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RESEARCH REPORT

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# Electroencephalographic interbrain synchronization in children with disabilities, their parents, and neurologic music therapists

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**Abstract**

As with typically developing children, children with cerebral palsy and autism spectrum disorder develop important socio-emotional rapport with their parents and healthcare providers. However, the neural mechanisms underlying these relationships have been less studied. By simultaneously measuring the brain activity of multiple individuals, interbrain synchronization could serve as a neurophysiological marker of social–emotional responses. Music evokes emotional and physiological responses and enhances social cohesion. These characteristics of music have fostered its deployment as a therapeutic medium in clinical settings. Therefore, this study investigated two aspects of interbrain synchronization, namely, its phase and directionality, in child–parent (CP) and child–therapist (CT) dyads during music and storytelling sessions (as a comparison). A total of 17 participants (seven cerebral palsy or autism spectrum disorder children [aged 12–18 years], their parents, and three neurologic music therapists) completed this study, comprising seven CP and seven CT dyads. Each music therapist worked with two or three children. We found that session type, dyadic relationship, frequency band, and brain region were significantly related to the degree of interbrain synchronization and its directionality. Particularly, music sessions and CP dyads were associated with higher interbrain synchronization and stronger directionality. Delta (.5–4 Hz) range showed the highest phase locking value in both CP and CT dyads in frontal brain regions. It appears that synchronization is directed predominantly from parent to child, that is, parents and music therapists' brain activity tended to influence a child's. Our findings encourage further research into

**Abbreviations:** CP, Child–parent dyads; CT, Child–music therapist dyads; EEG, Electroencephalography; PDC, Partial directed coherence; PLV, Phase locking value.

Tom Chau and Michael H Thaut contributed equally to this work.

neural synchrony in children with disabilities, especially in musical contexts, and its implications for social and emotional development.

**KEYWORDS**
children with disabilities, electroencephalography (EEG), hyperscanning, interbrain synchronization, music therapy

## 1 | INTRODUCTION

Children with physical and cognitive disabilities can be isolated due to their limited abilities to express their needs and feelings (Lindsay & McPherson, 2012). Parents of these children often struggle with understanding their child's emotions (Currie & Szabo, 2020). Healthcare providers may face similar challenges when they interact with children who have neurodevelopmental disorders and limited expressive communication. Much research has focused on the neural underpinnings of social impairments in children with autism spectrum disorder (ASD) (Kleinhans et al., 2009; White et al., 2014; Williams et al., 2006). Further, motor challenges that limit social relationship and activity have been studied extensively in cerebral palsy (Beckung & Hagberg, 2002). However, there is less understanding of coordinated dyadic brain activities (i.e., the interplay between the brains between two or more people) during social interactions involving these clinical populations. Given the heterogenous manifestation of delayed or limited social skills in both ASD and cerebral palsy, standardized and objective measurements (i.e., biomarkers) of social interaction are needed (Jeste et al., 2015). Particularly, robust parent–child (Guild et al., 2021) and therapist–child relationships (Särkämö et al., 2016) are critical to maximizing therapeutic outcomes in clinical settings. As social skills development in children with disabilities depends heavily on healthy family relationships (Bennett & Hay, 2007) and therapeutic rapport (Mössler et al., 2019), the investigation of neural mechanisms associated with these interpersonal connections is warranted.

Synchronizing to music in social environments results in behavioural and physiological responses. Children in all three age groups (2.5, 3.5, and 4.5 years) synchronized their drumming better with a human partner than with drum sounds from a speaker or drum machines (Kirschner & Tomasello, 2009). The frequency of clapping in unison increases as more people clap together (Thomson et al., 2018). In fact, music can promote the alignment of physiological and neural responses amongst individuals. For example, listening to music together can raise skin conductance and heart rate (Liljeström et al., 2013). Cardiovascular and respiratory rhythms can synchronize between individuals while listening to music (Bernardi et al., 2017). Further, brain networks relating to not only auditory processing but also attention and motor planning can become coupled between participants while listening to musical excerpts (Abrams et al., 2013). This close alliance between music and synchrony has led to the use of music for improving socio-emotional as well as motor skills in clinical settings (Thaut & Hoemberg, 2014). For instance, children with ASD who attended music therapy group sessions showed a significant difference in joint attention with their peers and eye contact compared with nonmusic, social skill training groups (Eren, 2015; LaGasse, 2014, 2017). Notably, neurologic music therapy has been used to improve motor skills in patient with cerebral palsy (Kim et al., 2020; Kwak, 2007). Although these studies provide evidence that music has potential to improve socio-emotional and motor skills in children with disabilities, it remains unclear how fundamental child–parent (CP) and child–therapist (CT) relationships emerge during therapeutic sessions. Biomarkers can provide objective measurements to characterize the biological response to therapeutic interventions (Working, 2001). One way to understand these dyadic relationships more deeply is through the continuous measurement of interbrain synchronization during natural interactions, using hyperscanning methods.

Hyperscanning refers to the simultaneous measurement of brain activity from two or more interacting individuals using functional magnetic resonance imaging (Montague et al., 2002), electroencephalography (EEG) (Duane & Behrendt, 1965), magnetoencephalography (Hirata et al., 2014), and functional near-infrared spectroscopy (Cui et al., 2012). EEG hyperscanning methods have largely been used to investigate various topics of social dynamics, such as empathy (Goldstein et al., 2018), coordination (e.g., finger tapping and imitation hand movement) (Konvalinka et al., 2014; Naeem et al., 2012; Tognoli et al., 2007), joint action (Lachat et al., 2012; Saito et al., 2010), turn-taking (EEG/magnetoencephalography) (Ahn et al., 2018), decision-making during flight simulations (Astolfi et al., 2011; Toppi et al., 2016), playing a card came (Astolfi et al., 2010), and cooperative gaming (Fallani et al., 2010; Jahng et al., 2017).

In particular, previous hyperscanning studies found interbrain synchrony in ecological contexts, such as during musical activities. Lindenberger et al. (2009) and Sänger et al. (2012) investigated interbrain synchrony during guitar duets. They found that higher coordinated action (e.g., preparatory metronome tempo setting and coordinated play onset) was accompanied by higher interbrain oscillatory couplings in delta (1–4 Hz) and theta (4–8 Hz) bands across fronto-central regions which are involved in motor and musical control (Zatorre et al., 2007) and theory of mind (Rizzolatti et al., 2001). Sänger et al. (2012) provided a new perspective of the musical roles of lead and supporting musicians reporting higher phase locking in the former. Subsequently, Sänger et al. (2013) investigated the directionality of between-brain couplings by measuring EEG data from pairs of leader–follower guitarists. Indeed, interbrain synchronization reflects a bidirectional attunement of one individual to another, which is likely a feature of vibrant social interactions where people assume complementary social roles (Dumas et al., 2010). Thus, in addition to the magnitude of interbrain synchronization, its directionality is an important consideration in understanding social interactions.

Hyperscanning methods have been extended by investigating the neural synchrony in relationships of dyads. For example, Pan et al. (2017) found higher interbrain synchronization in romantic couples compared with friends or strangers. Moreover, Reindl et al. (2018) observed that parent–child synchrony significantly emerged during cooperation tasks in the prefrontal and frontopolar cortex and dorsolateral prefrontal cortex, both of which are associated with emotional regulation, whereas no significant interbrain synchronization was observed in parent–child competition and stranger–child cooperation/competition tasks. Higher interbrain synchronization in close relationships (e.g., couples) suggests that the neural synchronization may reflect mutual bonding and intimacy of attachment.

Another crucial interpersonal relationship can be developed in educational or therapeutic settings. In this context, Pan et al. (2018) measured interbrain synchronization between an instructor and students while learning a song using functional near-infrared spectroscopy hyperscanning. The results showed stronger interpersonal synchrony during interactive learning in the bilateral inferior frontal cortex which is associated with shared emotional information (Babiloni et al., 2012) and understanding of others' intentions (de C. Hamilton & Grafton, 2008). Fachner et al. (2019) investigated neural synchrony between a client and a music therapist during classical music listening using EEG hyperscanning methods. They explored shared neural processing of emotions and imagery via frontal alpha asymmetry and frontal midline theta measurements, metrics which quantify emotional processing and positive emotional experience, respectively. Frontal alpha asymmetry was positive for both therapist and client at "moments of interest," suggestive of shared similar emotional processing at these times. This was the first report of synchrony between client and therapist using hyperscanning methods in guided imagery and music context. However, it was not possible to ascertain whether neural correlations were due to the perception of a common musical stimulus or therapeutic communication.

The above studies suggest that hyperscanning method may be feasible for understanding the neural mechanisms underlying various types of social interaction as well as dyadic relationships. However, despite the need to quantify CP and CT relationships during therapeutic interventions, to the best of our knowledge, there have only been two EEG hyperscanning studies exploring interbrain synchrony between children with disabilities and their parents (Kang et al., 2022; Samadani et al., 2021). Samadani et al. (2021) found significant CP interbrain synchrony in empathy-related brain regions (e.g., prefrontal and frontal areas) at beta (14–32 Hz) and lower gamma (32–64 Hz) bands. This finding demonstrated the potential of interbrain synchrony as a marker of socio-emotional response of children with severe disabilities. However, the question remains as to whether a child with disabilities can also develop this synchrony with a music therapist. To address this question, Kang et al. (2022) studied interbrain synchronization in both a child–mother dyad and a child–neurological music therapist dyad and discovered significant interbrain synchronization in the frontal and temporal regions in the delta-frequency bands for both dyads. Activities in these low-frequency bands were attributed in part to socio-emotional responses. Kang et al. (2022) also compared the interbrain synchronization between music and storytelling sessions to see if music perception preferentially evokes interbrain synchronization. Verbal storytelling possesses both auditory and temporal components as music, but speech sounds have different tonal and rhythmic inflection patterns compared with music; therefore, storytelling served as a control condition in this study.

To bridge the gap of previous hyperscanning studies in clinical settings (Fachner et al., 2019; Samadani et al., 2021) and to expand upon the triadic case study of Kang et al. (2022), the current study investigated the level and directionality of interbrain synchronization in both CP and CT dyads during music and storytelling sessions across frequency bands and brain regions. In light of previous findings using hyperscanning methods with children with disabilities (Kang et al., 2022), we expected that session type, dyadic relationship, frequency band, and brain region would be strongly related to the level and directionality of interbrain synchronization. We hypothesized that music sessions would result in a higher level of interbrain synchronization compared with storytelling sessions in frontal regions at low frequencies (e.g., delta and theta). Further, previous research found that close interpersonal relationships induced higher interbrain synchronization compared with unfamiliar relationships (e.g., strangers) (Reindl et al., 2018). Thus, we expected higher interbrain synchronization in CP dyads. In terms of directionality, a higher directed coupling from adult participants (e.g., parent or music therapist) to child participants than vice versa as the parent or therapist assumed a "leader role" (Sänger et al., 2013), anticipating the child's response.

Phase locking value (PLV) and partial directed coherence (PDC) were used to investigate the magnitude of phase synchrony and its directionality, respectively, during music and storytelling sessions between CP and CT dyads in this study. PLV has been previously used to calculate the phase synchrony for typically developing children (Doesburg et al., 2010) and children with ASD (Li et al., 2018), and PDC has been computed for directed synchronization for children with ASD (Tsiaras et al., 2011). As such, PLV and PDC were applied in this study. PLV is the absolute value of the mean phase differences between two signals from two electrodes (or two brains in the hyperscanning case), where each signal is represented as a complex vector (Lachaux et al., 1999). For example, if both marginal distributions and relative phases of the two signals are uniform, the PLV will be zero (no interbrain synchronization), whereas if the phase of the signals from two electrodes (or brains) are strongly coupled, the PLV will tend towards one (Bastos & Schoffelen, 2016). PLV is also called phase synchronization index (Müller et al., 2013). Spectral Granger causality indexes, such as PDC, can be estimated in the frequency domain. PDC represents the information propagation across different regions within- and between-brains. Although PLV measures the phase similarity of different neural signals (e.g., between electrodes or between brains), PDC estimates the directional information flow from one brain to another. Specifically, PDC quantifies the Granger causality in the frequency domain based on the absolute value of the mean phase difference between two different electrodes (or brain) (Baccalá & Sameshima, 2001). To the best of our knowledge, PDC has not been reported in any neural synchrony study in music therapy settings.

## 2 | MATERIALS AND METHODS

### 2.1 | Participants

A convenience sample of 17 participants (seven children, seven mothers, and three neurologic music therapists) was recruited, comprising seven CP and CT dyads. Each child–parent dyad was randomly assigned to one of the three neurologic music therapists to mitigate individual therapist effects. It is important to note that one child, her mother, and a music therapist of the current study were included in the previous case report (Kang et al., 2022). The age range of the child participants was 12 to 18 years old (mean, $M = 13.14$ years and standard deviation, $SD = 2.73$). Table 1 indicates participants' demographic information. The mean and standard deviation of the age of the music therapists and mothers were $M = 29.33$, $SD = 1.15$ and $M = 46.33$, $SD = 4.27$, respectively.

The study protocol was approved by the research ethics boards of the Holland Bloorview Kids Rehabilitation Hospital (Toronto, Ontario, Canada) and the University of Toronto. All participants gave written informed consent for their participation in accordance with the WMA Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects.

### 2.2 | Study design and procedures

All child participants and their mother or father participated in one music session and one storytelling session. Sessions occurred on separate weeks with a counterbalanced design to reduce potential order effects. Each session was 18 min long. All participants wore an EEG cap to measure their brainwaves simultaneously during the sessions. Each parent participant sat in a partitioned area of the same room and watched their child's responses via a live video link during each music session and each storytelling session (Figure 1).

Before starting the sessions, 3 min of baseline EEG data were collected for analytical purposes. During this baseline period, all participants (children, parents, and neurologic music therapists) were asked to sit naturally and avoid unnecessary movement. To control the level of familiarity with stimuli for each participant, parent participants were asked to provide a list of their children's favourite songs 1 week before the session and to bring their child's favourite books to the storytelling session rather than using the same music and stories for all participants. During the music session, the neurologic music therapist sang the designated favourite songs to the child

**TABLE 1** Participants' demographic information.

| Participant | Age | Gender | Diagnosis |
|---|---|---|---|
| P01 | 18 | F | Cerebral palsy |
| P02 | 11 | M | Cerebral palsy |
| P03 | 11 | F | Kleefstra syndrome/autism spectrum disorder |
| P04 | 12 | M | Autism spectrum disorder |
| P05 | 12 | F | Autism spectrum disorder |
| P06 | 16 | F | Autism spectrum disorder and fragile X syndrome |
| P07 | 12 | M | Autism spectrum disorder |

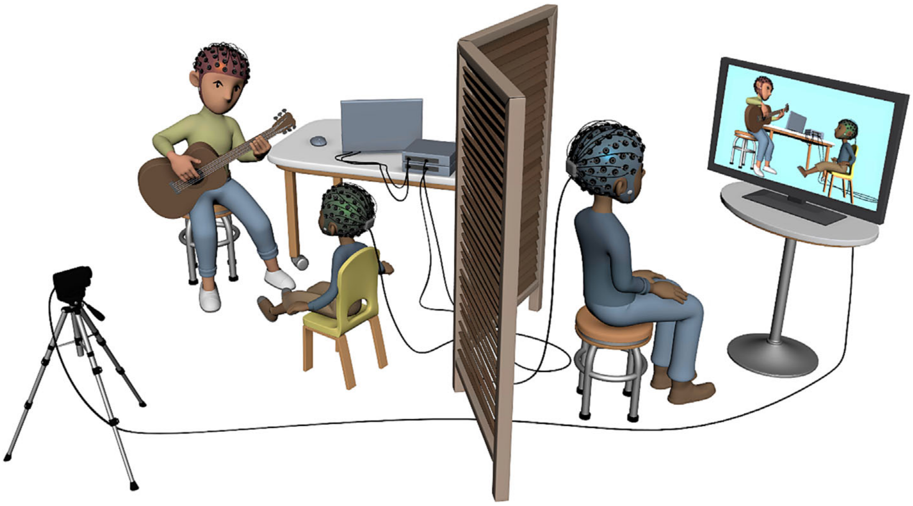

**FIGURE 1** Experimental setting. Adapted from Kang et al. (2022). Note that the therapist and child are depicted on the left whereas the mother is shown on the right.

participants accompanied by guitar playing. The same therapist who led the music session also read the child's favourite storybooks during the storytelling session. Because personally favourite song lists and books were used, the length of individual stimuli varied. In general, stories were longer than songs, resulting in more songs than stories during a 15-min session. Importantly, total stimuli (i.e., concatenation of songs or stories without breaks) exposure time was standardized across sessions. Thus, participants experienced sessional stimuli of comparable duration, which facilitated the study of continuous interbrain synchronization. The participants were randomly assigned to either a music or storytelling session first to minimize the sessional order effects. To minimize other potentially confounding factors, the neurologic music therapists tried to provide a similar amount of eye contact, interaction, and expressive gestures between the music and storytelling sessions.

## 2.3 | EEG data acquisition

EEG data were collected from all participants (children, their parents, and neurologic music therapists) simultaneously to measure the brain activity generated in each dyad (i.e., CP and CT). The 32-channel dry EEG system (actiCap XpressTwist BrainProducts®, Gilching, Germany) was used for the children and the parents, and the 20-channel wet and wireless EEG system (B-Alert X24, Advanced Brain Monitoring, Carlsbad, California, USA) was used for the music therapists to accommodate unconstrained movement and guitar playing. Electrodes were set up according to the International 10–20 system. A separate amplifier was connected to every participant. Each amplifier was linked to a single computer for data collection. The EEG signals were sampled at 1000 Hz (dry EEG systems) and at 256 Hz (wet EEG system). Data streams from each headset were synchronized.

## 2.4 | EEG data processing and analysis

The EEGLAB toolbox and in-house scripts for MATLAB were used for data processing (Delorme & Makeig, 2004). Data were visually inspected to identify signal segments and channels affected by ocular and movement artifacts. When noisy data segments were found, they were removed. Upon retrospective review of the video recordings of participants' sessions, we confirmed that gross movements (e.g., sudden extension of the limbs, head nodding, and postural changes) did not occur. This is expected as adult participants were asked to remain as still as possible. Music therapists were asked to reduce their body sway while playing the guitar (i.e., they performed minimal movements, such as strumming the guitar).

The EEG data collected with the dry system were downsampled to 256 Hz to match the sampling rate of the wet EEG data. For the first step of preprocessing, we used recorded event markers to match the temporal alignment of the two EEG files (32-channel dry/wired and 20-channel wet/wireless). The signals were preprocessed with a bandpass finite impulse response filter (.5 and 60 Hz). The filtered data were re-referenced to a common average. Independent component analysis (ICA) was then applied to remove artifacts subsequent to visual inspection. Following the data decomposition by ICA, we used the ICLabel function in the EEGLab (Delorme & Makeig, 2004) to identify artifactual independent components (Pion-Tonachini et al., 2019). The thresholds of independent components were determined based on previous research (Ma et al., 2022). To ensure reproducibility and to avoid subjective bias, over 80% of artifactual independent components were removed. These included independent components with eye blinks, muscle activity, line noise, and channel noise. On average, .7 and 1.9 independent components were removed for children/parents data and neurologic music therapist data, respectively.

The connectivity analysis (estimation of PLV and PDC) was performed with the FieldTrip toolbox (Oostenveld et al., 2011). The PLV quantified the degree of interbrain synchronization between CP and CT dyads. The PLV was obtained from the amplitude normalized Fourier transformed signals (Bastos & Schoffelen, 2016). The PDC was estimated as the ratio between the parameters of one node of the multivariate autoregressive model and all of the parameters corresponding to the outgoing information of this node (Baccalá & Sameshima, 2001). Both the PLV and PDC were calculated in nonoverlapping 10-s windows over the 15-min session, for the 32 corresponding channels between each child and their mother and the 20 corresponding channels between the children and their music therapists (Figure 2).

Using a bandpass finite impulse response filter with Kaiser window, we extracted signals from the following frequency ranges: delta (.5–4 Hz); theta (4–8 Hz); alpha (8–16 Hz); beta (16–31 Hz); and gamma (31–60 Hz) bands. The brain was divided into seven regions based on the topographic electrode location (Figure 2). In the CT dyads, we used the following: frontal left (FL; Fp1, AF3, F3, and F7); frontal right (FR; Fp2, AF4, F4, and F8); central left (CL; FC5, C3, T3, CP1, CP5, and TP9); centre (CC; Fz, Cz, Pz, and POz); central right (CR; FC6, C4, T4, CP2, CP6, and TP10); posterior left (PL; P3, T5, PO7, and O1); and posterior right (PR; P4, T6, PO8, and O2). In the CT dyads, we used the following: FL (Fp1, F3, and F7); FR (Fp2, F4, and F8); CL (C3 and T3); CC (Fz, Cz, Pz, and POz); CR (C4 and T4); PL (P3, T5, and O1); and PR (P4, T6, and O2).

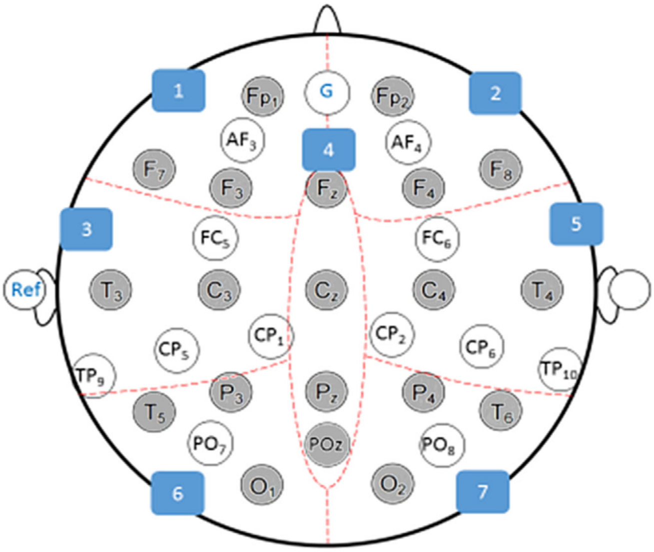

**FIGURE 2** Electrode locations and their clustering into seven brain regions for the children/parents and music therapists. Note the electrode locations for child/parent (32 electrodes) and music therapist (20 electrodes, grey) in seven regions. For child-parent dyads: (1) Fp1, AF3, F3, and F7; (2) Fp2, AF4, F4, and F8; (3) C3, T3, FC5, CP1, CP5, and TP9; (4) Fz, Cz, Pz, and POz; (5) C4, T4, FC6, CP2, CP6, and TP10; (6) P3, T5, PO7, and O1; (7) P4, T6, PO8, and O2. For child–therapist dyads: (1) Fp1, F3, and F7; (2) Fp2, F4, and F8; (3) C3 and T3; (4) Fz, Cz, Pz, and POz; (5) C4 and T4; (6) P3, T5, and O1; and (7) P4, T6, and O2.

## 2.5 | Statistical analysis

We obtained the PLV and PDC values for all electrodes (32 channels for CT dyads and 20 channels for CT dyads) across the frequency bands (.5–60 Hz) for seven CP and seven CT dyads. Only PLV and PDC values during the sessions (excluding baseline) were considered for statistical analysis.

Generalized linear mixed model (GLMM) was used to account for the nonnormal data distributions and the correlational structure within the data due to the repeated measures. The first model was developed to understand the values of interbrain synchronization (PLV) between the sessions in dyads across the frequency bands and brain regions. This model included a fixed effect for the session (music and storytelling session), dyads (CP and CT), frequency bands (delta, theta, alpha, beta, and gamma), and brain regions (FL, FR, CL, CC, CR, PL, and PR). A random effect for the intercept accounted for the correlational structure within participants over time. In the second model, the same fixed and random effects were used to examine the dyadic directionality of interbrain synchronization (PDC) between sessions, across the frequency bands and brain regions. However, the directionality of dyads (child → parent [C → P], parent → child [P → C], child → therapist [C → T], and therapist → child [T → C]) was included as a fixed effect instead of dyads in this model.

The GLMM was fitted using the R software (version 4.2.2) with the glmmTMB package (Brooks et al., 2017). The dependent variables were modelled using a beta distribution with a logit link function, and the significance of the fixed effect was assessed using a likelihood ratio test. We also assessed the goodness of fit of the model using the Akaike information criterion (AIC) and Bayesian information criterion (BIC).

To provide a better understanding of the overall significance of each predictor variable, a Type III Analysis of Variance (ANOVA) was also conducted. A post hoc test using pairwise comparisons determined which session induced higher interbrain synchronization (and its directionality) between dyads across the frequency bands and brain regions. To control for Type 1 errors due to multiple comparisons, we applied a Bonferroni-corrected significance level.

## 3 | RESULTS

### 3.1 | Interbrain synchronization (PLV)

Overall, the model had a very low AIC (−101299.6) and BIC (−101158.8), indicating a good fit to the data. This was further supported by the high log-likelihood (50664.8).

The GLMM revealed that the intercept was not significant (estimated coefficient ($\beta$) = −.027, Standard Errors (*SE*) = .131, *p*-values < .84), indicating that the average response value when all predictor variables were at zero was not significantly different from zero. However, all predictor variables, except for PL, were significantly associated with PLV at a level of significance of 0.05 (Table 2). Specifically, the storytelling session ($\beta = -.148$, *SE* = .004, $p < .001$) and CT dyad ($\beta = -1.303$, *SE* = .005, $p < .001$) predictors showed significant negative associations with PLV, suggesting that the storytelling session and CT dyad were predictive of decreased PLV. To account for the individual differences in PLV, the participants were considered as a random effect; the

**TABLE 2** Generalized linear mixed model table for phase locking value.

| Predictor | Estimate | *SE* | *z*-value | *p*-value | CI 95% |
|---|---|---|---|---|---|
| (Intercept) | −.027 | .131 | −.20 | .838 | −.283, .230 |
| sessionStory | −.148 | .004 | −32.87 | <.001*** | −.157, −.139 |
| dyadCT | −1.303 | .005 | −276.56 | <.001*** | −1.312, −1.293 |
| ClusterCL | .206 | .009 | 24.21 | <.001*** | .189, .223 |
| ClusterCR | .132 | .009 | 15.52 | <.001*** | .116, .149 |
| ClusterFL | .297 | .008 | 35.26 | <.001*** | .281, .314 |
| ClusterFR | .349 | .008 | 41.58 | <.001*** | .332, .365 |
| ClusterPL | .012 | .009 | 1.41 | .158 | −.005, .029 |
| ClusterPR | .029 | .009 | 3.35 | .001** | .012, .046 |
| Fbandbeta | −.108 | .007 | −15.06 | <.001*** | −.122, −.094 |
| Fbanddelta | .177 | .007 | 25.19 | <.001*** | .163, .191 |
| Fbandgamma | −.095 | .007 | −13.19 | <.001*** | −.101, −.080 |
| Fbandtheta | .098 | .007 | 13.94 | <.001*** | .084, .112 |

*Note*: All *p*-values are two-tailed.

Abbreviations: CI, confidence interval; CL, central left; cluster, brain regions; CR, central right; CT, child–therapist; Fband, frequency band; FL, frontal left; FR, frontal right; PL, posterior left; PR, posterior right; SE, standard error.

*$p < .05$; **$p < .01$; and ***$p < .001$.

estimated variance and standard deviation of the random intercept was .120 and .346, respectively.

In the Type III ANOVA, session ($F_{1,\ 88,181} = 742.74$, $p < .001$, $\eta^2 = .00018$), dyad ($F_{1,\ 88,181} = 86517.05$, $p < .001$, $\eta^2 = .0197$), brain regions ($F_{6,\ 88,181} = 408.03$, $p < .001$, $\eta^2 = .0028$), and frequency bands ($F_{4,\ 88,181} = 408.03$, $p < .001$, $\eta^2 = .0022$) were all significant predictors of the PLV (Table 3).

Pairwise comparisons between sessions showed that music sessions induced significantly higher interbrain synchronization levels (PLV) compared with storytelling sessions (estimated difference = .148, $SE = .005$, corrected $p$-values = $< .001$). In terms of the dyads, CP dyad showed significantly higher PLV compared with CT dyads (estimated difference = 1.300, $SE = .005$, $p < .001$). There were significant differences between the PLV means for all frequency band comparisons (all $p < .001$), except between beta and gamma. Figure 3 portrays the overall comparisons between music and storytelling sessions in each dyad across the frequency bands. Each participant's PLV comparison between-sessions is provided in Figures S1 and S2.

All comparisons of mean PLV between brain regions revealed significant differences (all $p < .001$), except between CC–PR (estimate difference = −.029, $SE = .009$, $p = .017$), CC–PL (estimate difference = −.012,

**TABLE 3** Type III analysis of variance results for phase locking value.

| Predictor | Sum of squares | *Df* | Mean square | *F* | *p* |
|---|---|---|---|---|---|
| Session | 15.81 | 1 | 15.81 | 742.74 | <.001*** |
| Dyad | 1841.06 | 1 | 1841.06 | 86,517.05 | <.001*** |
| Brain regions | 52.10 | 6 | 8.68 | 408.03 | <.001*** |
| Frequency bands | 43.65 | 4 | 10.91 | 512.84 | <.001*** |

*Note*: All *p*-values are two-tailed.
Abbreviation: *Df*, degree of freedom.
$*p < .05$; $**p < .01$; and $***p < .001$.

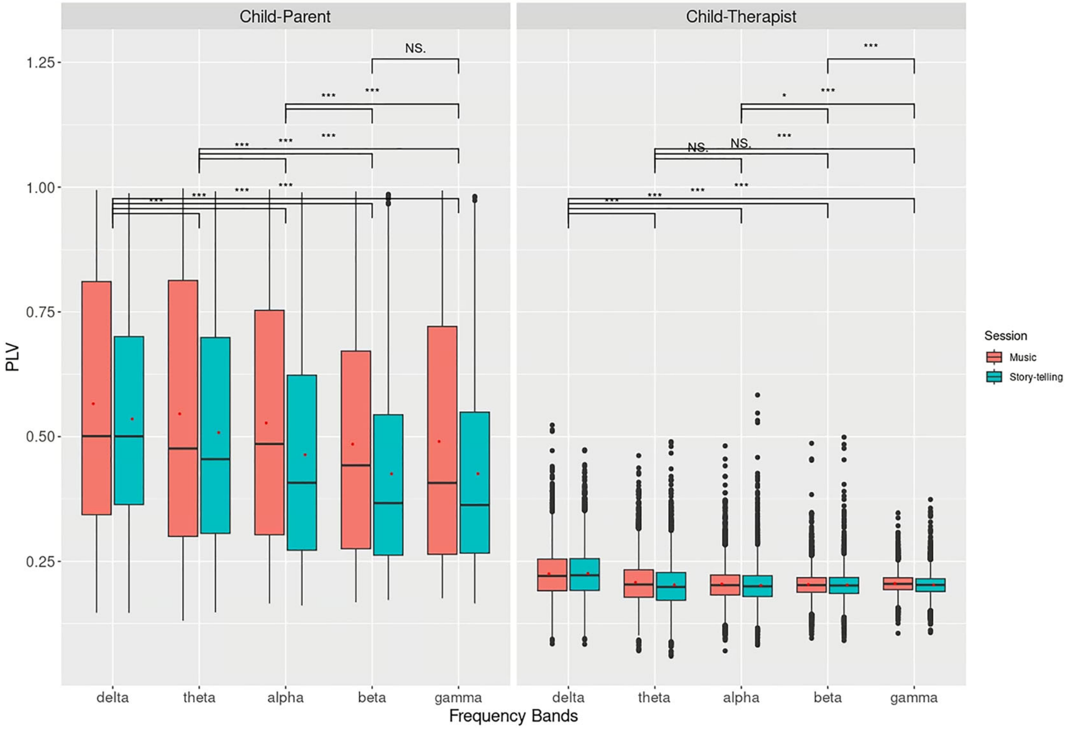

**FIGURE 3** Overall PLV comparisons for each frequency band between music and storytelling in child–parent and child–therapist dyads in PLV. Red dot represents the mean of PLV values. $*p < .05$; $**p < .01$; $***p < .001$. NS, nonsignificant; PLV, phase locking value.

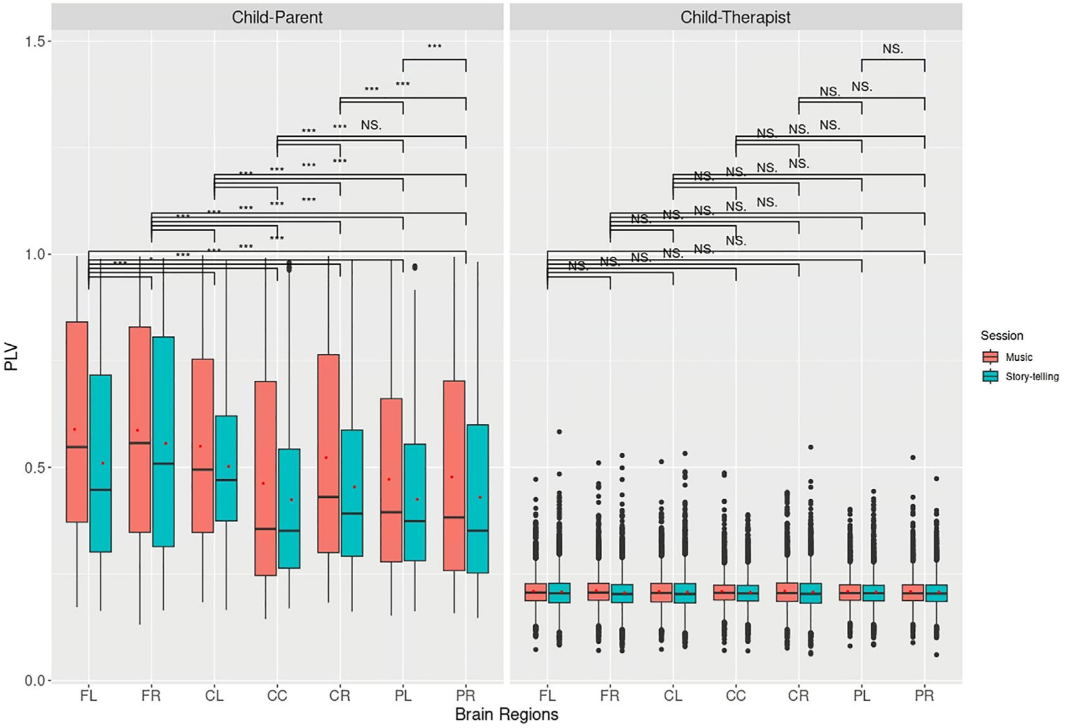

**FIGURE 4** Overall PLV comparisons for each brain region between music and storytelling in child–parent and child–therapist dyads in PLV. Red dot represents the mean of PLV values. *$p < .05$; **$p < .01$; ***$p < .001$. NS, nonsignificant; PLV, phase locking value.

$SE = .009$, corr. $p = 1.000$), and PL–PR (estimate difference $= -.017$, $SE = .009$, corr. $p = 1.000$). Figure 4 provides the overall comparisons between music and storytelling sessions in each dyad across brain regions. A brain region comparison between the sessions for each dyad is provided in Figures S3 and S4.

## 3.2 | Partial directed coherence

This model's AIC (−196100.3) and BIC (−195929.0) were also very low and log-likelihood (98067.2) high, suggesting a good fit to the data.

The intercept in the GLMM model for PDC was significant ($\beta = -1.051$, $SE = .065$, $p < .001$), indicating that the average response value when all predictor variables were at zero was significantly different from zero. All predictor variables, except for CL, CR, and PR, were significantly associated with PDC at a level of significance of 0.05. In particular, similar to our PLV's results, storytelling sessions ($\beta = -.121$, SE $= .004$, $p < .001$) had significant negative associations with PDC. Moreover, directionality from C → T showed significant negative associations with PDC, and P → C and T → C dyads showed positive associations with PDC (Table 4). The estimated variance of the random effect was .029, and its standard deviation was .171.

In the Type III ANOVA, we found that session ($F_{1,\ 176{,}379} = 520.995$, $p < .001$, $\eta^2 = .00003$), directionality of dyadic influence ($F_{3,\ 176{,}379} = 36625.612$, $p < .001$, $\eta^2 = .3835$), brain region ($F_{6,\ 176{,}379} = 32.355$, $p < .001$, $\eta^2 = .0001$), and frequency band ($F_{4,\ 176{,}379} = 301.608$, $p < .001$, $\eta^2 = .0006$) were all significant predictors of PDC (Table 5).

Pairwise comparisons of PDC values between sessions showed that music sessions induced significantly stronger directionality compared with storytelling sessions (estimated difference $= .121$, $SE = .004$, corr. $p < .001$). P → C and T → C PDC values were significantly different from those of C → P and C → T (C → P – P → C: $-.880$, $SE = .005$, $p < .001$; C → T – T → C: $-1.517$, $SE = .006$, $p < .001$), implying that adult participants directed interbrain synchronization. All PDC comparisons between frequency band pairs were significant (all $p < .001$, except alpha–gamma). Overall comparisons of PDC in each dyad directionality are provided in Figure 5. A frequency band comparison between the sessions for each dyadic directionality is indicated in Figure S5.

In terms of the brain regions, FL and FR regions revealed significantly higher PDC compared with CC, CL (all $p < .001$), CR (FL: $p = .01$; FR: $p = 0.02$), PL (all $p < .001$), and PR (all $p < .001$). Figure 6 summarizes the overall PDC comparisons between music and storytelling

TABLE 4 Generalized linear mixed model table for partial directed coherence.

| Predictor | Estimate | *SE* | *z*-value | *p*-value | CI (95%) |
|---|---|---|---|---|---|
| (Intercept) | −1.051 | .065 | −16.17 | <.001*** | −1.178, −.923 |
| sessionStory | −.121 | .004 | −32.05 | <.001*** | −.128, −.113 |
| Direc_C→T | −.891 | .006 | −150.84 | <.001*** | −.902, −.879 |
| Direc_P→C | .880 | .005 | 168.81 | <.001*** | .869, .890 |
| Direc_T→C | .626 | .005 | 119.47 | <.001*** | .616, .636 |
| ClusterCL | −.012 | .007 | −1.66 | .100 | −.026, .002 |
| ClusterCR | .008 | .007 | 1.17 | .241 | −.006, .022 |
| ClusterFL | .033 | .007 | 4.67 | <.001*** | .019, .047 |
| ClusterFR | .032 | .007 | 4.45 | <.001*** | .018, .046 |
| ClusterPL | −.033 | .007 | −4.64 | <.001*** | −.047, −.019 |
| ClusterPR | .00 | .007 | .24 | .810 | −.012, .016 |
| Fbandbeta | −.048 | .006 | −7.96 | <.001*** | −.059, −.036 |
| Fbanddelta | .130 | .006 | 21.92 | <.001*** | .118, .141 |
| Fbandgamma | −.023 | .006 | −3.90 | .0005 | −.035, −.012 |
| Fbandtheta | .045 | .006 | 7.53 | <.001*** | .033, .056 |

*Note*: All *p*-values are two-tailed.
Abbreviations: C → T, child to therapist; CI, confidence interval; CL, central left; cluster, brain regions; CR, central right; CT, child-therapist; Direc, direction; Fband, frequency band; FL, frontal left; FR, frontal right; P → C, parent to child; PL, posterior left; PR, posterior right; SE, standard error; T → C, therapist to child.
**p* < .05; ***p* < .01; and ****p* < .001.

TABLE 5 Type III analysis of variance results for partial directed coherence.

| Predictor | Sum of squares | *Df* | Mean square | *F* | *p* |
|---|---|---|---|---|---|
| Session | 14.74 | 1 | 14.74 | 520.995 | <.001*** |
| Dyad_directionality | 3108.74 | 3 | 1036.25 | 36,625.612 | <.001*** |
| Brain regions | 5.49 | 6 | .92 | 32.355 | <.001*** |
| Frequency bands | 34.13 | 4 | 8.53 | 301.608 | <.001*** |

*Note*: All *p*-values are two-tailed.
Abbreviation: *Df*, degree of freedom.
**p* < .05; ***p* < .01; and ****p* < .001.

sessions in each dyad directionality. Each participant's PDC comparison between-sessions is shown in Figure S6.

## 4 | DISCUSSION

Using EEG-based hyperscanning, the present study investigated the nature of interbrain synchronization in CP and CT dyads during music and storytelling sessions, where the paediatric participants had cerebral palsy or ASD. Specifically, we analysed both the magnitude of phase differences (PLV) and directionality (PDC) in the brain signals of CP and CT dyads.

Overall, it was found that all predictors (e.g., session type, dyadic relationship, frequency band, and brain region) were highly related to the degree of interbrain synchronization and its directionality. Specifically, CP dyads exhibited greater brain synchronization (PLV) compared with CT dyads, which was consistent with the case study findings of Kang et al. (2022). We also observed that interbrain phase synchronization (PLV) was the strongest specifically in delta (.5–4 Hz) frequencies in both CP and CT dyads in frontal brain regions (e.g., FL and FR). The direction of synchronization was largely from adult to child, namely, the brain activity of parents and music therapists tended to influence children's brain activity.

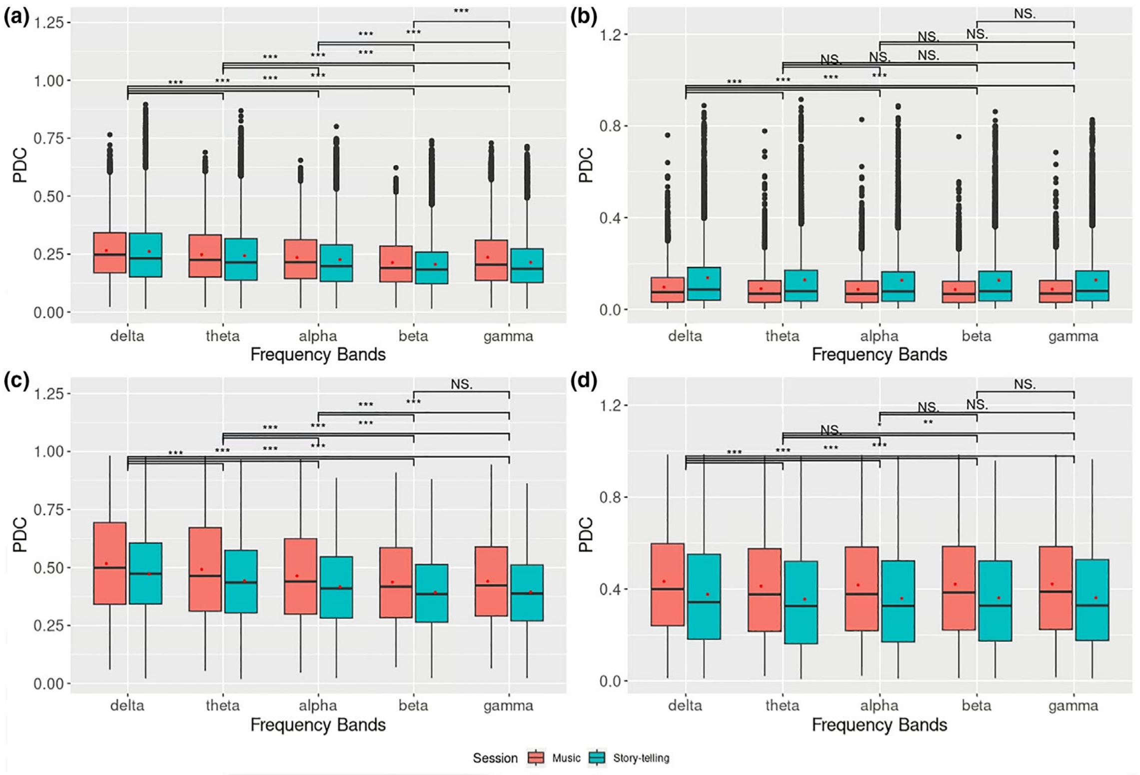

**FIGURE 5** Overall PDC comparisons for each frequency band between music and storytelling in each dyad directionality. (a) Child → parent, (b) child → therapist, (c) parent → child, and (d) therapist → child. Red dot represents the mean of PDC values. NS, nonsignificant; PDC, partial directed coherence.

The higher CP's PLV exclusively during music sessions is perhaps unsurprising given that one of the fundamental effects of music is to arouse emotional response (Reybrouck & Eerola, 2017) and heighten the sense of social connectedness (Savage et al., 2020). The preferential emergence of interbrain synchronization during the music sessions may reflect emotional synchronization. It is important to note that, although the mothers/father did not explicitly interact with their children during the sessions, a significant interbrain synchronization was shown in CP dyads. This finding might support the idea that overt or direct interpersonal interaction is not the only contributing factor to interbrain synchronization. There is evidence that interbrain synchronization can exist by simply sharing emotional processing without explicit interactions (Ardizzi et al., 2020; Golland et al., 2015). Furthermore, the deeper baseline social connectedness between child and mother (affiliative pair) compared with child and therapist (strangers) might have provided a more labile substrate for interbrain synchronization in CP dyads (Kinreich et al., 2017). Previous research has contended that people tend to synchronize to a greater degree with known companions or loved ones rather than with strangers (Anders et al., 2011; Reindl et al., 2018).

Similarly, mother/father–child familiarity with the music and stories may have also contributed to their higher interbrain synchronization. The music therapists requested that parents bring their child's favourite songs and storybooks to the sessions. In this case, the child and mother/father were better acquainted with the songs or stories. There is much evidence indicating that the strength of emotional response to music is closely linked to one's familiarity with the musical stimuli (Pereira et al., 2011).

Additionally, it has been previously reported that mothers of children with disabilities tend to emotionally cope with their children's diagnosis (Barak-Levy & Atzaba-Poria, 2013) and describe greater emotional pain in their relationship with their children, especially those with cerebral palsy (Button et al., 2001). The unique and close attachment between mother and child, their familiarity with the music, and maternal emotional predisposition may collectively explain the more intense synchrony in CP dyads.

In terms of the frequency bands, a previous hyperscanning study in a music therapy setting (Samadani et al., 2021) found interbrain synchronization between child and parents in beta and low gamma bands. In contrast, we observed interbrain synchronization primarily

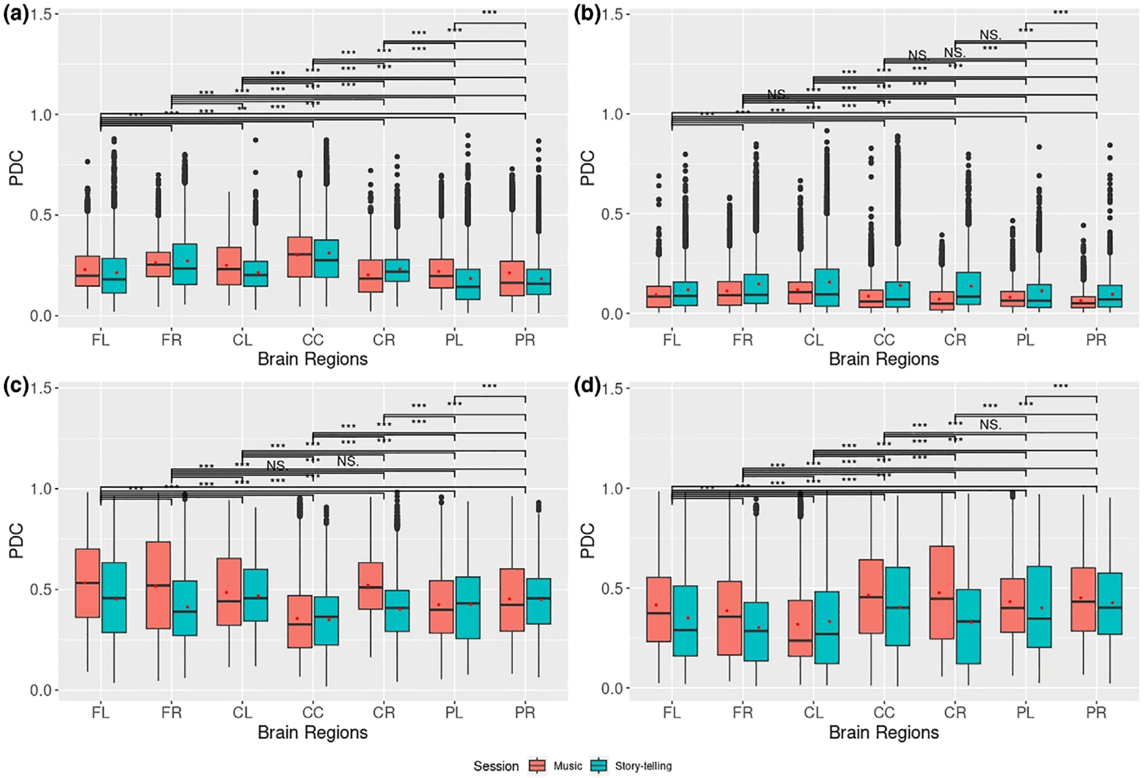

FIGURE 6 Overall PDC comparisons for each brain region between music and storytelling in each dyad directionality. (a) Child → parent, (b) child → therapist, (c) parent → child, and (d) therapist → child. Red dot represents the mean of PDC values. NS, nonsignificant; PDC, partial directed coherence.

in delta and theta bands, similar to Kang et al. (2022). One important difference is that in Samadani et al. (2021), children were engaged in a more interactive music therapy session (e.g., the music therapist encouraged children's active participation by interacting with instruments). In the present study, children passively listened to music. Activity in the higher frequency bands, such as beta and gamma, is associated with cognition, including vibrotactile working memory load (Herding et al., 2017; von Lautz et al., 2017). Thus, interbrain synchronization in different frequency bands may in part be due to the differential level of child engagement between studies. Based on the evidence that low-frequency bands, specifically delta bands, are coupled with empathetic processing, including attention, prediction, and motivation (Knyazev, 2012; Lakatos et al., 2008), the observed low-frequency interbrain synchronization may have been induced by socio-emotional responses between CP and CT dyads. These socio-emotional related frequency bands (e.g., low-frequency bands) have also been previously described, and individuals shared emotional and musical experiences (Lindenberger et al., 2009; Müller et al., 2013; Sänger et al., 2012).

In the present study, we included the directionality of interbrain synchronization to understand if directed brain coupling contributes to different roles in interpersonal relationships. There has been evidence to suggest that one person's brain activity can "drive" another's brain activity in a role-dependent fashion. For example, the brain activity of the lead musician in an ensemble tended to precede the brain activities of other ensemble members (Sänger et al., 2013; Vanzella et al., 2019). Similar observations have been reported for lead individuals in a music class (Pan et al., 2018) and in romantic relationships (Anders et al., 2011). We found that brain activity recorded from the child participants were predicted by those of the adult participants. The parents and music therapists may have anticipated the children's responses; they may have predicted the part of the song or story that their child (in the case of the mothers/father) or children in general (in the case of the therapists) most enjoy based on their previous experiences. It is noteworthy to mention that children would have also been aware of the part of the song or story that they enjoy the most. However, the parents and music therapists may have been actively and diligently discerning the behaviours of the children to anticipate certain responses (e.g., happy or sad) and to adapt their own behaviour accordingly to maintain engagement. On the other hand, the child participants may have taken a more passive role, largely responding to the music and storytelling efforts and thus contributing to the observed leader–follower directionality of brain influence from adult to child.

The lower child-to-adult directionality of interbrain influence may also be attributable in part to the lower propensity for synchrony due to ongoing brain maturation in the child participants. Previous research has reported a general decrease in the EEG power spectrum in adolescents/young adults, aged 10 to 20 years, putatively associated with developmental synaptic pruning and reduction in the number of cortical synapses (Matsuura et al., 1985; Whitford et al., 2007). The neurodevelopmental conditions of the children may also have been a contributing factor. The EEG power spectrum in ASD has been described as “U-shaped” with stronger power exhibited in low- and high-frequency bands and attenuated power in alpha and beta bands compared with spectra of typically developing individuals (Wang et al., 2013). Wideband and narrow band suppression of EEG energy may suggest a reduced capacity for interbrain synchrony in children with neurodevelopmental conditions. Further, Milne (2011) suggested that compared with neurotypical individuals, those with ASD generally have lower capacity to internally synchronize stimulus-locked brain activity, resulting in more “neural noise.” Likewise, Kurz et al. (2013) found that children with cerebral palsy exhibited desynchronization rather than synchronization in the sensorimotor cortices upon tactile stimulation. Compromised within-individual brain synchrony may translate to lower propensity for between-individual synchrony, which in our study, might explain the lower child-to-adult directional brain influence.

To better understand the contributing mechanisms of interbrain synchronization in dyads, specifically involving those with limited physical and cognitive capacity, future research ought to study the associations between neural synchrony and subtle behavioural responses. For example, automated facial expression analysis may allow us to quantify the children’s empathetic behaviour. Facial expression for individuals who have limitations in verbal expressions is a crucial component of social interaction. Video-based facial expression analysis has been used for people with Parkinson’s disease (Bandini et al., 2017) and children with cerebral palsy (Orlandi et al., 2020). The future combination of quantified facial expression and interbrain synchronization may shed light on the association between behavioural and neurophysiological manifestations of empathy in children with disabilities.

Several limitations can be identified in this study. First, the small sample size was due to the practical difficulty of recruiting children with disabilities for more than one hospital-based session; it is logistically challenging to orchestrate multisession in situ brain signal data collection among triads that contain children with severe disabilities (e.g., arranging accessible transportation, scheduling among multiple recurring medical and therapy appointments, organizing childcare for other siblings, and repeated rebooking due to illness, pain, fatigue, poor sleep, or just “bad days”). Despite the small sample size, this exploratory study leads to important findings related to interbrain synchronization in children with disabilities. It bears highlighting that brain measurements were continuously recorded for 15 min. This duration of recording provided ample epochs for detecting the emergence of dyadic interbrain synchronization. Furthermore, previous hyperscanning studies of musical ensembles have also reported insights into the neural mechanisms of socio-emotional responses between dyads with small sample sizes (Kang et al., 2022, and Fachner et al., 2019: one dyad; Babiloni et al., 2012: one quartet; Müller et al., 2013: one quartet; Babiloni et al., 2012: three quartets; Vanzella et al., 2019: five dyads). A second limitation is the heterogeneity of the youth participants, which may have inflated variations in interbrain synchronization capacity. Nevertheless, we found consistent results across participants, especially, a stronger directed coupling from adult to child. In the future, cluster analysis with larger sample sizes might determine if different types of disabilities induce different patterns of interbrain synchronization. In the present study, we measured the overall, sessional interbrain synchronization. To determine specific moments of brain alignment, for example, when a music therapist sings familiar or nonfamiliar music to participants, a moment-to-moment analysis should be considered in future work.

Notwithstanding these limitations, this study confirmed the presence and dominant directionality of interbrain synchronization between children with disabilities and an adult, during separate music and storytelling sessions.

## 5 | CONCLUSION

Using hyperscanning methods during music and storytelling sessions, we explored the magnitude and directionality of interbrain synchronization in specific frequency ranges and brain regions (electrode locations) in CP and CT dyads. Interbrain synchronization was stronger in music compared to storytelling sessions where mothers/father strictly observed their child through video. Interbrain synchrony was most prominent in the delta band, and the dominant direction of brain coupling was from adult to child. Taken together, our findings suggest a capacity for interbrain synchronization between children with disabilities and their mothers/father and music therapists during a shared musical experience, even when the child is a passive participant. The role of musically facilitated interbrain synchronization on socio-empathetic development deserves further study.

## AUTHOR CONTRIBUTIONS

KK: study conception and design, acquisition of data, analysis and interpretation of data, drafting of the manuscript, and critical revision; SO: built the coding for data analysis, supervision, and critical revision; JL: built/ran the coding for the statistical analysis and critical revision; MA: statistical analysis input and critical revision; NR: develop the coding for data analysis; TC: study design, supervision, and critical revision; MT: study design, supervision, and critical revision; All authors reviewed the final manuscript.

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## CONFLICT OF INTEREST STATEMENT

The authors report no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Due to the nature of this research, participants of this study did not agree for their data to be shared publicly due to confidentiality concerns, so supporting data are not available.

## PEER REVIEW

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ejn.16036.

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## SUPPORTING INFORMATION

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