



Technologically-assisted communication attenuates inter-brain synchrony

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ABSTRACT

The transition to technologically-assisted communication has permeated all facets of human social life; yet, its impact on the social brain is still unknown and the effects may be particularly intense during periods of developmental transitions. Applying a two-brain perspective, the current preregistered study utilized hyperscanning EEG to measure brain-to-brain synchrony in 62 mother-child pairs at the transition to adolescence (child age; $M = 12.26$, range 10–14) during live face-to-face interaction versus technologically-assisted remote communication. The live interaction elicited 9 significant cross-brain links between densely inter-connected frontal and temporal areas in the beta range [14–30 Hz]. Mother's right frontal region connected with the child's right and left frontal, temporal, and central regions, suggesting its regulatory role in organizing the two-brain dynamics. In contrast, the remote interaction elicited only 1 significant cross-brain-cross-hemisphere link, attenuating the robust right-to-right-brain connectivity during live social moments that communicates socio-affective signals. Furthermore, while the level of social behavior was comparable between the two interactions, brain-behavior associations emerged only during the live exchange. Mother-child right temporal-temporal synchrony linked with moments of shared gaze and the degree of child engagement and empathic behavior correlated with right frontal-frontal synchrony. Our findings indicate that human co-presence is underpinned by specific neurobiological processes that should be studied in depth. Much further research is needed to tease apart whether the "Zoom fatigue" experienced during technological communication may stem, in part, from overload on more limited inter-brain connections and to address the potential cost of social technology for brain maturation, particularly among youth.

1. Introduction

Face-focused social interactions are a defining feature of humans that begin with the first social exchange between mother and infant, continue across childhood, adolescence, and adulthood, and afford the coordination of non-verbal social signals with the synchrony of physiological processes (Feldman, 2017; Hari et al., 2015), charting a mechanism of *bio-behavioral synchrony* that sustains humans' sociality throughout life (Feldman, 2012; 2021; Mogan et al., 2017). Indeed, collaborative abilities, proficiency in reading others' intent, and the capacity to share others' mental states have been theorized as key determinants of humans' supremacy over the animal kingdom (De Waal and Preston, 2017; Dunbar and Shultz, 2007). As socially-oriented creatures, humans' daily face-to-face interactions support maturation of complex cognitive skills, empathic abilities, and brain structure and functions (Hari et al., 2015; Hasson et al., 2012).

One mechanism hypothesized to underpin the universal effects of face-focused communication is inter-brain synchrony (Babiloni and Astolfi, 2014; Czeszumski et al., 2020; Liu et al., 2018). Inter-brain synchrony is defined as the temporal coherence of neural dynamics between multiple brains and has become a growing focus of research in social neuroscience (Czeszumski et al., 2020; Liu et al., 2018; Reindl et al., 2018). Several features of face-focused interactions have been highlighted as particularly important for enhancing inter-brain synchrony in ecological contexts, including the increased opportunities for shared gaze, social engagement, empathic resonance, and interpersonal reciprocity that are embedded in moments of social dialogue in daily life (Dikker et al., 2021; Djalovski et al., 2021). In particular, shared gaze has been repeatedly shown to facilitate inter-brain synchrony and enhance the communication of social signals toward the execution of a joint goal (Endevelt-Shapira et al., 2021; Hirsch et al., 2017; Kinreich et al., 2017; Koike et al., 2019; Leong et al., 2017; Piazza et al., 2020). Shared gaze is a key concomitant of neural coordination, asso-

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ciated with greater brain-to-brain coupling as compared to moments of averted gaze in both infants (Leong et al., 2017; Piazza et al., 2020) and adults in studies using both fNIRS (Hirsch et al., 2017) and dual EEG (Kinreich et al., 2017).

Still, while our species' enlarged brain has arguably expanded across primate evolution through social interactions in the natural ecology (Dunbar and Shultz, 2007), modern technology has offered the transfer of face-focused interactions to other modes of communication that do not require the partners' physical co-presence, an evolution that stretches our cultural and biological heritage to uncharted territories. We now communicate remotely through a variety of platforms and social media channels, such as Zoom or Skype (Anderson and Jiang, 2018). Social communication via technology has become a daily practice not only with business associates but also within close relationships, generating a paradigm shift in the development of our species with a potential impact on the social brain that is still unknown. With the COVID-19 pandemic, technologically-assisted communication became the main mode of social contact; children attended school via internet platforms, families met on Zoom, and classes, businesses, cultural activities, and, in fact, much of social life have turned into a technologically-assisted mode that enables people to keep in touch through screens.

However, despite opening possibilities for remote contact, technological communication has its drawbacks, among which is the reported "Zoom fatigue", the manifestation of tiredness associated with virtual communication (Wiederhold, 2020; Williams, 2021) that may be especially hazardous for adolescents. Data collected during the pandemic indicate that video chats are more exhausting (Nesher Shoshan and Wehrt, 2021) and the amount of daily usage predicts fatigue (Fauville et al., 2021) and depressive symptoms (Elbogen et al., 2022). Zoom fatigue may stem from four factors that are unique to remote communication and may intensify in adolescence. These include eye-gaze, the constant gazing during video chats; reduced mobility, the need to stay still in a narrow camera cone; mirror anxiety, stemming from the constant observation of own face; and cognitive load, the strain of managing multiple channels of verbal and nonverbal communication in a novel setting (Bailenson, 2021). These factors may be particularly difficult for adolescents, who are highly self-conscious (Fuhrmann et al., 2015), sensitive to evaluation-based anxiety (Gonzales and Hancock, 2011), and have an intense need for constant social connection (Frost and Rickwood, 2017; Hoare et al., 2016).

An additional aspect related to screen-based communication in adolescence is the growing increase in the amount of daily usage. Prior to the COVID-19, about a half of US teens reported being almost constantly online (Anderson and Jiang, 2018) and during the pandemic 97% of youth reported using social media to interact with friends (Villones et al., 2022). These data are worrisome in light of reports indicating that a dose of more than 2–3 h per day of technology-based communication is associated with poorer mental health (for review see Hoare et al. 2016). The transition to adolescence is a period of rapid brain reorganization (Blakemore, 2008), which marks it a time of increased vulnerability for psychopathology and social maladjustment (Fuhrmann et al., 2015). The combination of the aforementioned factors; the growing use of online communication, the heightened anxiety it elicits, the need for social contact, and the rapid brain maturation, renders research on the impact of technology on adolescents' social brain an important topic for social neuroscience that bears critical implications for tomorrow's world.

In light of the above, the current study examined the effects of technological communication on adolescents' social brain by utilizing a two-brain approach. We measured inter-brain synchrony between young adolescents and their mothers during live face-to-face interaction versus a remote video-chat using hyperscanning EEG. We focused on free interactions in ecological contexts consistent with the call to complement controlled experiments of the single brain with ecologically-valid studies of two-brain coordination during naturalistic exchanges (Hasson et al., 2012; Redcay and Schilbach, 2019). The choice to study the mother-

child relationship stemmed from the fact that this is the first context where processes of biobehavioral synchrony are acquired and practiced (Feldman, 2012, 2016, 2020), and studies have shown that mother-child interactions elicit greater neural coupling as compared to a female stranger (Endevelt-Shapira et al., 2021; Reindl et al., 2018); hence, this may provide an optimal context for such research by including partners who are highly familiar with each other's non-verbal signals and can use even the partial cues available through screens. Adolescents are the first generation for whom technologically-assisted communication is natural and practiced daily and this eliminates the potential confounding effects of unease or unfamiliarity on neural coordination.

Our specific study hypotheses were based on prior hyperscanning EEG and fNIRS studies that pinpointed several brain regions of inter-brain connectivity during naturalistic social interactions. These include; (a) homolog connectivity of same-area-same-hemisphere, such as temporal-to-temporal (EEG, Djalovski et al., 2021; EEG, Kinreich et al., 2017), central-to-central (Djalovski et al., 2021), and frontal-to-frontal connectivity (fNIRS, Azhari et al., 2019; fNIRS, Cui et al., 2012; fNIRS, Kruppa et al., 2021; fNIRS, Pan et al., 2017; fNIRS, Reindl et al., 2018; fNIRS, Wang et al., 2020); (b) cross-hemisphere same-region linkage, such as left temporal to right temporal connectivity; and (c) non-homolog multi-region linkage of same or different hemisphere, such as frontal-to-temporal (EEG, Pérez et al., 2017), frontal-to-parietal (fNIRS, Piva et al., 2017), central-to-temporal (EEG, Endevelt-Shapira et al., 2021; Pérez et al., 2017), central-to-parieto-occipital and centro-parietal and parieto-occipital connectivity (EEG, Dumas et al., 2010). Notably, most studies reported right-hemisphere connectivity of homolog or non-homolog regions (Cui et al., 2012; Dumas et al., 2010; Endevelt-Shapira et al., 2021; EEG, Jahng et al., 2017; fNIRS, Noah et al., 2020; Pan et al., 2017; EEG, Sciaraffa et al., 2021), suggesting that the right hemisphere, which matures early (Geschwind and Galaburda, 1985) and is implicated in non-verbal affective processing (Borod et al., 1998), may be particularly sensitive to two-brain communication. The multiple areas of neural linkage underscore the richness of cross-brain possibilities afforded by naturalistic interactions involving co-presence that may reflect numerous mechanisms triggered by different social goals.

Adolescence has rarely been studied from a two-brain perspective and our hypotheses were thus based on parent-child or affiliated adult pairs, which exhibit greater neural coupling as compared to strangers (Djalovski et al., 2021; Endevelt-Shapira et al., 2021). Cross-brain studies of younger children and parents showed frontal and temporal linkage. In fNIRS study of mother-child dyads (5–9 years), Reindl et al. (2018) found inter-brain synchrony in frontal areas, including dorsolateral prefrontal and frontopolar cortex during a cooperation interaction (Reindl et al., 2018). A set of studies conducted on preschoolers (4–6) and their mothers revealed that the dyads exhibited neural synchrony in temporo-parietal and prefrontal areas during free conversation (fNIRS, Nguyen et al., 2021) as well as cooperative play (fNIRS, Nguyen et al., 2020b) and greater frontal neural synchrony emerged during recovery as compared to a frustration task (fNIRS, Quiñones-Camacho et al., 2020). Miller et al. (2019) replicated the frontal right dorsolateral and PFC synchrony during cooperation between mothers and their 8–13-year-old children (fNIRS, Miller et al., 2019). Wang et al. (2020) found that children (5–11) with ASD showed higher parent-child inter-brain synchrony in frontal regions during cooperation compared to non-interactive tasks and neural synchrony was modulated by autism symptoms, highlighting the contribution of the child's ability for social engagement to cross-brain linkage (Wang et al., 2020). Finally, in cooperation versus competition tasks across wide age range (8–18), frontal-frontal synchrony emerged in both cooperation and competition (Kruppa et al., 2021), suggesting a shift in neural dynamics as children grow (Jager et al., 2015). Mother-daughter dyads aged 10–18 showed greater synchrony as compared to stranger-child dyads for both competition and cooperation in prefrontal areas (Reindl et al., 2022). Studies of other affiliative bonds, such as romantic partners or close friends, implicated temporal regions of cross-brain

connectivity (Djalovski et al., 2021; Kinreich et al., 2017) and showed their links with episodes of shared gaze and the partners' reciprocity and social engagement. Overall, these studies pinpointed frontal and temporal areas as potential targets for cross-brain linkage between attachment partners and demonstrated brain-behavior coupling with involved social behavior.

Framed within the emerging field of naturalistic cross-brain neuroscience, three hypotheses were formulated. First, we expected the live face-to-face interaction to trigger significantly more inter-brain connections across widely-distributed areas compared to the technologically-assisted communication. Second, focusing on frontal, temporal, and central regions that have been detected in prior hyperscanning EEG and fNIRS studies, we expected the live interaction to elicit inter-brain linkage of three types: (a) homologous (same area, same hemisphere), (b) cross-brain (same area, different hemisphere), and (c) multi-dimensional (cross-region of both same and cross hemisphere). Consistent with prior studies of affiliated partners, we hypothesized strong linkage of frontal and temporal regions. Finally, guided by the *bio-behavioral synchrony* frame (Feldman, 2012, 2017, 2021), we complemented assessment of neural synchrony with both micro-level coding and global rating of social behavior and focused on episodes of shared gaze and on the degree of children's empathic social engagement, consistent with studies that pinpoint their contribution to inter-brain synchrony (Dikker et al., 2021; Kinreich et al., 2017). Based on prior work (Djalovski et al., 2021; Endevelt-Shapira et al., 2021; Kinreich et al., 2017; Levy et al., 2017), we expected brain-behavior coupling during the live social interaction (Mu et al., 2016), with more neural connectivity linked with increased gaze synchrony and greater social engagement. The degree of brain-behavior coupling in the remote interaction, however, remained an open question. Finally, beta rhythms have been implicated in parent-child attachment processes in both mothers' (Hernández-González et al., 2016; Kringelbach et al., 2008) and young adolescents' brains (Pratt et al., 2018). In naturalistic cross-brain studies, beta synchrony has been shown to sustain communication between romantic couples and close friends (Djalovski et al., 2021), to underpin empathy and compassion (Ciaramidaro et al., 2018), and to link with behavioral social engagement and shared gaze (Dikker et al., 2021), and we thus focused our search on cross-brain beta-band synchrony.

2. Materials and methods

The entire study was preregistered: <https://osf.io/swun7/>

2.1. Participants

We recruited 140 participants, comprising 70 mother-child pairs, through ads posted in schools and social media. Children were 12.26 years old (SD = 1.21, 44% males, 66% firstborn), healthy, and attended state-controlled typical (not special education) schools. Mothers were 43.74 years old (SD = 4.41), had an average 16.96 years of education (SD = 2.5), and were the biological mother and primary caregiver. All families were of middle-class background and 81% lived in the same household as the child's father. The study was completed before the COVID-19 pandemic. The experiment was approved by the Reichman University institutional ethics committee and all mothers signed a written informed consent for themselves and their children. All procedures were explained to the participants prior to the experiment and they were free to leave the experiment at any time with full compensation. Participants were reimbursed for study participation (\$30 per hour).

2.2. Procedure

The study took place in two adjacent experimental rooms and included three sessions recorded with dual-EEG. The first session was a recording of the mother and child's brain in rest state (Rest) when partners are in the same room facing the wall and instructed not to interact.

The second and the third sessions were counter balanced across participants, with half of the participants beginning with the live interaction (Face-to-face) and half with the remote communication paradigm (Video-chat). In the live interaction, the mother and child were sitting facing each other and were instructed to socially interact on a planned positive topic (see below). In the video-chat interaction the mother and child communicated through a computer screen from two separate rooms and socially interacted on a planned positive topic with doors locked (Fig. 2A). All sessions were videotaped for offline behavioral coding.

Upon arrival, oral and written explanations of the procedures were given and participants signed informed consent. Following attachment to dual-EEG devices the mother and child sat 50 cm apart facing the wall and were instructed to look ahead and not interact for 2 minutes for the rest state condition. Following the rest state paradigm, two counter-balanced positive-valence naturalistic interactions of three minutes each were recorded, during which mother and child were requested to either plan a fun day to spend together (option 1), plan a camping trip (option 2) or plan an amusement park visit (option 3). All options were counter-balanced across participants. In one interaction, the mother and child set and interacted face-to-face, and in the second they interacted via a video-chat from two separate rooms (Fig. 2A).

During the video-chat interaction participants sat in two adjacent rooms in front of a 24" S2415H DELL screen with 1920*1080 resolution and 60-frames-per-second refresh rate. Both computers were wired and connected to the same internal network. Each computer was equipped with an additional HD web camera and speakers to ensure quality auditory and visual input and output. The participants communicated using the free Skype application installed in both computers that ensures a 30-frames-per-second high quality video. A senior technician was present in all experiments to ensure quality control. The camera recording of the two rooms were manually inspected (using the Mangold Interact, Mangold International GmbH software) for a sample of 15 participants to evaluate the delay in communication between the two interactors and was found to be lower than 400 ms ($M = 370$ ms, $SD = 190$ ms).

2.3. Dual neural and behavioral data acquisition

EEG activity of both mother and child was recorded simultaneously and continuously throughout the experiment. Data acquisition was performed using a 64-channels BrainAmp amplifier from Brain Products Company (Germany). The EEG system is composed of two BrainCap helmets including 32 electrodes each, arranged according to the international 10/20 system. The impedances were maintained below 10 kOhm and the ground electrode was placed on the AFz electrode. Both helmets were connected to the same amplifier to ensure millisecond-range synchrony between the EEG recording of the mother and child.

2.4. EEG Preprocessing

Preprocessing was conducted using Python 3.8, utilizing MNE software (v0.17.0). First, EEG data of each dyad was separated into two data files, one for the child and one for the mother, to enable separate preprocessing. Data was average referenced and a 1 to 50 Hz band-pass filter was applied on all data files, consistent with prior studies (Djalovski et al., 2021; Endevelt-Shapira et al., 2021), following, data was segmented into 1000 ms epochs with 500 ms overlap between epochs. Autoreject v0.1 (Jas et al., 2017) unsupervised algorithm with Bayesian optimization as the threshold method was utilized to remove trials containing transient jumps in isolated EEG channels and artifacts affecting groups of channels. Notably, while AutoReject specializes in excluding trials containing transient jumps in specific channels, systematic physiological artifacts that may affect multiple sensors, such as eye blinks or muscular movements is not optimally removed by this algorithm. Therefore, MNE's implementations of Infomax and CORRMAP

(Viola et al., 2009) were used to remove systematic physiological artifacts that affected the data. Following AR, a sample of the first 5 seconds of each participant was visually inspected pre and post AR correction to verify the algorithm's output. Notably, this specific AR algorithm (Jas et al., 2017) has been used in over 180 studies and while visual inspection may still be the "golden standard" for EEG data, the automatic algorithms ensures better replicability of the results when different labs analyze the same data. Next, independent components (IC) were manually selected for exclusion and served as templates for selecting and excluding similar components in all other participants across all the paradigms, so that the same IC templates were used across all conditions. IC components were used to exclude eye blinks, eye movements, muscular artifacts, and non-physiological noise (see Supplementary Fig. S1). The removal of eye movement components was particularly necessary in our study, as we evaluated the associations between gaze synchrony on interbrain synchrony. Following preprocessing, we ascertained that the final number of epochs was similar across the three experimental conditions (see Supplementary Fig. S2).

2.5. Connectivity analysis

Inter-brain synchrony was calculated using weighted phase lag index (wPLI), an inter-brain connectivity method that had been used in previous studies of naturalistic social interactions (Endevelt-Shapira et al., 2021; Levy et al., 2017). The wPLI method reduces the probability of detecting "false positive" connectivity in case of a shared noise source, which may lead to false-positive hyper-connections resulting from similar sensory experiences for participants who are sharing the same settings and is considered an alternative method to phase locking value (PLV) in naturalistic hyperscanning EEG studies (Burgess, 2013; Dikker et al., 2021). The wPLI method weighs each phase difference according to the magnitude of the lag so that phase differences around zero only marginally affect the calculation of the wPLI and was therefore suggested as an appropriate inter-brain connectivity method for assessing inter-brain connection during naturalistic social interactions. Importantly, while the wPLI was our main measure, we re-computed the data using PLV to ascertain that all the cross-brain links found with the wPLI also show a significant linkage using the PLV method. Our results indicate that all face-to-face connections that were found using wPLI were indeed replicated using PLV. The results of this analysis are reported in Supplementary Table S1.

The dyad inter-brain neural connectivity values were calculated for the Beta frequency band (13.5–29.5 Hz). Analytic signals were computed using FIR filtering, with a Hamming window to avoid distortion and border effects, and the Hilbert transform (Ayrolles et al., 2021). Consistent with prior research, we divided the EEG cap into pre-defined areas of interest based on the research hypotheses (Djalovski et al., 2021; Dumas et al., 2010), so that the EEG electrodes were grouped into pre-defined regions of interest (Djalovski et al., 2021; Kinreich et al., 2017), resulting in a total of 6 ROIs that were examined in this study, each consisting of 3 electrodes: right frontal (RF - Fp2, F4, F8), left frontal (LF - Fp1, F3, F7), right central (RC - FC2, CP2, C4), left central (LC - FC1, CP1, C3), right temporal (RT - T8, TP10, P8), and left temporal (LT - T7, TP9, P7). The grouping of channels enhance reliability of region specification, and provides a more meaningful and realistic interpretation of the results (Azhari et al., 2019). Overall, this resulted in 36 possible combinations of linkage between the mother's and child's ROIs. The respective wPLI value of partners' ROIs was calculated as the mean connectivity value of each of the 3 electrodes in one target ROI with each of the 3 electrodes in the second target ROI, resulting in a total of 9 connectivity values averaged for each combination of 2 ROIs.

Of the 70 dyads participating in the experiment, data files of 2 dyads were corrupted and discarded and 6 dyads did not share sufficient common epochs following AutoReject and IC rejection and connectivity could not be measured, resulting in a total of 62 dyads that completed all conditions. However, participants were excluded from a specific analy-

sis if the difference in their connectivity values varied in more than 3 SD than the mean connectivity difference of all participants. This was calculated separately for each pair of ROIs for each analysis, that is, face-to-face vs rest state or video-chat vs. rest state. The same rest condition was calculated for both comparisons. Notably, no more than 3 participants were removed per analysis per comparison (face-to-face compare to rest analysis – exclusion average = 1.39 ± 0.64 , video-chat compared to rest analysis – exclusion average = 1.61 ± 0.6).

2.6. Behavioral coding

To assess brain-behavior correlations, each paradigm was coded offline twice using two well-validated coding schemes: micro-coding and global rating using the Coding Interactive Behavior manual (CIB, Feldman, 1998)

The Interactive Behavior manual (CIB) is a well-validated rating system used for coding social interactions that has yielded over 200 publications across multiple cultures, age range, and pathological conditions (see Feldman, 2012, 2021 for review), including hyper-scanning research (Djalovski et al., 2021; Endevelt-Shapira et al., 2021). The CIB yields 52 codes, each rated on 5-point scales that aggregate into theoretically-based constructs. Here, we used the *Child empathic social engagement* construct, which comprises the following CIB scales: Child gaze, child openness to parent, child involvement, child approach, child empathy, and child collaboration. *Child empathic social engagement* is a meaningful feature of the parent-child interaction at this age, when children are assuming a greater role in the dyadic interactions. This construct has been shown to be individually-stable from infancy to adolescence (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., 2020, 2018), and was thus examined in relation to live versus remote interactions at this age. Each interactive context (face-to-face, video-chat) was coded separately. Coding was conducted by trained coders who were blind to study hypotheses with inter-rater reliability for 20% of the interactions exceeding 90% on all codes (intra-class $r = .93$, range = .89–99).

The micro-coding utilized second-by-second coding of a previously validated coding scheme (Feldman and Eidelman, 2007, 2004) that has shown linkage with the brain basis of attachment in both parent (Atzil et al., 2014) and child (Pratt et al., 2018). Coding was conducted by two trained coders, a main coder who had over 300 h of experience with micro-coding and a second coder for reliability of the current sample and both were blind to the study hypotheses. Coding was conducted using a computerized system (Mangold Interact, Mangold International GmbH). All interactions were recorded from four different cameras that were placed on four walls of the observational room for maximum coverage. Gaze direction was manually micro-coded after examining the camera recording from several different angles for each second of the interaction. The gaze behavior of each participant was coded separately along four codes, consistent with prior research; to partner, to object, unfocused, and gaze aversion. Shared gaze was computed as a conditional probability; child gaze at mother given mother gaze at child by the Mangold Interact program.

2.7. Statistical analysis

2.7.1. Comparing neural synchrony during social interactions versus surrogate data

As a first step, we examined whether inter-brain connectivity values in each condition were significant as compared to rest state. For that end, connectivity in each condition was evaluated relative to surrogate data, consistent with prior two-brain research (Nguyen et al., 2020a, 2020b; Reindl et al., 2018).

To control for spurious findings, we first conducted a validation analysis of the results relative to surrogate data. Surrogate data was

computed for each paradigm separately by computing all possible permutations of neural synchrony between the epochs of one participant (mother) with the epochs of the other (child) in each of the other dyads separately (i.e., inter-brain synchrony between a mother's neural data with a random child's data). Overall, a total of 3782 surrogate mother-child combinations were created for the 62 dyads for each of the face-to-face, video-chat and the rest paradigms. Following, the surrogate connectivity for each mother was averaged across all possible surrogate combinations, leading to a single average surrogate value for each dyad. A total of 6 ROIs were examined in the current study: RF, LF, RC, LC, RT, LT, and inter-brain synchrony evaluated for each pair.

Following, we computed a repeated-measure analysis of variance on the original connectivity value (real connectivity of the original mother-child dyad) and the surrogate data (averaged across all possible combinations of the mother-other-child pairs), with type of data (real connectivity, surrogate data) and ROI (all 36 possible combinations) as within-subject factors. This analysis was first conducted for each experimental condition separately relative to their respective baselines.

2.7.2. . Comparing neural synchrony across conditions

Next, we conducted a repeated-measure ANOVA on all 3 experimental conditions (face-to-face, video-chat, rest state) with difference in inter-brain connectivity as a within-subject factor to examine the effect of condition on inter-brain synchrony. Difference in inter-brain connectivity was evaluated for each of the 36 possible ROI links between the real connectivity data and the connectivity values obtained from the surrogate data of the same ROI combinations, averaged across all participants.

2.7.3. . Patterns of inter-brain synchrony in the face-to-face and video-chat conditions

After testing whether face-to-face and video-chat conditions show greater inter-brain synchrony relative to baseline (surrogate data), our next analysis focused on specific inter-brain connectivity patterns triggered by each condition relative to the rest state. To that end, we compared the real inter-brain connectivity values of each dyad in each experimental condition relative to the real connectivity values of the rest condition.

The analysis was conducted using "eelbrain", an open source Python module for accessible statistical analysis of MEG and EEG data (v0.31.7, <https://github.com/christianbrodbeck/eelbrain>, DOI 10.5281/zenodo.598150). A non-parametric permutation test with mass-univariate was utilized as it uses a distribution derived from permuting the observed scores of the data and to avoid multiple comparisons (Maris and Oostenveld, 2007).

The permutation test was used to compute the F value for each of the ROI pairs in order to compare connectivity patterns across the conditions in the study. The same procedure was repeated in 1000 random permutations of the original data, shuffling the condition labels within participant to accommodate the within-subject nature of the design used in this study. For each permutation, the largest F value was retained to form the nonparametric estimate of the distribution under the null hypothesis that condition labels are exchangeable. The p -value was computed for each ROI pair as the proportion of permutations that yielded a comparison with a larger F value than the comparison under question. Following the permutation tests, only electrode pairs that reached a p -value of 0.05 or smaller were further examined. Next, we used a more conservative method and applied a set of nonparametric Bonferroni corrected Wilcoxon signed-rank tests on all 36 possible Mother-Child ROI combinations in each condition. Only ROI pairs which reached a p -value of 0.05 or smaller following Bonferroni correction, are reported in the results section.

To further ensure the validity of our data, we conducted a set of two follow-up analysis: First, to validate that the observed differences in wPLI inter-brain connectivity are not related to changes in power (Marriott Haresign et al., 2022), beta power spectral density (PSD) was

calculated for each of the mother and child ROIs and correlated with the inter-brain connectivity of the relevant ROI. PSD was calculated using MNE's implementation of PSD using multitaper, and PSD scores were calculated for each electrode in each paradigm separately. Then, the power of each ROI was calculated as the average of the 3 relevant electrodes comprising each ROI. The power values of each ROI in each condition (face-to-face/ video-chat) were then correlated with each of the wPLI connectivity values observed for the relevant ROI. Our results indicate that power did not correlate with any of the wPLI values in any of the experimental conditions in this study (see Supplementary Table S2). Therefore, the analysis revealed that power had no effect on the inter-brain connectivity values reported in our study, and the two separate measures were independent. In our next analysis we examined our data as compared to shuffled data: For each of the experimental paradigms (face-to-face/ video-chat) we randomly shuffled the epochs of one member of each dyad 100 times and compared the original connectivity values of each of the significant inter-brain links reported in the results section to the connectivity values obtained from the shuffled data for that relevant ROI pair link. Once averaging the 100 iterations of the shuffled data, each of the inter-brain links in the original data was found to be significantly higher than the shuffled data (see Supplementary Fig. S3 for all significant links).

Notably, although we suggest wPLI is the more suited technique to measure inter-brain connectivity in natural settings, to further validate our main findings, we conducted a complimentary PLV connectivity analysis to further examine inter-brain synchrony between the 6 ROIs of the mother and child. PLV analysis results ensures that all significant connections found in the face-to-face condition using wPLI were replicated using PLV. However, the video-chat resulted in no significant linkages at all using PLV analysis (see Supplementary Table S1).

Finally, brain-behavior correlations were used to examine how social interaction affected neural synchrony. Consistent with previous research, indicating brain-behavior coupling with homolog connectivity patterns (Djalovski et al., 2021; Kinreich et al., 2017), and findings suggesting strong linkage of frontal and temporal regions, we a-priori selected to examine the correlations of gaze synchrony and empathic social engagement with the temporal-temporal and frontal-frontal links. First, Pearson correlations were calculated between the neural synchrony and the behavioral measurement. Then, Fisher's Z transformation test was used to examine the difference between the magnitudes of the correlations.

3. Results

3.1. Comparing neural synchrony during social interactions versus surrogate data

3.1.1. Face-to-face interaction

Repeated measures ANOVA with type of data (real face-to-face connectivity, surrogate data) and ROI (all possible 36 combinations) as within-subject variables revealed a main effect for condition ($F(1, 57) = 30.57, p < 0.001, \eta^2p = 0.35$), but no main effect for ROI ($F(35, 1995) = 1.06, p = 0.38, \eta^2p = 0.02$), and no interaction ($F(35, 1995) = 0.9, p = 0.64, \eta^2p = 0.02$). These findings indicate that inter-brain synchrony improves overall during face-to-face interactions relative to baseline across all ROIs.

3.1.2. Video-chat communication

Repeated measures ANOVA with type of data (real video-chat connectivity, surrogate data of interaction) and ROI (all possible 36 combinations) as within-subject variables revealed a main effect for condition ($F(1, 57) = 44.95, p < 0.001, \eta^2p = 0.44$), indicating an overall improvement in interbrain connectivity when participants are communicated from afar relative to baseline. No main effect for ROI ($F(35, 1995) = 0.91, p = 0.62, \eta^2p = 0.02$), and no interaction between condition and ROI were found ($F(35, 1995) = 0.72, p = 0.89, \eta^2p = 0.01$).

These results demonstrate increased interbrain connectivity during the video-chat conversation across all ROIs.

3.1.3. Rest state

Repeated measures ANOVA with type of data (real rest state connectivity, surrogate data of rest state) and ROI (all possible 36 combinations) as within-subject variables revealed no effect for ROI ($F(35, 1785) = 1.09$, $p = 0.34$, $\eta^2p = 0.02$), and no interaction between condition and ROI ($F(35, 1785) = 1.06$, $p = 0.37$, $\eta^2p = 0.02$), but a main effect of Condition ($F(1, 51) = 30.01$, $p < 0.001$, $\eta^2p = 0.37$), reflecting a lower performance in the real rest condition than surrogate data. These findings indicate that while social interactions increase inter-brain synchrony as compared to baseline, when partners are not interacting so clearly inter-brain connectivity is no greater than baseline.

3.1.4. Comparing inter-brain synchrony across experimental conditions

Next, the improvement in inter-brain connectivity was compared between all three conditions (face-to-face, video-chat, rest state) across participants and all 36 ROI links. A repeated measured ANOVA was used to evaluate improvement in interbrain connectivity relative to surrogate data across all participants in the pre-designed ROIs. A highly significant main effect emerged for Condition ($F(2, 70) = 839$, $p < 0.001$, $\eta^2p = 0.96$). A set of Bonferroni-corrected post-hoc tests indicated that this effect stemmed from greater increase in interbrain connectivity in both the face-to-face- ($t(35) = 37.18$, $p < 0.001$, Cohen's $d = 8.31$) and video-chat interactions compared to rest state ($t(35) = 33.52$, $p < 0.001$, Cohen's $d = 7.49$). Another significant difference was found between the two interactive conditions and resulted from greater inter-brain synchrony during face-to-face than video-chat interaction ($t(35) = 3.67$, $p = 0.001$, Cohen's $d = 0.82$) (Fig. 1). These findings support our first hypothesis by showing that remote communication is characterized by significantly lower inter-brain synchrony compared to face-to-face interactions involving co-presence.

3.2. Neural synchrony patterns during live face-to-face interactions compared to rest state

We next sought to pinpoint specific inter-brain synchrony patterns during each social condition relatively to the rest state. We first compared neural synchrony during the face-to-face interaction and the rest condition by using nonparametric permutation test with mass-univariate analysis of variance (ANOVA) based on one-way repeated-measures ANOVA designed to detect effects stemming from the face-to-face interaction as compared to rest on wPLI scores. Results indicated a significant main effect of the face-to-face compared to rest; ($F(1,61) = 23.83$, $p = .001$).

Following the main effect, a more conservative method was used to calculate inter-brain connectivity between each ROI of the mother's and child's brains. We utilized nonparametric Wilcoxon signed-rank tests to detect differences in wPLI connectivity between the face-to-face interaction and the rest state. All results were Bonferroni-corrected to accommodate 36 comparisons. Significant ($p < 0.05$) inter-brain linkage was observed in 9 out of the possible 36 links (Fig. 2A, 2B, Table 1, and Supplementary Fig. S4), which showed greater neural synchrony in the face-to-face interaction compared to the rest condition and comprised four sub-groups: (a) *Homologous linkage between mother's and child's frontal and temporal regions*, (b) *inter-hemispheric same-region linkage of mother and child's frontal and temporal regions*, (c) *linkage between mother's frontal region and child's temporal region*, and (d) *linkage between mother's right frontal region and child's central region*:

(a) *Homologous linkage between mother's and child's frontal and temporal regions* – two homolog connectivity patterns were found: A right-temporal-right-temporal connectivity between mother and child ($W = 1380$, $Z = 3.42$, $p_{(\text{Bonferroni corrected})} = .022$) and a right-frontal-right-frontal connectivity between mother and child ($W = 1466$,

$Z = 4.06$, $p_{(\text{Bonferroni corrected})} = .002$), both demonstrating linkage in the right hemisphere.

- (b) *Inter-hemispheric same-region linkage of mother and child's frontal and temporal regions*. In addition to the homolog frontal and temporal connectivity, two cross-hemispheric links connected the mother's and child frontal and temporal regions. Mother's right frontal region linked with the child's left frontal region ($W = 1441$, $Z = 3.87$, $p_{(\text{Bonferroni corrected})} = .004$); and mother's left temporal region linked with the child's right temporal region ($W = 1408$, $Z = 3.32$, $p_{(\text{Bonferroni corrected})} = .032$), underscoring the tight connectivity of mother's and child's frontal and temporal regions.
- (c) *Linkage between mother's frontal region and child's temporal region*. Three inter-brain links connected mother's frontal region and child's temporal region. First, mother's right frontal region linked with child's right temporal region ($W = 1498$, $Z = 4.29$, $p_{(\text{Bonferroni corrected})} < .001$); second, mother's right frontal region linked with child's left temporal region ($W = 1416$, $Z = 3.69$, $p_{(\text{Bonferroni corrected})} = .008$); and third, mother's left frontal region connected with child's right temporal region ($W = 1463$, $Z = 4.03$, $p_{(\text{Bonferroni corrected})} = .007$). These patterns highlight the tight cross-brain same and cross-hemisphere connectivity between the mother's frontal region and the child's temporal region.
- (d) *Linkage between mother's right frontal region and child's central region*. This included two links; between the mother's right frontal region and the child's left central region ($W = 1404$, $Z = 3.6$, $p_{(\text{Bonferroni corrected})} = .011$), and between the mother's right frontal region and the child's right central region ($W = 1392$, $Z = 3.51$, $p_{(\text{Bonferroni corrected})} = .016$) (Fig. 2B).

As seen, a wide net of connections links mother and child's brains during live social interactions. Particularly salient in these connectivity patterns are the mother's right frontal and the child's right temporal regions. Mother's *right frontal region* connected with each of the six child's ROIs measured here; the child's right and left frontal, right and left temporal, and right and left central regions. Similarly, the child's *right temporal region* was multiply connected; with the mother's right and left frontal regions and right and left temporal regions. Notably, the mother's frontal and child's temporal areas showed not only same-hemisphere linkage but also cross-hemispheric connectivity, highlighting these two areas in mother and child as densely inter-connected during live social exchanges.

3.3. Neural synchrony during video-chat compared to rest state

The next analysis compared inter-brain synchrony during the video-chat compared to the rest state condition using the same analysis; nonparametric permutation test with mass-univariate analysis of variance (ANOVA) based on one-way repeated-measures ANOVA design to detect effects associated with the video-chat free interaction compared to the rest condition on wPLI scores. Results indicated a significant overall main effect for the video-chat compared to the ($F(1,61) = 17.11$, $p = .001$). A follow-up nonparametric Bonferroni-corrected Wilcoxon tests to detect differences on wPLI connectivity measures corrected for 36 comparisons was conducted, similar to the face-to-face condition. Following Bonferroni correction, only a single significant inter-brain link emerged of the possible 36 links; between the mother's right frontal region and the child's left temporal region ($W = 1384$, $Z = 3.45$, $p_{(\text{Bonferroni corrected})} = .02$), (Table 1, Fig. 3B). Overall, our findings demonstrate the marked decrease in brain-to-brain connectivity when interactions are moderated by technology. The single inter-brain link found during the video-chat further underscores the mother-frontal-child-temporal link as central for supporting mother-child social interactions during both during live or remote communication.

Table 1

Increased inter-brain neural synchrony following face-to-face interaction or Video-chat interaction. Reported here are the significant comparisons following nonparametric Wilcoxon test to detect differences on wPLI connectivity measures between face-to-face or skype interactions and rest. All results were Bonferroni-corrected to 36 comparisons. Inter-brain neural synchrony was found in nine connections in the face-to-face paradigm, while a single inter-brain connection emerged in the video-chat paradigm. * $P < 0.05$ ** $P < 0.01$, *** $P < 0.001$.

Sig (*)	p (Bonferroni corrected)	wPLI Rest	wPLI Face	Mother ROI	Child ROI
Face-to-Face Vs Rest					
**	0.002	0.100 (.026)	0.118 (.031)	Right Frontal	Right Frontal
*	0.022	0.098 (.022)	0.117 (.035)	Right Temporal	Right Temporal
**	0.004	0.099 (.021)	0.115 (.030)	Right Frontal	Left Frontal
*	0.032	0.100 (.028)	0.115 (.032)	Left Temporal	Right Temporal
***	<.001	0.100 (.023)	0.118 (.036)	Right Frontal	Right Temporal
**	0.008	0.098 (.021)	0.117 (.033)	Right Frontal	Left Temporal
**	0.007	0.100 (.024)	0.118 (.033)	Left Frontal	Right Temporal
*	0.011	0.098 (.022)	0.12 (.040)	Right Frontal	Left Central
*	0.016	0.101 (.022)	0.12 (.038)	Right Frontal	Right Central
Video-Chat Vs Rest					
*	0.02	0.100 (.029)	0.113 (.031)	Right Frontal	Left Temporal

3.4. Comparing inter-brain connectivity during face-to-face and video-chat conditions

Z-test for Two Proportions was used to examine differences between the statically significant inter-brain connections during the face-to-face and video-chat. A significant difference was found between the overall inter-brain connections during the live versus video-chat interaction ($Z = 2.27$, $p = .006$), supporting our main hypothesis of a robust decrease in inter-brain synchrony when interactions are mediated by technology.

3.5. Brain-behavior coupling

Consistent with previous studies that indicated brain-behavior coupling with homolog connectivity patterns (Djalovski et al., 2021; Kinreich et al., 2017), we a-priori selected to test correlations between gaze synchrony and empathic social engagement with the temporal-temporal and frontal-frontal links.

Gaze synchrony links with live temporal-temporal synchrony – Moments of shared gaze between mother and child – gaze synchrony – correlated with mother-child temporal-temporal link during the live face-to-face interaction ($r = 0.28$, $p = 0.032$) (Fig. 4A); so that greater gaze synchrony correlated with greater right temporal connectivity. Gaze synchrony was unrelated to temporal-temporal synchrony in the video-chat condition ($r = 0.15$, $p > 0.25$); still, Fisher's Z transformation examining the difference between these two correlations was not significant ($Z = 0.79$, $p = 0.21$). Finally, Mother-child frontal-frontal connectivity was unrelated to gaze synchrony in both the live face-to-face ($r = 0.23$, $p = 0.083$), and video-chat ($r = 0.23$, $p = 0.097$) communication conditions. Notably, as shared gaze was correlated with neural synchrony only in the face-to-face condition and only for the linkage between mother's right temporal and child's right temporal areas, it is unlikely that the correlation reflects eye-movement artifacts that were removed by ICA during preprocessing.

Child empathic social engagement links with live frontal-frontal synchrony - child empathic social engagement correlated with mother-child frontal-frontal connectivity in the face-to-face interaction ($r = 0.35$, $p = 0.007$) (Fig. 4B), but not during the video-chat interaction, ($r = 0.06$, $p > 0.25$). Fisher's Z transformation test showed significant difference between the magnitude of the correlations ($Z = 1.7$, $p = 0.045$).

Following the a-priori assessment of brain-behavior coupling in homolog connectivity patterns, we also used a post-hoc exploratory analysis to examine the association between *Child empathic engagement* and the single inter-brain link that was significant during both the live and video-chat interactions. Results showed that the mother-right-frontal-child-left-temporal link correlated with *child empathic engagement* during the live face-to-face ($r = 0.26$, $p = 0.043$) (Fig. 3C), but not dur-

ing the video-chat interaction ($r = -0.03$, $p > 0.25$). Following Fisher's Z transformation, the two correlations showed marginally significant difference ($Z = 1.62$, $p = 0.052$). As hypothesized, while the micro- and macro behavioral constructs correlated with neural coordination in the live face-to-face interaction, brain-behavior correlations during the technologically-assisted video-chat communication were not significant

4. Discussion

The COVID-19 pandemic has accelerated an already ongoing revolution of proportion and consequences unbeknown to our species, making remote communication a topic of high public concern. Our study is the first to tackle this issue from a two-brain perspective that focuses on inter-brain synchrony, a key mechanism sustaining human social life (Feldman, 2021, 2020). Several important and novel findings are shown by the data. First, we found that human social interactions, whether live or remote, induce neural coupling between the interacting partners, while the partners' mere co-presence without social dialogue did not increase neural synchrony above and beyond chance. These findings support perspectives which suggest that daily face-focused interactions tune humans' social brain through bottom-up bio-behavioral processes (Feldman, 2020; Hari et al., 2015; Hasson et al., 2012; Schilbach et al., 2013) and add the dimension of inter-brain connectedness. Second, results show that technologically-assisted communication attenuates the level of inter-brain coordination produced by naturalistic social interactions that involve co-presence and highlight the difference between the dense cross-brain connectivity patterns during live interactions and the single neural linkage of remote contact. Finally, only during the live interaction significant associations emerged between inter-brain and behavioral markers, including shared gaze and empathic engagement. Our results, therefore, open a much needed discussion on the neural processes that underpin remote communication and call to further study its expressions across ages, social partners, and high-risk conditions.

Our findings clearly demonstrate the price we pay for technology. As seen, during mother-adolescent live face-to-face interaction a wide net of connections unfolds between the two brains, including (a) homolog same-region-same-hemisphere links; (b) same-region-different-hemisphere links; and (c) multi-region patterns of connectivity. Particularly salient were links between the mother's and the child's frontal and temporal regions, which were inter-connected in nearly every possible way and rode on beta rhythms. In contrast to the 9 significant links working in tandem during the live interaction, only 1 link connected the two brains during video-chat communication: between the mother's right frontal region and the child's left temporal region. Remote interaction, therefore, eliminates the rich right-to-right brain linkage repeatedly found during naturalistic cross-brain studies

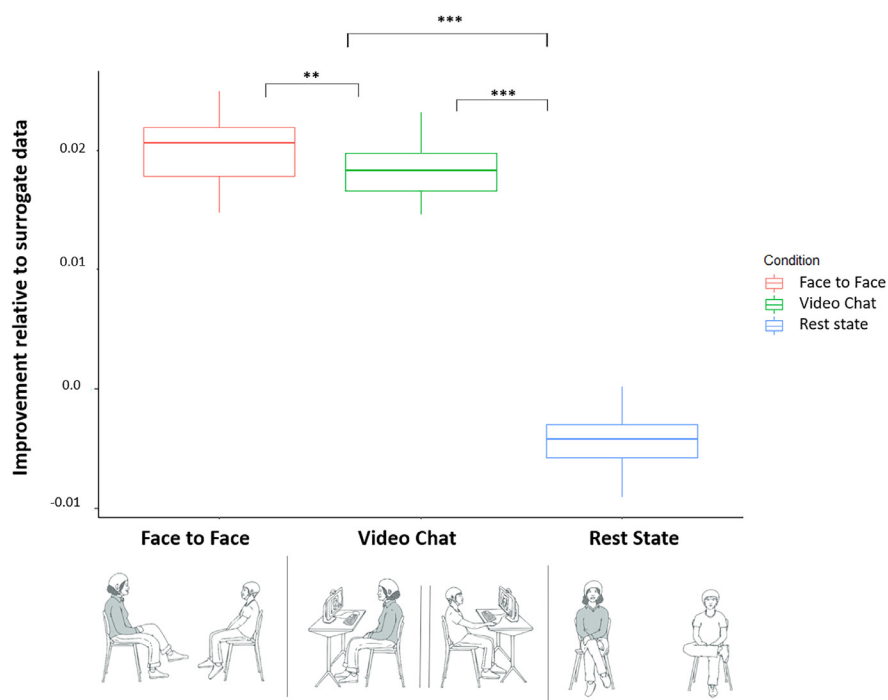


Fig. 1. Analysis of inter-brain synchrony during the three experimental conditions relative to surrogate data. Inter-brain synchrony was evaluated for each experimental condition (face-to-face, video-chat, rest state) relative to surrogate data in the pre-designed ROIs. Findings show highly significant effect for Condition ($p < 0.001$), stemming from a greater increase in inter-brain connectivity in the face-to-face interactions relative to rest state ($p < 0.001$) and the video-chat relative to rest state ($p < 0.001$), and from a significant improvement in face-to-face interbrain synchrony relative to the video-chat interaction. ($p = 0.001$).

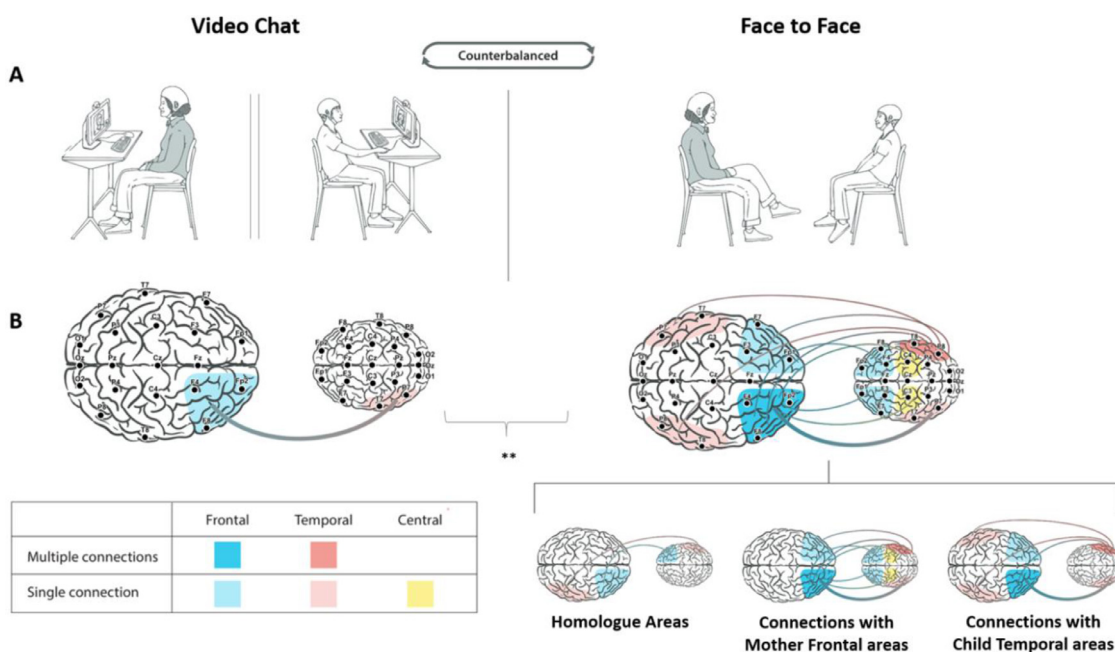


Fig. 2. Experimental procedures and main findings. (A) Experiment paradigm. Neuroelectric activity of mother-child dyads was recorded simultaneously and continuously throughout the entire experiment (hyperscanning) during rest paradigm, face-to-face interaction, and while communicating via video-chat from two separate locations (B) Main findings: Illustration of mother-child inter-brain neural synchrony in both Face-to-face and Video-chat paradigms. Inter-brain neural synchrony values were calculated for Beta frequency band (13.5 to 29.5 Hz) using weighted phase lag index (wPLI). 6 regions of interest were predefined and examined, each consisting of 3 electrodes. Region of interest were right and left Frontal, Central and Temporal areas. Connectivity scores were computed for the 6 regions of interest, resulting in 36 wPLI possible combinations between mother and child synchrony per condition. During the face-to-face interactions 9 inter-brain connections emerged between the mother and child, while in the video-chat only one inter-brain connection was found. ($*p < 0.05$ $**p < 0.01$, $***p < 0.001$.)

(Cui et al., 2012; Kruppa et al., 2021; Pan et al., 2017; Reindl et al., 2018) that are theorized to transmit the partners' non-verbal social cues and affective states (Borod et al., 1998). Our findings suggest that the gains to social development, empathic abilities, and brain maturation afforded by face-to-face interactions may not translate to technological encounters, but this hypothesis requires much further research.

During the mother-child face-to-face interaction, two homolog inter-brain connections were found; between mother and child's (1) right frontal regions and (2) right temporal regions. The frontal linkage is consistent with much prior research. A recent rodent study demonstrated the causal involvement of frontal inter-brain synchrony in sociality; when frontal neurons were activated synchronously the animals were socially engaged but when the same neurons activated asyn-

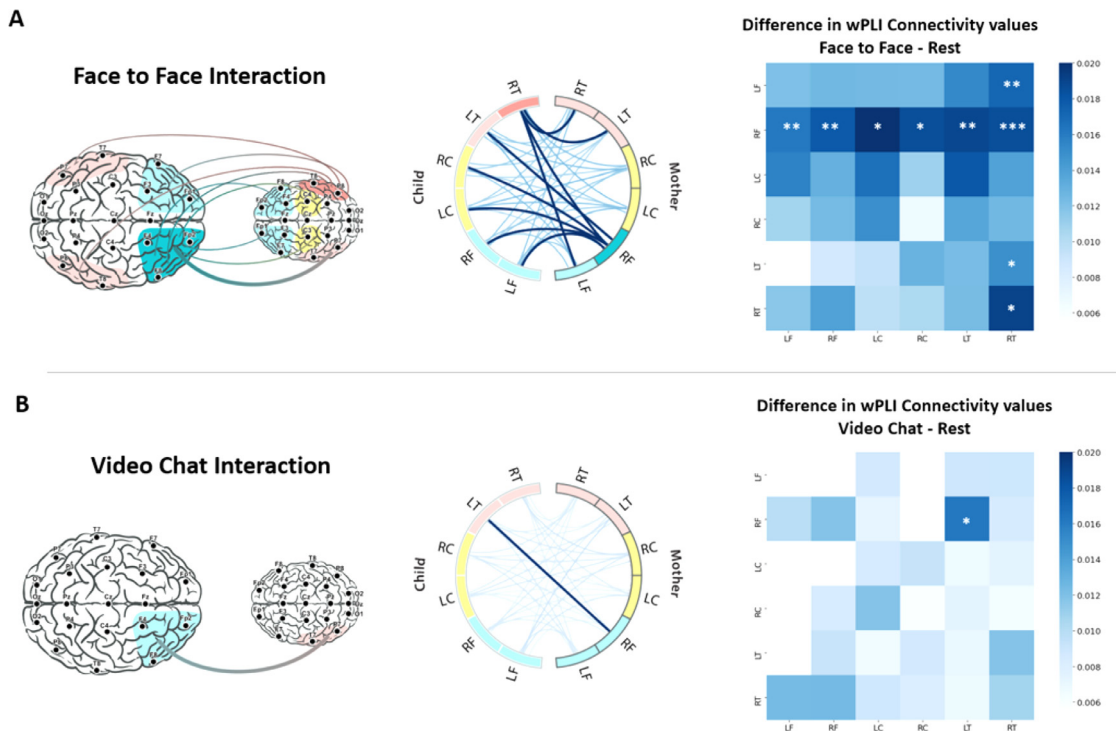


Fig. 3. Visualization of significant Inter-brain Connections: Higher inter-brain synchrony was detected during face-to-face and Video-chat interactions compared to rest condition, with 9 inter-brain connections found during face-to-face interaction, and a single connection in the video-chat interaction. RT – right temporal, LT – left temporal, RC- right central, LC – left central, RF – right frontal, LF- left frontal. (A) Visualization of connectivity values (wPLI) during face-to-face interaction compared to rest. Circles represents mean connectivity values for the 36 possible combinations of region of interest in the mother and child brains. Within each circle, the significant links are marked in dark blue. Next, the difference in connectivity values across brain regions combinations between the face-to-face interaction and rest. The x axis represents the child’s brain region, while the y axis represents the mother’s brain regions. Darker squares represent comparisons with higher connectivity score differences between face-to-face and rest paradigms. Nonparametric permutation testing with mass-univariate ANOVA revealed significant main effect for face-to-face interaction compared to rest $F(1,61) = 23.83, p = .001$. A conservative nonparametric Wilcoxon test was used to detect differences in wPLI connectivity measures, with all results Bonferroni-corrected to 36 comparison. 9 significant inter-brain connections were found post correction of the possible 36 combinations. The significant comparisons are marked. (B) Similar visualization of connectivity values (wPLI) during video-chat interaction compared to rest condition. A single brain connection emerged between the Mother’s right frontal region and the child’s left temporal region following Bonferroni-corrections ($F(1,61) = 17.11, p = .001$). (* $p < 0.05$ ** $p < 0.01$, *** $p < 0.001$.)

Brain-Behaviour Correlations during Face to Face Interaction

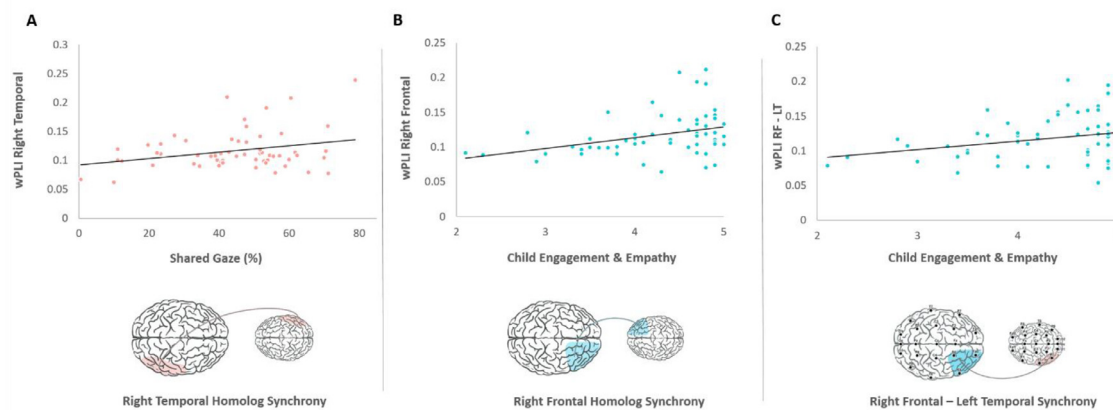


Fig. 4. Visualization of brain-behaviour correlations in the Face-to-Face Paradigm. (A) Visualization of mother-child dyads shared gaze during interactions correlation with wPLI values of inter-brain synchrony. Neural synchrony was highly correlated with synchronous gaze shared between the mother and child in the right temporal area ($r = 0.28, p = 0.032$). (B + C) Visualization of the CIB codes of child Engagements and Empathy correlations with wPLI values of inter-brain neural synchrony. The extent of child engagement and empathy towards the mother affected synchrony in the homolog frontal right areas of the mother and child ($r = 0.35, p = 0.007$), and in the frontal right area of the mother with the temporal left area of the child ($r = 0.26, p = 0.043$).

chronously, they lost social interest (Yang et al., 2022). Hyperscanning studies have similarly shown that right frontal-frontal synchrony sustains human affiliation, including parent-child (Kruppa et al., 2021; Reindl et al., 2018) and romantic attachment (Pan et al., 2017); frontal-frontal synchrony decreases when mothers are stressed (Azhari et al., 2019); and frontal-frontal synchrony links with perceived similarity between partners (Hu et al., 2017) and sense of effective communication (Stephens et al., 2010). We found that the mother's frontal region linked with every single region of the child's brain measured here; child's right and left frontal, right and left central, and right and left temporal areas (Fig. 2B), suggesting a unique role for the mother's right frontal area in sustaining inter-brain synchrony. The mother's right frontal region may be involved in monitoring the interaction and dynamically adjusting its features to ensure rich inter-brain coupling at multiple levels of the child's neural processing. The frontal cortex is implicated in higher-order social functions, including social cognition, mental state knowledge, and social decision-making (Amodio and Frith, 2006; Rilling and Sanfey, 2011), abilities that are known to develop in the context of maternal care (Monroy et al., 2010). The dense cross-brain linkage emanating from the mother's right frontal cortex accords with the well-known mechanism of "external regulation" (Hofer, 1995), the process by which the mature maternal brain molds the child's immature brain and tunes it to social life through inter-brain mechanisms embedded within coordinated social behavior (Feldman, 2015, 2021).

The right temporal-temporal link is similarly consistent with previous research during interactions between attachment partners, suggesting its role in the formation of affiliative bonds (Djalovski et al., 2021; Kinreich et al., 2017). The right temporal region is involved in empathy, embodiment, and mentalization and underpins the capacity to understand others' goals and create shared intentionality during social moments (Frith and Frith, 2001). Increased beta activations were found in right temporal regions when children observe their own mother-child videos (Pratt et al., 2018), when mothers are exposed to infant-related emotional stimuli (Hernández-González et al., 2016), and when romantic partners engage in empathic dialogue (Djalovski et al., 2021) and it has been suggested that temporal beta serves as a neural marker of attachment (Hernández-González et al., 2016). During adolescence, the social brain undergoes profound reorganization in both the PFC and the posterior superior temporal sulcus (Blakemore, 2008). We found that during a period of rapid maturation of these areas, moments of naturalistic mother-adolescent social interaction trigger not only a homolog right-brain linkage of these areas, but also a dense inter-connection between mother and child's right and left frontal and temporal regions. The fronto-temporal network underpins key socio-cognitive functions (Frith and Frith, 2001; Hastings et al., 2013), and hyperscanning studies indicated frontal-temporal neural synchrony during social exchanges (Pérez et al., 2017; Tang et al., 2015; Zhang et al., 2017). This suggests that mothers utilize inter-brain mechanisms to support maturation of the social brain during its sensitive periods of development in stage-specific ways that target the specific areas that undergo rapid development, findings that lend further support to the perspective that inter-brain synchrony is a mechanism by which mature brains regulate immature brains to social living (Feldman, 2020, 2016).

All inter-brain links found here implicated beta rhythms. Inter-brain processes are sustained by neural oscillations, a pervasive component of neuronal activity that underpins the dynamic organization of neural functions (Donner and Siegel, 2011), and their temporal consistency builds a model of self and partner's behavior that can guide neuronal activity toward a smooth interpersonal exchange (Seth and Friston, 2016). Beta oscillations are involved in post-synaptic gains in neuronal sensitivity that modify predictions and determine information flow towards higher-order targets (Bressler and Richter, 2015; Friston et al., 2015). Beta rhythms are involved in complex social functions, such as empathy (Levy et al., 2018) and attachment (Pratt et al., 2018), and underpin key functions that enable cross-brain communication, including active information processing (Donner and Siegel, 2011), mentalization (Soto-

Icaza et al., 2019), predicting others' actions (Koelewijn et al., 2008), perception and integration of sensory information (Hipp et al., 2011), and constant adaptations and updating of predictions (Sedley et al., 2016). During social interactions, these beta-modulated functions enable the rapid adaptation and mutual entrainment that are required for inter-brain coordination (Hasson and Frith, 2016).

Hyperscanning studies revealed cross-brain synchrony of beta rhythms across multiple tasks, such as response to positive social gestures (Balconi and Fronda, 2020), compassion during third-party punishment (Ciaramidaro et al., 2018), and leader-follower cooperation (Yun et al., 2012). Inter-brain beta synchrony has been found during synchronized movements and the increase in inter-brain beta during episodes of coordinated movement was interpreted as representing top-down modulations in social interactions that derive from joint action, social attention, and imitation (Dumas et al., 2010). Enhanced beta-band synchronization emerged during cooperation, as compared to competition paradigms when partners are co-present (Sinha et al., 2016). Furthermore, consistent with the current results, inter-brain beta during cooperation was found in both frontal and right-temporo-parietal areas (Sciaraffa et al., 2021) and was suggested to derive from the active thinking, joint focus, and metallizing processes that are triggered by coordination dynamics. Finally, interpersonal factors, such as trait empathy, engagement, and social behavior of joint engagement and eye contact were found to predict inter-brain beta during real-world face-to-face interactions (Dikker et al., 2021).

Consistent with the bio-behavioral synchrony model (Feldman, 2016, 2015, 2012), inter-brain synchrony linked with shared gaze and empathic engagement during the live, but not the video-chat interaction. Extant inter-brain research demonstrates the eliciting effect of shared gaze on inter-brain synchrony (Endevelt-Shapira et al., 2021; Hirsch et al., 2017; Kinreich et al., 2017; Koike et al., 2019; Leong et al., 2017; Piazza et al., 2020). Hyperscanning studies found increased frontal and temporal connectivity during face-to-face interactions involving shared gaze (Hirsch et al., 2017); neural synchrony was found to be embedded in moments of gaze synchrony (Kinreich et al., 2017); and face-to-face interactions involving shared gaze triggered more neural synchrony than a pre-filmed video of interacting faces (Noah et al., 2020). It has been suggested that episodes of shared gaze enhance neural coordination by supporting the ability to communicate social signals, predict ongoing intent, identify the partner's affective state, and execute a joint goal (Schilbach et al., 2013; Tang et al., 2015). Our findings add the dimension that the facilitatory role of shared gaze may be limited to moments of co-present interactions and not to conditions of technological communication.

In addition, we found that adolescents' involvement in the dialogue, empathy, collaboration, and social motivation, reflected in the *empathic social engagement* construct, facilitated mother-child right frontal-frontal and frontal-temporal synchrony during live interactions. This is consistent with studies showing that children's engagement and empathy during interactions with their mother predict well-being and lower psychopathological symptoms (Halevi et al., 2017). The expressions of child empathy and collaboration, higher-order abilities known to sustain inter-brain synchrony, were comparable during the live and remote communication, still, these social behaviors connected with greater frontal-frontal and frontal-temporal synchrony only in the live interaction and showed no significant correlations with neural coupling in the remote communication. Our results may suggest that live social interactions provide the evolutionary-typical context for the maturation of neural coupling, findings that raise concerns about the rates of youth involvement in technologically-assisted communication and the potential risk this poses to the development empathy and collaboration.

While our study did not test for "Zoom fatigue" directly, we carefully postulate that it is possible that the reduced neural linkage observed during technologically-assisted communication may increase cognitive overload, which is considered among the reasons for Zoom fatigue (Bailenson, 2021; Fauville et al., 2021). Nonverbal cues enhance in-

terpersonal communication (Burgoon et al., 2002) and are interpreted naturally during in-person contact (Hall et al., 2019). Video-chats may require additional effort to produce and interpret nonverbal cues, such as body language and facial expressions that are easily observed during face-to-face conversations (Bailenson, 2021). Possibly, the multiple verbal and non-verbal signals that transfer via the dense inter-brain connections and facilitate smooth communication during live interactions are not fully functional during remote contact, but this hypothesis requires much further targeted research. Future research should examine the biological mechanisms implicated in "co-presence" between two humans and the potential long-term effects of significant reduction in live social interactions on maturation of the social brain, particularly among youth.

Although adolescents are accustomed to technological communication (Anderson and Jiang, 2018), adolescents and young adults who use technology daily are still experiencing severe hardships in adjusting to Zoom chats and remote communication. Kuhfeld et al (2020) reported a severe reduction in academic skills that are gained during a typical school year of junior or senior high school as compared to a year of the pandemic when learning took place remotely via technology (Kuhfeld et al., 2020). Most college undergraduates rated online learning between "somewhat difficult" to "extremely difficult" (Peper et al., 2021). Several reasons were hypothesized to cause "Zoom fatigue" ranging from a delay in social feedback, difficulties in maintaining attention, interactors not showing their faces, slouching, or delays in response time due to mute microphones that were suggested to increase zoom fatigue (Peper et al., 2021; Williams, 2021). Our findings suggest that the reduced inter-brain coordination during remote interaction may be another factor. As seen, remote communication using a video-chat trafficked through a single inter-brain link, whereas the brain is accustomed to a dense net of connections that transmit information at various levels across the neuroaxis, including sensory, motor, linguistic, affective, and shared meaning, with each level possibly riding on a different cross-brain link. This is consistent with the suggestion that cognitive load is one reason for Zoom fatigue (Fauville et al., 2021). Our results add to this literature the dimension of inter-brain connection and show that even under the best circumstances; partners are familiar with each other's signals, technology was fully adjusted, only two partners interacted, and the topic was a relaxed conversation, inter-brain coordination was significantly severed.

While we emphasize the drawback of technological communication, it is important to note that technology, and particularly remote communication became a necessity during the pandemic, allowing individuals to work, learn, and communicate with loved ones during the COVID-19 pandemic when face-to-face interactions were unavailable. Even post-pandemic, remote communication remained a part of daily life that allows the sharing of ideas, working from home, and keeping in touch from afar. Our findings show that despite the lack of co-presence, brains can still synchronize via screens, albeit to a lesser extent. Thus, our results point to the need for much further research that can pinpoint the degree of remote communication that may be beneficial versus harmful to mental health at each developmental stage and the multiple ways in which technological communication impact well-being of both the individual and the community.

Several study limitations should be mentioned. First, as this study was, to our knowledge, the first hyperscanning study targeting remote communication vs face-to-face interactions, we included mother-child dyads in order to select partners within a strong affiliative bond and to minimize variations among participants. We believe that for partners who share a weaker bond (e.g., classmates) or are unfamiliar, the effects would be even stronger, but this requires further systematic research. Another limitation relates to the choice to focus only on frontal, central, and temporal areas, consistent with previous hyperscanning EEG studies of naturalistic interactions (Djalovski et al., 2021; Endevelt-shapira et al., 2021; Kinreich et al., 2017). While it is possible that occipital areas engage in lower-level synchrony based on sharing the same

environment, future research should include measurement of these areas.

We are only beginning to understand how social technology impacts the human social brain and this topic is in urgent need of further research. We need to understand the cross-brain consequences of technological communication at different stages of child development and with different familiar and unfamiliar partners. As technologically-assisted communication is assuming an increasing portion of our social life, we must address the broader implications of this change; how remote communication impacts parenting, falling in love, couple relationships, social communities, self-identity, and resilience. We must learn to quantify the amount of technologically-assisted communication that may tilt the developing brain to less favorable outcomes at each stage of development. Finally, a key goal for future technology and research is to test whether there are components of the human biological co-presence that can be adapted to screen-mediated interaction. Technology offers a wealth of possibilities and, with it, the option to alter what it means to be a social human. More empirical knowledge may help address these questions with wisdom and foresight for the future development of tomorrow's citizens.

Data and code availability statement

We will comply with the requirements and regulations of the journal regarding data and code availability.

As in previous publications from the last year in our lab (Endevelt-Shapira et al., 2021. Maternal chemosignals enhance infant-adult brain-to-brain synchrony. *Science Advances*, 7(50), p.eabg6867.), we intend to upload that data supporting the findings of this study.

The videos of interactions containing information that could compromise the privacy of research participants would not be publicly available.

Data Availability

Data will be made available on request.

Credit authorship contribution statement

Linoy Schwartz: Conceptualization, Writing – original draft, Investigation, Visualization. **Jonathan Levy:** Visualization, Methodology, Investigation, Supervision. **Yaara Endevelt-Shapira:** Writing – original draft, Formal analysis, Supervision. **Amir Djalovski:** Investigation. **Olga Hayut:** Software. **Guillaume Dumas:** Methodology, Supervision, Software, Formal analysis, Supervision. **Ruth Feldman:** Conceptualization, Writing – original draft, Visualization, Supervision.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.neuroimage.2022.119677](https://doi.org/10.1016/j.neuroimage.2022.119677).

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