon completion of the post-interaction resting-state recording, saliva samples were collected again from both mother and child to assess Oxytocin changes following the social interaction sequence.

2.3. Dual EEG data Acquisition

We conducted simultaneous and continuous EEG recording for both participants throughout the experiment using a 64-channel BrainAmp amplifier (Brain Products Company, Germany). The EEG system comprised two Brain Product standard subtemporal BrainCaps, each equipped with an integrated chin belt and 32 electrodes. The electrodes were directly attached to the cap and arranged according to the international 10/10 system, an extension of the standard 10/20 system.

An analog 0.1–500 Hz band-pass filter has been applied, and data was sampled at 1000 Hz. Electrode impedances were maintained below 10 kOhm, with the ground electrode positioned at AFz. To ensure millisecond-range synchrony between the EEG recordings of the two participants, both EEG helmets were connected to the same amplifier.

2.4. EEG preprocessing

EEG data preprocessing was performed using Spyder 5.05 and Python 3.8, with the MNE software package (v0.17.0). Initially, each dyad's EEG recording was separated into two individual files to enable participant-specific preprocessing. Data were re-referenced to the Fz electrode, and a bandpass filter (1–50 Hz) was applied, following established protocols (Djalovski et al., 2021; Endevelt-Shapira et al., 2021; Endevelt-Shapira & Feldman, 2023; Schwartz et al., 2022;

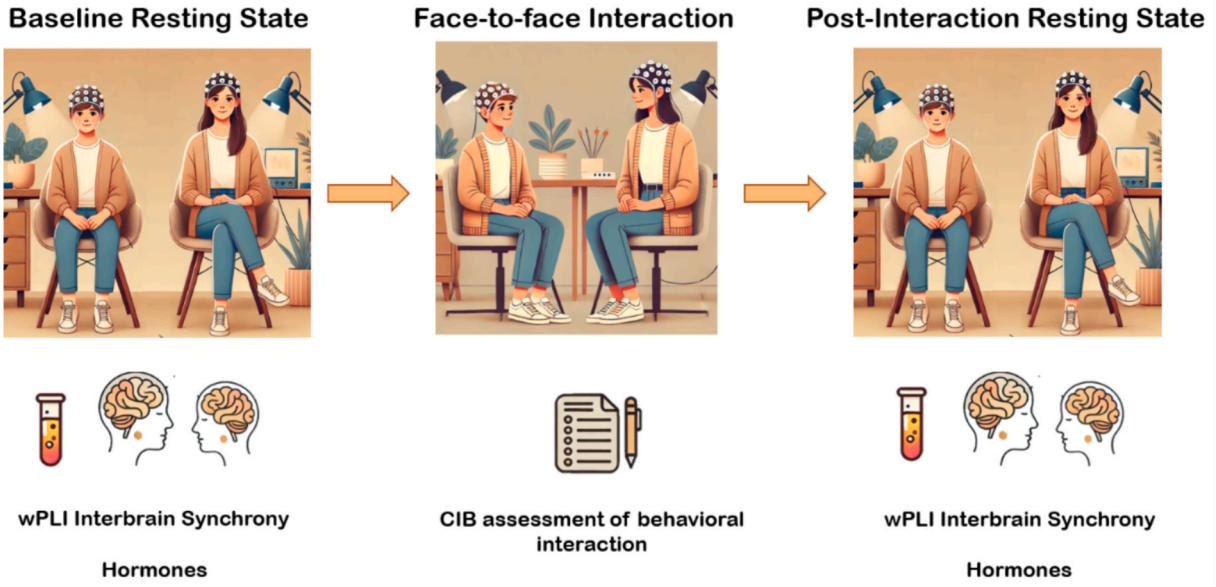


Fig. 1. Visualization of Study Procedure: Our research examined 55 mother–child dyads across a structured experimental sequence: The protocol began with baseline saliva collection for later Oxytocin analysis, followed by a 2-minute resting-state EEG recording, during which participants sat quietly 50 cm apart, facing a wall to avoid social cues. Dyads then engaged in a 3-minute naturalistic face-to-face interaction that was video-recorded for subsequent behavioral synchrony coding. Following the interaction, a second 2-minute resting-state EEG recording was conducted under identical conditions to the first baseline. The procedure concluded with post-interaction saliva collection for comparative hormonal analysis. This design enabled measuring changes in inter-brain neural synchrony from pre- to post-interaction while assessing behavioral and neuroendocrine correlates.

Schwartz, Hayut, et al., 2024; Schwartz, Levy, et al., 2024). The EEG data were then segmented into 1000 ms epochs with a 500 ms sliding window. Artifact removal proceeded in two stages: first, using an unsupervised Bayesian optimization algorithm (AR) to eliminate trials containing transient jumps in isolated channels and artifacts affecting channel groups, and second, through Independent Component Analysis (ICA). The ICA procedure utilized MNE's implementations of fastica and CORRMAP (Viola et al., 2009) to remove systematic physiological artifacts. Independent components related to non-physiological signals, eye blinks, eye movements, and muscle artifacts were manually identified and excluded, with these components serving as templates for systematic artifact removal across all participants (see Supplementary Fig. S1 for detailed visualization of artifact templates).

2.4.1. *Exclusion criteria*

Data quality assessment was conducted in two sequential stages: In the first stage, we excluded dyads with insufficient data quality, defined as fewer than 40 shared clean epochs (n = 3). The second stage of exclusion, following preprocessing, removed dyads exhibiting extreme neural synchrony values, defined as weighted phase lag index (wPLI) values exceeding ± 2.5 standard deviations from the condition mean within each sample (n = 3). Following these quality control procedures, the final analytical sample comprised 55 mother–child dyads.

For Oxytocin sample, samples with values exceeding ± 2.5 standard deviations from the condition mean within each sample were also removed from analysis, resulting in the exclusion of 6 samples (3 in each time point).

2.5. *Inter-brain connectivity analysis of the fronto-temporal network*

Inter-brain synchrony was calculated using the weighted phase lag index (wPLI), a robust connectivity measure (Vinck et al., 2011) that has been extensively validated for inter-brain connectivity studies across different developmental populations (Endevelt-Shapira et al., 2021; Endevelt-Shapira & Feldman, 2023; Levy et al., 2017; Schwartz et al., 2022, 2025; Schwartz, Hayut, et al., 2024; Schwartz, Levy, et al., 2024). The wPLI quantifies the consistency of phase relationships between neural oscillations while minimizing the influence of volume conduction and shared environmental artifacts that can lead to false-positive connectivity in naturalistic settings (Hardmeier et al., 2014; Vinck et al., 2011). This method employs a weighting scheme that ensures phase differences near zero (which may reflect volume conduction) contribute minimally to the connectivity estimate, while consistent non-zero phase lags reflecting genuine neural communication are emphasized (for implementation details, see Vinck et al., 2011; for MATLAB toolbox, see FieldTrip: (Oostenveld et al., 2011)).

Inter-brain synchrony was analyzed in the beta rhythm (13.5–29.5 Hz), during both baseline and post-interaction periods. The choice of beta frequencies was based on previous research, in which the beta rhythm has emerged as a critical marker of social connection and empathy: Studies have demonstrated that inter-brain beta synchrony underlies empathic communication between both attachment partners and strangers (Djalovski et al., 2021; Kinreich et al., 2017), as well as in experiencing compassion (Ciaramidaro et al., 2018) and cooperation (Sinha et al., 2016; Yun et al., 2012). The Beta rhythm has also been found to be involved in active thinking, joint attention, and mentalizing processes triggered by shared coordination (Sciaraffa et al, 2021). Furthermore, trait empathy and joint attention have been found to predict synchronization levels during face-to-face interactions (Dikker et al., 2021). In parent–child relationships, beta synchrony was found during both direct encounters and physical separation (Schwartz et al., 2021; 2023a, 2023b), and when exposed the same empathy-inducing stimuli in different rooms (Schwartz et al., 2025).

Analytic signals were computed using IIR filtering with a Hamming window to mitigate distortion and border effects, followed by the Hilbert transform (Ayrolles et al., 2021). In line with prior research (Djalovski et al., 2021; Dumas et al., 2010; Schwartz et al., 2022; Schwartz, Hayut, et al., 2024; Schwartz, Levy, et al., 2024), we divided the EEG cap into pre-defined regions of interest (ROIs) based on our research hypotheses, concentrating on frontal and temporal areas. We

focused our analysis on four ROIs, each represented by one electrode. The ROIs included the right frontal (RF – F4), left frontal (LF – F3), right temporal (RT – T8), and left temporal (LT – T7) brain regions. This resulted in 16 possible combinations of linkages between the four ROIs across both participants. wPLI inter-brain connectivity has been calculated for each dyad's ROI pair, and later for the entire shared network during both resting-state tasks, and allowed for a comprehensive assessment of inter-brain synchrony across key regions, while also providing a robust measure of the overall inter-brain network connectivity.

2.6. Behavioral coding

Notably, we distinguish between two levels of synchrony measurement in this study, reflecting different but theoretically related aspects of dyadic coordination. Behavioral synchrony, assessed through the macro-coding of dyadic behavior during face-to-face interaction, represents coordinated interaction patterns encompassing mutual responsiveness, empathic and emotional attunement. Neural synchrony, measured via wPLI, specifically quantifies phase synchronization between oscillatory brain signals for each paradigm, reflecting temporal alignment of neural activity between dyad members.

This multi-level approach allows us to examine complementary aspects of parent–child coordination, as behavioral and neural synchrony may capture different mechanisms underlying dyadic attunement. While these measures are theoretically related, they may operate through distinct pathways and show differential associations with neurobiological markers, providing a more comprehensive understanding of the multiple levels at which synchronization occurs during social interaction.

For the behavioral coding of the mother–child interactions during the face-to-face paradigm we used the coding interactive behavior manual (CIB; (Feldman, 1998)), a well-validated observational coding system. The CIB has been extensively employed across diverse cultural contexts, age groups, and clinical populations, generating over 300 publications (Feldman, 2012, 2021) and has been successfully implemented in hyperscanning research (Djalovski et al., 2021; Endevelt-Shapira & Feldman, 2023; Schwartz et al., 2022, 2025; Schwartz, Hayut, et al., 2024). The CIB is a macro-coding system that yields a total of 52 codes, each rated on 5-point scales that aggregate into theoretically-based constructs. In this study, we used the *Dyadic behavioral synchrony* construct, which comprises seven CIB codes: Dyadic reciprocity, Dyadic flow, Dyadic tension (reverse-coded), Dyadic reduction (reverse-coded), touch, child perseverance, and maternal expression fit. The *Dyadic behavioral synchrony* type of construct has been shown to be individually-stable in mother–child relationships (Feldman, 2010), to differentiate healthy from pathological conditions (Halevi et al., 2017), and to be associated with biomarkers including Oxytocin, Cortisol, and immune biomarkers (Yirmiya et al., 2018, 2020).

Behavioral coding was conducted by trained coders who were blind to study hypotheses. Inter-rater reliability was established using 20% of the interactions, with all codes exceeding 90% agreement (intra-class r = 0.93, range = 0.89-0.99). These behavioral assessments were then examined in relation to neural synchrony measures to investigate brain-behavior relationships.

2.7. Statistical analysis

2.7.1. Validation analysis – comparing inter-brain synchrony during Baseline Resting-state to Surrogate data

To validate the specificity of neural synchrony during baseline resting-state, we compared the inter-brain connectivity values (wPLI) between real dyads and surrogate data. Surrogate data were generated for dyads included in the main analysis by computing connectivity values between one member of a dyad (the mother) and the second member (the child) from another dyad. This process was repeated for all possible mother- other-child combinations. We applied a stringent quality control criterion, including only surrogate dyads that shared at least 50% clean epochs from the entire interaction period. This process excluded 4 surrogate dyads that did not meet the minimum epoch sharing threshold. The computation of surrogate connectivity values followed identical procedures to those used for real dyads. For each original dyad, surrogate values were averaged across all permutations to create a single representative surrogate value. Values exceeding 2.5 standard deviations from the mean of each inter-brain link were excluded as outliers.

To compare real versus surrogate connectivity patterns, we conducted a repeated-measures analysis of variance (ANOVA) with two within-subject factors: Condition (real connectivity vs. surrogate data) and ROI (16 possible combinations of inter-brain links).

2.7.2. Comparing inter-brain synchrony Baseline Resting-state to Post-Interaction Resting-state data

Following the validation analysis, our main analysis directly compared inter-brain connectivity values between baseline and post-interaction resting states. We employed a repeated-measures ANOVA with Condition (baseline resting-state, post-interaction resting-state) and ROI (all 16 possible combinations) as within-subject factors, examining connectivity across 16 ROI combinations using wPLI.

2.7.3. Brain-Behavior analysis

2.7.3.1. Mediation analysis. All statistical analyses were performed using Python (version 3.8) in a Windows 10 environment. Data were managed and processed with the pandas package, and ordinary least squares (OLS) regression models were fitted using the statsmodels package. Monte Carlo simulations has been used to estimate the indirect effect and its confidence intervals were conducted with numpy, employing a fixed random seed to ensure reproducibility. All scripts were executed in the Spyder IDE (Anaconda distribution). This workflow enabled systematic estimation of path coefficients, standard errors, p-values, and indirect effects within the mediation models.

To examine potential mechanisms underlying the relationship between baseline and post-interaction neural synchrony, we conducted a mediation analysis with dyadic behavioral synchrony occurring during the face-to-face interaction as the hypothesized mediator. Dyadic behavioral synchrony was quantified using the coding interactive behavior (CIB) system's dyadic synchrony construct (Feldman, 1998), which comprises measures of dyadic flow, reciprocity, perseverance, expression fit and touch, as well as tension and reduction (reverse-coded).

The analysis was conducted on complete cases (n = 51) from the original sample (N = 55), with four dyads excluded due to unavailable behavioral coding. The mediation model, employing ordinary least squares (OLS) regression, tested whether dyadic behavioral synchrony during face-to-face interaction mediated the relationship between baseline and post-interaction neural synchrony. We employed a standard three-path mediation analysis: (1) the effect of baseline resting-state neural synchrony on dyadic behavioral synchrony during interaction (path a), (2) the effect of behavioral synchrony during interaction on post-interaction neural synchrony controlling for baseline (path b), and (3) the direct effect of baseline resting-state on post-interaction resting-state neural synchrony controlling for dyadic behavioral synchrony (path c).

The significance of the indirect effect was tested using Monte Carlo simulation with 10,000 iterations, which generates a sampling distribution by randomly sampling from the distributions of the paths. Model assumptions were assessed using the Jarque-Bera test for normality of residuals and the Durbin-Watson test for independence of observations.

2.7.3.2. Multiple regression analysis. Finally, to examine the relationship between Oxytocin (OT) dynamics and post-interaction neural synchrony, we conducted an exploratory multiple regression analysis. Change in OT levels (ΔOT) was calculated as the difference between post-experiment and baseline Oxytocin levels ($\Delta OT = OT_{post\text{-}interaction} - OT_{baseline}$), with baseline samples collected upon arrival and post-experiment samples collected after the final resting-state recording. A multiple ordinary least squares (OLS) regression model was constructed with post-interaction neural synchrony as the dependent variable. The model included four predictor variables: (1) baseline neural synchrony, (2) dyadic behavioral synchrony during face-to-face interaction, (3) maternal ΔOT, and (4) child ΔOT. Model assumptions were assessed using the Jarque-Bera test for normality of residuals and the Durbin-Watson test for independence of observations.

2.8. Saliva sampling –Oxytocin measurement

Saliva samples were collected via passive drooling. In cases where participants experienced difficulty producing adequate saliva, they were instructed to perform jaw massage. All samples were maintained in ice throughout the experiment and subsequently stored at − 20°C.

Sample preparation involved multiple processing steps to optimize measurement accuracy. Initially, samples underwent three freeze–thaw cycles between −80°C and 4°C to facilitate mucus precipitation. The samples were then centrifuged at 1500g (4500 rpm) for 30 min. Following centrifugation, the supernatant was carefully transferred to clean tubes and stored at −80°C for a minimum of three days prior to freeze-drying. To enhance assay sensitivity, samples were concentrated four-fold through a four-day freeze-drying process, resulting in a powder form. This powder was stored at −20°C until analysis.

Oxytocin concentration was determined using the Cayman-OT ELISA kit (Cayman Chemicals, Ann Arbor, Michigan, USA), a widely accepted enzyme-linked immunosorbent assay methodology for salivary hormone quantification. On the day of analysis, samples were completely thawed and reconstituted in sample buffer. The assay was performed according to manufacturer's instructions using an auto-analyzer EVO75 (Tecan Germany), with all samples measured in duplicate. OT concentrations (in picograms per milliliter) were calculated using the Magellan program based on the kit's calibration curve.

Quality control measures included the addition of three internal controls (low, mid, and high range) to each plate. Samples from plates showing control deviations exceeding two standard deviations were excluded and reanalyzed. The inter-assay coefficients for both samples and controls were maintained below 24.1%, falling within the manufacturer's specified range.

3. Results

3.1. Validation analysis − comparing inter-brain synchrony during Baseline Resting-state to Surrogate data

To evaluate whether the baseline resting-state paradigm, in which the mother–child dyads were co-present, yet were not socially interacting, elicited significant neural synchrony, we compared the inter-brain connectivity values (wPLI) of the fronto-temporal inter-brain network of real mother–child dyads relative to surrogate data, comprised of mother-other-child surrogate dyads.

A repeated measures ANOVA has been conducted with Data type (real dyads, surrogate data) and ROI (16 possible combinations of the 4 ROIs comprising the dyads' fronto-tempoal network) as within-subject variables. First, a main effect for Data type has been observed ($F(1, 49) = 6.08$, $p = 0.017$, $\eta^2p = 0.11$), indicating a significantly greater inter-brain synchrony for the real dyads relative to the surrogate data in the baseline resting-state paradigm across the entire fronto-temporal network. No effect has been found for ROI ($F(15, 735) = 1.077$, $p = 0.38$, $\eta^2p = 0.02$), and no interaction between Data type and ROI has been found ($F(15, 735) = 1.01$, $p = 0.45$, $\eta^2p = 0.02$), indicating that the entire fronto-temporal network showed a similar pattern of greater synchrony for the real data, reflecting that mother–child formed inter-brain synchrony during their baseline resting-state interaction (See Supp. Table S1 for inter-brain synchrony in each inter-brain link).

3.2. Comparing inter-brain synchrony of mother–child dyads during Baseline and Post-Interaction Resting-state interactions

To examine whether positive dyadic interactions influence subsequent inter-brain coupling, we analyzed mother–child neural synchrony (wPLI) across the fronto-temporal network during pre-interaction (Baseline) and post-interaction resting-state periods.

A repeated measures ANOVA was conducted with Condition (baseline resting-state, post-interaction resting-state) and ROI (16 possible combinations of the 4 ROIs comprising the dyads' fronto-temporal network) as within-subject variables. While no significant effect was found for ROI ($F(15, 810) = 1.145$, $p = 0.31$, $\eta^2p = 0.02$), a main effect for Condition has been observed ($F(1, 54) = 9.69$, $p = 0.003$, $\eta^2p = 0.15$), indicating an overall greater inter-brain synchrony for the Post-interaction resting-state relative to the Baseline resting state across the entire fronto-temporal network. Finally, no interaction between Condition and ROI was observed ($F(15, 810) = 0.78$, $p = 0.7$, $\eta^2p = 0.01$), indicating that the entire fronto-temporal network showed a similar affect of greater neural synchrony following a positive face-to-face interaction (See Fig. 2 for main effect, Supp. Table S2 and Fig. S2 for detailed illustration of inter-brain synchrony in each inter-brain link).

3.3. Behavioral synchrony mediates changes in post-interaction neural synchrony

To examine the relationship between baseline and post-interaction neural synchrony, we conducted a mediation analysis evaluating both direct and indirect pathways, with the latter mediated by *Dyadic behavioral synchrony* during face-to-face interaction. Given the absence of ROI-specific effects in both baseline and post-interaction conditions, neural synchrony was quantified as the mean connectivity across the entire fronto-temporal network by averaging all 16 ROI combinations. Dyadic behavioral synchrony was assessed using the coding interactive behavior (CIB) system's dyadic synchrony construct (Feldman, 1998), which includes measures of dyadic flow, reciprocity, perseverance, expression fit, and touch, with tension and reduction as reverse-coded variables. This composite score ranges from 7 (minimum possible score, representing the lowest rating of 1 on each subscale) to 35 (maximum possible score). Our sample demonstrated scores in the upper range of this scale ($M = 27.4$, $SD = 2.24$), indicating generally high-quality dyadic interactions.

The overall model significantly predicted post-interaction neural synchrony ($F(1,49) = 5.430$, $p = 0.024$), explaining 10% of the variance ($R^2 = 0.100$), indicating a positive association between baseline neural synchrony and post-interaction neural synchrony (see Fig. 3).

While examining specific pathways, in the first phase of the model, baseline neural synchrony significantly predicted dyadic behavioral synchrony during face-to-face interaction (($F(1,49) = 8.06$, $p = 0.007$, path a: $\beta = 39.097$, $SE = 13.771$, 95 % CI [11.422, 66.771]), explaining 14.1 % of the variance of the Dyadic behavioral synchrony following Baseline resting-state ($R^2 = 0.141$) (See Fig. 3A).

In the second phase, the full model including both baseline neural synchrony and dyadic behavioral synchrony as predictors significantly predicted post-interaction neural synchrony ($F(2,48) = 6.709$, $p = 0.003$), explaining 21.8 % of the variance of post-interaction neural synchrony ($R2 = 0.218$). While the direct effect of baseline neural synchrony became non-significant (path c': $\beta = 0.179$, $SE = 0.140$, 95 % CI [-0.102, 0.459], $p = 0.207$), dyadic behavioral synchrony showed a significant effect (path b: $\beta = 0.004$, $SE = 0.001$, 95 % CI [.001, 0.006], $p = 0.010$) (See Fig. 3A).

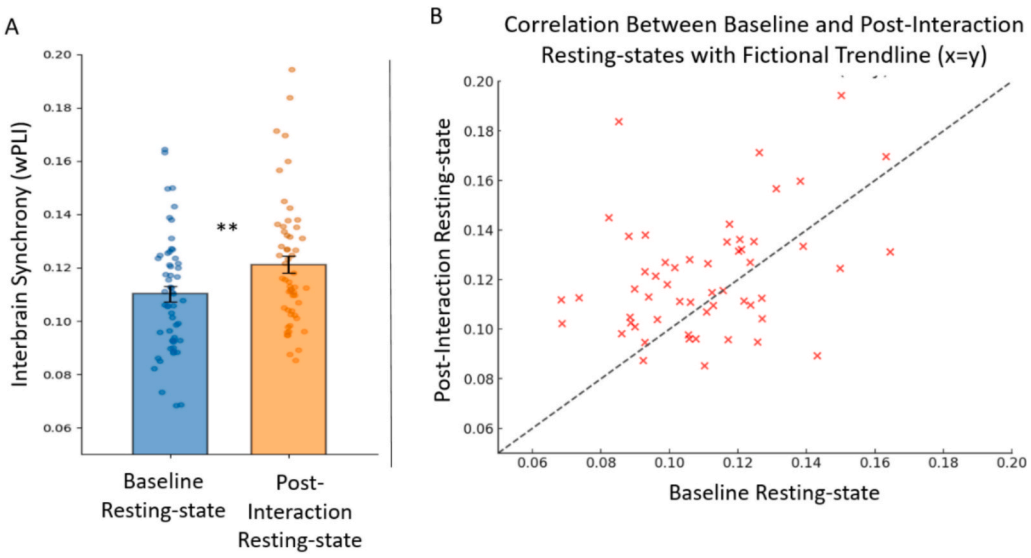


Fig. 2. Visualization of inter-brain synchrony analysis conducted on Baseline vs Post-Interaction Resting-state conditions: A: Visualization of inter-brain connectivity values (wPLI) measured during the Baseline and Post-Interaction Resting-states. The bar plot on the left depicts the overall connectivity (mean wPLI values) for each condition. The blue bar represents "Baseline Resting-state", and the orange bar represents "Post-Interaction Resting-state", with individual data points overlaid on each bar. Error bars denote standard errors of the mean (SE). B: Scatter plot on the right shows the relationship between Baseline Resting-state and Post-Interaction Resting-state values. Each red "X" represents an individual data point (wPLI values from Baseline and Post-Interaction Resting-states). The dashed dark gray line represents a fictional trendline (x = y) for reference, indicating equal values in both conditions. Axes are scaled from 0.05 to 0.2, reflecting the observed range of wPLI values. The scatter plot illustrates individual variability in inter-brain synchrony, highlighting greater synchrony during the Post-Interaction Resting-state phase.) (* = $p < 0.05$, ** = $p < 0.01$).

To test the significance of the indirect effect, we employed Monte Carlo simulation with 10,000 iterations. This analysis indicated that the total effect of the model was significant ($\beta = 0.320$, SE = 0.137, 95 % CI [.044, 0.596], $p = 0.024$), and confirmed that while the direct path became non-significant ($\beta = 0.18$, 95 % CI [-0.089, 0.45], p = 0.19] the indirect path through dyadic behavioral synchrony was significant ($\beta = 0.142$, 95 % CI [.021, 0.310], $p = 0.015$), with the mediation effect accounting for 44.2 % of the total effect (95 % CI [-0.04, 1.76]). The results indicate that behavioral synchrony significantly mediated the relationship between baseline and post-interaction neural synchrony (Fig. 3). Model diagnostics indicated appropriate distributions (Jarque-Bera test: JB = 2.882, $p = 0.237$) and independence of observations (Durbin-Watson = 2.210).

3.4. Behavioral synchrony and changes in hormonal levels predicts changes in Post-Interaction neural synchrony

Finally, to complement our mediation analysis and provide a comprehensive picture of factors influencing the post-interaction inter-brain synchrony, we examined how hormonal changes contributed to the enhancement in neural synchrony between baseline to post-interaction, alongside the previously identified behavioral and neural factors. Specifically, Oxytocin samples have been acquired from both participants upon arrival, as well as at the end of the experiment, and the changes in Oxytocin levels have been assessed in the model.

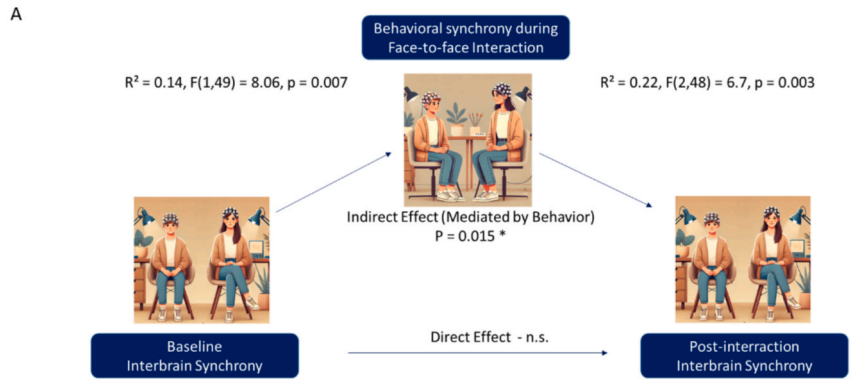
We conducted an OLS multiple regression analysis, with baseline neural synchrony, dyadic behavioral synchrony during face-to-face interaction, and both mother and child Oxytocin level change as predictors. The model significantly explained 41.3% of the variance of the post-interaction inter-brain synchrony ($R^2 = 0.413$, adjusted $R^2 = 0.355$, $F(4, 40) = 7.048$, $p < 0.001$) (see Table 1, Fig. 4).

Consistent with our previous findings, both baseline inter-brain synchrony ($\beta = 0.323 \pm 0.134$, standardized $\beta = 0.326$, p = 0.021) and dyadic behavioral synchrony during the face-to-face interaction ($\beta = 0.003 \pm 0.001$, standardized $\beta = 0.311$, $p = 0.042$) significantly predicted post-interaction inter-brain synchrony scores. Additionally, we found that the child's increase in Oxytocin following interaction positively predicted post-interaction inter-brain synchrony ($\beta = 0.0004 \pm 0.0002$, standardized $\beta = 0.311$, $p = 0.020$). The mother's changes in Oxytocin levels, on the other hand, did not significantly predict post-interaction inter-brain synchrony (β = -0.0002 ± 0.0001, standardized β = -0.171, $p = 0.225$, see Fig. 4B). Model diagnostics confirmed normality (Jarque-Bera test: JB = 0.373, $p = 0.830$) and appropriate independence of observations (Durbin-Watson = 2.161).

4. Discussion

A fundamental question in social neuroscience concerns how social experiences influence neural activity. While extensive research has established that individual brains exhibit plasticity in response to experience (Davidson & Mcewen, 2012; Kolb & Gibb, 2011; Tost et al., 2015; Valk et al., 2017, 2023; Zatorre et al., 2012), the capacity for social interactions to induce short-term changes in neural coupling between individuals remains elusive. The present study aimed to address this gap by investigating whether mother–child interactions could induce sustained changes in neural synchrony and how such changes are modulated by behavioral and hormonal factors. Guided by the biobehavioral synchrony framework (Feldman, 2017), we evaluated whether mother–child interactions could enhance fronto-temporal synchrony beyond the immediate interaction period. We also investigated the mechanisms by which social experiences may influence patterns of coordinated neural activity between interacting partners.

Several key findings emerged from our study. First, we found enhanced neural synchronization within the fronto-temporal network of mother–child dyads that persisted beyond the interaction period. These results extend previous research documenting real-time neural coupling between mothers and children during active interactions (Endevelt-Shapira et al., 2021; Q. Liu, Zhu, et al., 2024; S. Liu et al., 2024; J. G. Miller et al., 2019; Reindl et al., 2018, 2022; Santamaria et al., 2020; Schwartz et al., 2022; Schwartz, Levy, et al., 2024) Importantly, by demonstrating that neural coupling can persist into a post-interaction resting state, our findings suggest a temporary state of heightened



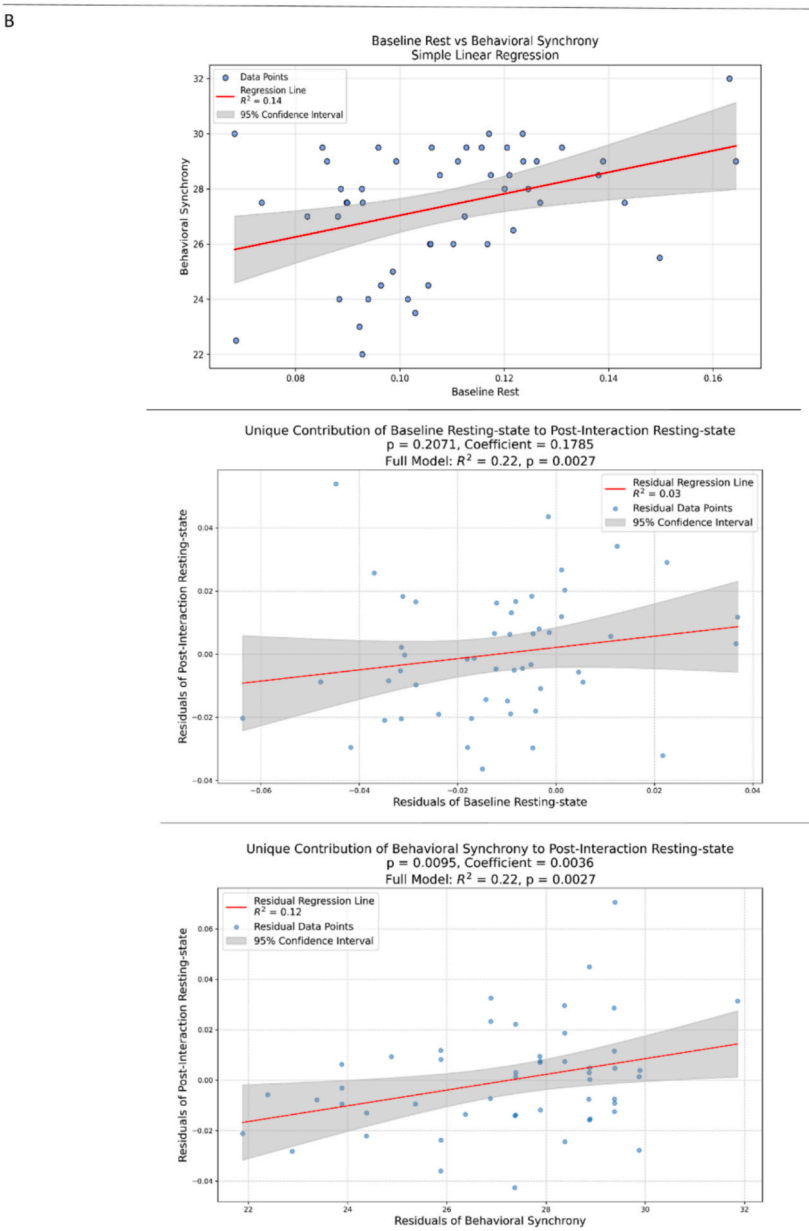


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Fig. 3. A. Behavioral synchrony mediates improvement in resting-state inter-brain synchrony. The mediation model illustrates the relationship between Baseline Inter-brain Synchrony, Dyadic Behavioral synchrony during interaction, and Post-interaction Inter-brain Synchrony. Baseline Inter-brain Synchrony (left) significantly predicted the Dyadic Behavioral synchrony during face-to-face interaction. The model then evaluated how Dyadic ehavioral synchrony and Baseline synchrony predict post-interaction inter-brain synchrony (right). While the contribution of Dyadic Behavioral synchrony was significant, the direct relationship between Baseline and Post-interaction Inter-brain Synchrony was not significant. Monte Carlo simulation with 10,000 iterations revealed that while the direct effect of the model was insignificant, the indirect effect of the model, mediated through Dyadic Behavioral synchrony was significant, with the mediation effect accounting for 44.2 % of the total effect. B. Illustrations of regression and contribution of each factor. First, path a of the model – Baseline Inter-brain Synchrony predicting Face-to-face Dyadic Behavioral synchrony. Second and third, the second part of the model, with both Baseline neural synchrony and Dyadic Behavioral synchrony as predictors of Post-interaction resting-state ($p < 0.05$).

Table 1
Regression Analysis of Resting-state Functional Connectivity Predictors.

Predictor	Unstandardized β ± SE	95 % CI	Standardized β	p-value
Baseline resting-state	0.323 ± 0.134	[0.051, 0.594]	0.326	0.021*
Dyadic behavioral synchrony	0.003 ± 0.001	[0.000, 0.006]	0.311	0.042*
Child OT change	0.0004 ± 0.0002	[0.0001, 0.001]	0.311	0.020*
Mother OT change	−0.0002 ± 0.0001	[-0.0004, 0.0001]	−0.171	0.225

inter-brain connectivity that extends beyond active engagement. This persistence complements perspectives suggesting that mother–child coordination serves as a fundamental template for social interaction, wherein maternal neural patterns may temporarily influence the child's brain activity following social engagement (Feldman, 2012, 2015a, 2020).

These findings contribute to the understanding of how social experiences influence neural functioning across development. Longitudinal research shows that maternal sensitivity is associated with children's neural development across multiple domains, from gray matter volume to functional connectivity in social-cognitive networks (Dégeilh et al., 2018; Kok et al., 2015; Rifkin-Graboi et al., 2015). Our results suggest a potential intermediate mechanism: single episodes of positive interaction may induce temporary changes in neural coupling that persist beyond the immediate interaction period. We propose that such temporary enhancement may represent a pathway by which repeated social experiences contribute to more stable neural adaptations, potentially explaining how early maternal behavior influences neural responses years later (Levy et al., 2019; Morgan et al., 2023; Pratt et al., 2019; Schwartz, Hayut, et al., 2024; Yaniv et al., 2021).

The observation of sustained synchrony specifically within the fronto-temporal network is consistent with these regions' established role in social cognition (Amodio & Frith, 2006b; Mars et al., 2012; Rilling & Sanfey, 2011) and their capacity for experience-dependent plasticity (Davidson & Mcewen, 2012; Kolb & Gibb, 2011; Lövdén et al., 2013; Valk et al., 2017, 2023). These networks exhibit functional flexibility, reflecting their capacity for dynamic reconfiguration in response to social experiences. The persistence of synchrony in these regions aligns with extensive hyperscanning literature suggesting that fronto-temporal areas serve as critical neural hubs facilitating neural alignment during social interaction (Zhao et al., 2024). Our findingngs suggest that these regions may maintain neural coupling patterns beyond social engagement, potentially supporting temporary maintenance of shared neural representations between interaction partners.

While the present study focus on social-emotional outcomes, the sustained neural coordination and Oxytocin reactivity following dyadic positive exchanges may have broader developmental implications. The enhanced inter-brain connectivity in fronto-temporal networks, regions critical for executive function, could create physiological states that scaffold subsequent cognitive processes (Werchan & Amso, 2017). This interpretation aligns with research demonstrating that parent–child interaction quality influences children's executive functions, attention regulation, and academic outcomes (Feldman et al., 1996; Feldman & Eidelman, 2009; Feldman & Greenbaum, 1997; Meuwissen & Zelazo, 2014). The neural synchrony and hormonal changes we observed may thus represent key mechanisms through which positive caregiver interactions promote broader cognitive development. Future research examining the temporal dynamics between caregiver-child neural synchrony and subsequent cognitive performance would provide valuable insights into these cross-domain effects during middle childhood and pre-adolescence.

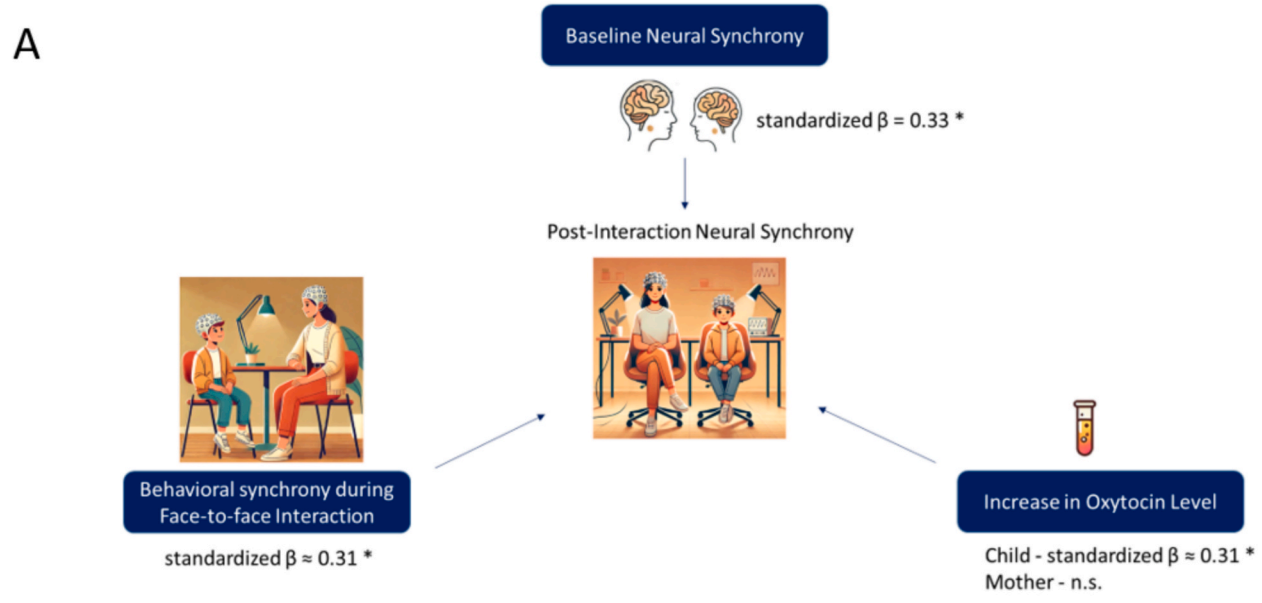
Our findings point to several factors that may modulate post-interaction neural synchrony. The robust link between dyadic behaviors during face-to-face interactions and subsequent inter-brain synchrony extends previous research connecting neural synchrony to prosocial behaviors (Djalovski et al., 2021; Endevelt-Shapira & Feldman, 2023; Schwartz et al., 2022). Notably, behavioral synchrony appears to influence not only immediate neural coupling but also its persistence beyond the interaction period, suggesting that interaction quality has lasting neural consequences.

The modulation by Oxytocin levels provides insight into neuroendocrine mechanisms underlying sustained inter-brain coordination. Notably, children's but not maternal Oxytocin change predicted enhanced inter-brain synchrony, reflecting developmental differences in Oxytocin system reactivity (Feldman, 2015a; Shamay-Tsoory & Abu-Akel, 2016). This finding aligns with evidence that children's Oxytocin systems exhibit greater plasticity and responsiveness to social experiences compared to adult systems (Feldman et al., 2013; Feldman & Bakermans-Kranenburg, 2017; Gordon et al., 2017; Scatliffe et al., 2019), enabling their neurobiological systems to more dynamically track social interaction quality. We propose that child Oxytocin reactivity may serve as a sensitive neurobiological indicator of empathic exchanges and a key mechanism through which social experiences become encoded in sustained neural coordination patterns.

At the mechanistic level, the persistence of neural synchrony suggests processes similar to short-term memory maintenance, where post-event neural activity reflects integration of recent experiences (Dudai, 2004; McGaugh, 2000). Just as memories become stabilized through post-encoding neural processes, social interactions may induce sustained neural coupling that supports temporary maintenance of shared social experiences. This aligns with neuroplasticity principles: when regions in different brains activate simultaneously during positive interaction, their coupling may persist briefly afterward (Markram et al., 2011), creating a neural 'echo' of the social experience.

Our findings align with several theoretical frameworks in social neuroscience. The biobehavioral synchrony model (Feldman, 2017) provides a comprehensive framework for understanding how inter-brain synchrony is influenced by relationship qualities, behavior, and neuroendocrine mechanisms. Our results support this model by demonstrating how behavioral synchrony and Oxytocin levels associate with neural coupling persistence. These findings also align with predictive processing frameworks (Friston, 2010) and the interactive brain hypothesis (Di Paolo & De Jaegher, 2012), which propose that social cognition emerges from dynamic interactions between individuals' neural systems. The observed persistence of enhanced neural coupling provides a potential mechanistic link between immediate neural synchronization and longer-term developmental effects that may emerge with repeated interactions.

The present study provides empirical support for theoretical



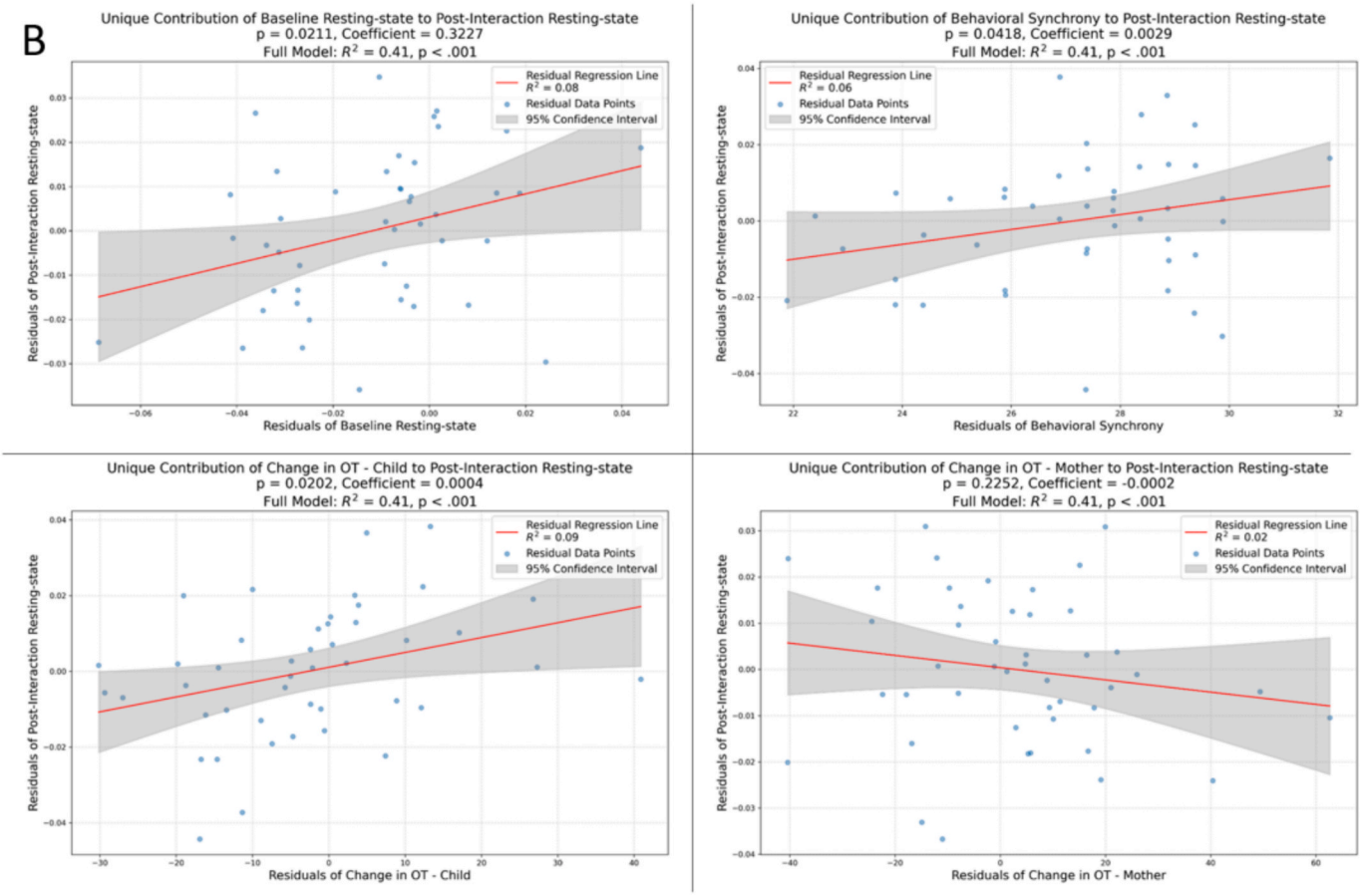


Fig. 4. A. Baseline neural synchrony, hormonal changes, and dyadic behavioral synchrony as predictors of post-interaction inter-brain synchrony. This model demonstrates how Baseline inter-brain synchrony, Dyadic behavioral synchrony during face-to-face interaction, and Oxytocin changes influence post-interaction neural synchrony in mother–child dyads. This model explains 41.3 % of the variance in post-interaction neural synchrony ($R^2 = 0.413$, adjusted $R^2 = 0.355$, $F(4,40) = 7.05$, $p < 0.001$). Baseline neural synchrony, as well as Dyadic behavioral synchrony during face-to-face interaction significantly predicted Post-interaction neural synchrony. Changes in Oxytocin levels in children significantly contribute to post-interaction synchrony, whereas maternal Oxytocin changes did not predict post-interaction inter-brain synchrony. B. Regression figures describing the specific contribution of each factor in the model to the multiple regression analysis (* = $p < 0.05$, ** = $p < 0.01$).

perspectives through dual-EEG hyperscanning, which enables simultaneous recording from multiple individuals (Babiloni & Astolfi, 2014; Czeszumski et al., 2020; Hasson et al., 2012; Konvalinka & Roepstorff, 2012). While previous hyperscanning studies focused on neural synchrony during active interactions (Djalovski et al., 2021; Endevelt-Shapira et al., 2021; Leong et al., 2017; J. G. Miller et al., 2019; Reindl et al., 2018; Schwartz et al., 2022), ur approach uniquely examined how neural alignment persists beyond interaction timeframes. This methodological advance has important theoretical implications: it suggests that temporary enhanced coupling states might contribute to more enduring neural activity patterns with developmental repetition, consistent with principles of experience-dependent neural adaptation (Blakemore & Mills, 2014; Davidson & Mcewen, 2012; Holtmaat & Svoboda, 2009; Kolb & Gibb, 2011).

While this study focused on inter-brain connectivity within fronto-temporal regions of mother–child dyads, future research examining both intra- and inter-brain synchrony changes could provide more comprehensive understanding of the neural mechanisms underlying these post-interaction effects. Investigating how individual neural organization changes from pre- to post-interaction could illuminate the scaffolding processes suggested by our findings and determine whether enhanced inter-brain synchrony reflects neural reorganization within individual brains, emergent dyadic coordination, or complementary processes at both levels. Understanding these dynamics would provide insights into how social experiences may reorganize individual neural networks and contribute to developmental effects of parent–child interaction.

Several methodological considerations should be noted when interpreting these findings. First, while dual-EEG hyperscanning provides unique insights into shared neural processes, the laboratory setting necessary for controlled EEG recordings may limit the ecological validity of social interactions. Second, our focus on fronto-temporal synchrony in the beta band, though well-justified by previous research, captures only one aspect of the complex neural dynamics underlying social interaction. Finally, our study examines short-term changes in neural synchrony and cannot address questions about long-term structural brain changes, which would require longitudinal neuroimaging designs.

Our findings suggest several directions for future research. First, multimodal neuroimaging approaches could provide more comprehensive characterization of the neural systems supporting sustained interpersonal coupling. Second, systematic manipulation of interaction parameters could help identify critical features that enhance or diminish post-interaction neural synchrony. Third, longitudinal designs could illuminate how repeated experiences of temporary neural coupling might relate to the development of social brain networks over time. Finally, investigation of different relationship types and interaction contexts could clarify the specificity and generalizability of these effects beyond mother–child dyads.

In conclusion, our findings advance understanding of how social interactions create temporary states of enhanced neural synchrony between mothers and children. The observed enhancement of inter-brain coupling following positive social interaction, modulated by both behavioral and neuroendocrine factors, reveals novel mechanisms by which social experiences may influence coordinated brain activity. These findings contribute to growing evidence that social interactions have immediate and measurable neural consequences, with important implications for understanding how early social experiences may shape neural development and social cognition.

CRediT authorship contribution statement

Linoy Schwartz: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jonathan Levy:** Conceptualization. **Carmel Salomonski:** Formal analysis, Data curation. **Itai Peleg:** Software, Investigation, Formal analysis. **Olga Hayut:** Investigation. **Orna Zagoory:** Investigation, Formal analysis. **Ruth Feldman:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.brainres.2025.149856.

Data availability

Data will be made available on request.

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