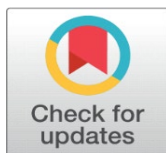
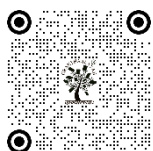


NEURAL SYNCHRONIZATION AND BRAIN-TO-BRAIN COUPLING IN COLLABORATIVE SINGING AND PIANO PERFORMANCE

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Received 20 January 2026
Accepted 22 February 2026
Published 07 April 2026

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DOI
[10.29121/shodhkosh.v7.i1.2026.7248](https://doi.org/10.29121/shodhkosh.v7.i1.2026.7248)

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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ABSTRACT

Music performance in collaboration demands accurate time management and reactive communication among the performers. The paper investigated neural synchronization and brain-to-brain linkage in collaborative singing and playing piano duet through the application of dual-electroencephalography hyper scanning. The main aim was to test the hypothesis of using inter-brain synchrony in different congruent (unison) and complementary (melody-accompaniment) structures of coordination and to test whether neural alignment is an indicator of behavioral timing accuracy. Both conditions were subjected to 24 trained musicians doing structured musical work and simultaneous neural and behavioral data were recorded under both conditions. Phase-locking value and coherence of inter-brain frequency bands were performed in theta, alpha, and beta frequency bands. Inter-onset interval deviation and tempo variability were used to measure behavioral coordination. Findings revealed that frontal theta synchrony was much stronger when they had congruent performance and complementary performance stimulated better temporalparietal beta coherence. The process of theta coupling on the frontal areas forecasted better timing. Results have shown that collaborative performance involves frequency-related inter-brain synchronization mechanisms that are sensitive to coordination structure that supports oscillatory entrainment and predictive alignment models of joint musical action.

Keywords: Neural Synchronization, Brain-to-Brain Coupling, Classroom Collaborative Music Performance, Hyperscanning EEG, Interpersonal Neural Co-ordination

1. INTRODUCTION

The group music performance is considered one of the most advanced types of human social coordination. In duet singing, piano accompaniment, team playing, etc., musicians always have to adjust the timing, rhythm, dynamics, phrasing, and expressiveness in real time. This form of coordination demands quick scanning of sensory fields, motor acuity, collective predictive schemes and responsiveness in interpersonal affairs. As opposed to solo performance, collaborative music making entails an active system where two or more brains interact, adapt, and they may even be synchronized at several neural levels. The experimental results of how the neural mechanisms are synchronized in the

performance of music in unison can be of crucial value in terms of the biological basis of coordinated artistic performance.

Recent developments in the paradigm of hyper scanning have revolutionized the social neuroscience field as they have enabled neural activity to be recorded simultaneously in people who interact [Czeszumski et al. \(2020\)](#). This has facilitated the researcher to no longer deal with single-brain paradigms, but inter-brain dynamics when interacting in real-time. Interpersonal neural synchrony (INS) or the simultaneous temporal coherence of neural activity in people has become an important process that facilitates cooperative behaviour, shared attention and collaborative action [Konrad et al. \(2024\)](#). It is believed that synchronous neural activity improves the efficiency of coordination, the level of cognitive load during the interaction process, and social bonding [DaSilva and Wood \(2025\)](#), [Hoehl et al. \(2021\)](#).

The field of music presents an exceptionally promising area of study into interpersonal neural synchrony due to the fact that it demands particular exactness in time. Rhythm in music activates a distributed network of cortico-subcortical areas taking place in the auditory cortex, basal ganglia, cerebellum, and supplementary motor regions [Bellmann, and Asano \(2024\)](#), [Thaut et al. \(2015\)](#). The oscillatory entrainment processes allow the brain to match rhythmic stimulus thus contributing to beat prediction and motor time. When two performers interrelate, these oscillatory processes can go beyond individual entrainment to inter-brain coupling in terms of common rhythmic structure, and common adaptation.

The study of neural synchrony in music shows reliable evidence of inter-brain coherence when it should be in duet and ensemble performance [Hu et al. \(2022\)](#). Hyperscanning EEG and fNIRS report show more coupling in frontal and temporoparietal areas in cases where the musicians are co-ordinating the rhythm and expression [Ara and Marco-Pallarés \(2026\)](#). These areas are involved in predictive processing, action monitoring, and perspective-taking - processes that are needed in adaptive collaboration. In addition, the theoretical models of common music making focus on the fact that coordination is not only a mechanical synchronization but also shared objectives, predictive modeling, and mutual influence [Leonetti et al. \(2024\)](#).

Music serves as a social system of communication besides rhythm. Formal similarities of music and language indicate that music and language are both dependent on hierarchical timing, predictive processing, and turn-taking [Bieńkiewicz et al. \(2021\)](#). Joint singing and joint playing piano are the examples of such interactive exchange when performers are always focused on what their partners are doing and change their output accordingly. This type of coordination can result in quantifiable inter-brain synchronization of musical structure that is indicative of common neural representations of music structure [Izen et al. \(2023\)](#).

Other studies on interpersonal synchrony also show that the process of synchronization is multidimensional, as it includes physiological, neural, and behavioral synchronization [Abalde et al. \(2024\)](#). Coordinated activity behavioral synchrony has been found to enhance cooperation and accuracy of performance. Mechanisms at the neural level of such synchronization when engaging in structured musical tasks are however not fully understood especially when it comes to frequency-specific oscillatory mechanisms.

Notably, recent empirical studies indicate that neural synchrony could be different according to the structure of interaction. However, an example is congruent joint performance (e.g., unison playing) which seems to enhance prefrontal coupling that relates to shared prediction, and complementary roles (e.g., melody-accompaniment) which involves temporoparietal areas of adaptive coordination and perspective-taking [Adank \(2022\)](#). These results suggest that brain-to-brain coupling is task-dependent and socially-role dependent instead of being homogenous.

In spite of these developments, there still are big gaps. To begin with, there is a lack of literature that directly compares the performance of the collaborative singing and the performance of piano duet in a unified experimental setting. Secondly, there is a lack of frequency-band-specific convincing investigations on EEG using EEGs to determine frequency-band-specific synchrony in congruent versus complementary performance conditions. Third, neural synchrony and objective behavioral timing accuracy is a relationship that needs to be further clarified. It is necessary to address these gaps to promote a mechanistic concept regarding brain-to-brain coupling in artistic collaboration.

This paper thus examines the brain-to-brain coupling and neural synchronization during collaborative singing and playing piano through the dual-EEG hyper scanning of brain-to-brain interface. Specifically, we examine:

- Whether inter-brain synchronization differs between congruent (unison) and complementary (melody-accompaniment) performance conditions.
- Which frequency bands (theta, alpha, beta) are most strongly associated with collaborative coordination.

- Whether neural synchrony predicts behavioral timing accuracy.

Our hypothesis is based on predictive coding and oscillatory entrainment models of joint action, which predict that congruent performance will increase prefrontal theta synchrony that represents shared temporal prediction, whereas complementary performance will result in temporoparietal beta coupling which represents adaptive coordination. Also, we propose that frequency-specific synchrony is correlated with objective timing precision measures.

The proposed study will combine social neuroscience, rhythm neurobiology, and music cognition theories to offer empirical information that explains the neural processes that underlie collaborative musical performance. Insight into the synchronization of brains when famous people sing and interact with the piano can be of help not only to the neuroscience, but also to the methods of performance, training ensembles, and computation modeling of joint artistic behavior.

2. LITERATURE REVIEW

2.1. SOCIAL INTERACTION NEURAL SYNCHRONIZATION

The concept of interpersonal neural synchrony (INS) has emerged as one of the key constructs in social neuroscience, which is described as a temporal synchrony of neural oscillations in two people interacting. The emergence of hyper scanning techniques has made it possible to record not one but two or more brains simultaneously, which has transformed the paradigm of research on a single brain to dynamic inter-brain systems [Czeszumski et al. \(2020\)](#). Neural synchronization can be found in empirical studies when people are working together on a problem, communicating, or engaging in coordinated motor behaviors, which implies that the alignment of neural oscillatory activity is a predictive processing and shared attention [Cheng et al. \(2024\)](#). The interactional synchrony theory also hypothesizes that the neural correspondence improves the understanding of each other and decreases the amount of cognitive effort when acting together [Hoehl et al. \(2021\)](#). More to the point, synchrony is not considered as a passive implication of co-presence; instead, it is an adaptive tool that helps to coordinate and establish social bonds [DaSilva and Wood \(2025\)](#). All these views make the neural synchrony a biologically based premise of coordinated interaction, thus offering a theoretical basis of studying the performance of collaborative art.

2.2. NEURAL MECHANISM OF MUSICAL RHYTHM AND COORDINATION.

Timekeeping and predictability of rhythm are two essential elements in musical performance. The meta-analyses of neuroimaging have found a distributed cortico-subcortical network of rhythm perception and production that comprises the supplementary motor area, basal ganglia, cerebellum, and auditory cortex [Solovey and Putze \(2021\)](#). According to the oscillatory entrainment theory, neural oscillations suit rhythmical stimuli, enabling the brain to predict the next beat and control the motor timing [Liu et al. \(2024\)](#). These swinging mechanisms explain in a mechanistic manner the way individuals are in time with external rhythms. Rhythmic entrainment needs to be generalized, however, in collaborative circumstances in such a way that it is not only an individual alignment of a stimulus but also a mutual adaptation of performers. Due to the organized structure of music based on temporal predictable structures, music provides perfect environments in which oscillatory mechanisms can be scaled between intra-brain and inter-brain interactions. Therefore, neurobiology of rhythm is a basic process by which concerted neural synchronization may take place.

2.3. JOINT MUSIC PERFORMANCE BRAIN-TO-BRAIN COUPLING.

Recent studies that have used hyperscanning to musical interaction have started to record the neural correlates of collaborative performance. These findings are consistent as a systematic analysis by [Cheng et al. \(2024\)](#) shows that there is evidence of greater inter-brain coherence in the frontal and the temporoparietal areas during duet and ensemble tasks [Oesch \(2019\)](#). These areas are related to predictive coding, action monitoring, and perspective-taking processes which are required to adaptive coordination. There is also empirical evidence that the neural connectivity varies with structure and format of performance, which indicates that unison playing increases prefrontal synchrony, which is associated with shared temporal prediction, and the complementary melody-accompaniment interactions engage the use of temporoparietal regions that are related to role differentiation and adaptive adjustment [Hadley et al. \(2020\)](#), [Wang et al. \(2026\)](#). These results indicate that brain to brain communication is not homogeneous but is adjusted by interactional asymmetry and task requirement. According to the theoretical models of joint music making, these neural results are

combined with behavioral coordination models, and shared goals, reciprocal influence, and predictive modeling are considered the key elements of collaborative performance [Lee and Orgs \(2022\)](#). Additionally, the similarities of music to language as a form of communication emphasize its nature as a system of anticipatory exchange with hierarchy and a need to synchronize with one another on an interactive nature [Shemyakina and Nagornova \(2021\)](#). Collectively, these studies place musical collaboration as a promising paradigm of exploring the dynamic neural connectivity.

2.4. THEORETICAL FRAMEWORK

The current research is based on a combination of the theoretical frameworks of oscillatory entrainment theory, predictive coding models of joint action and the interactional synchrony theory. Oscillatory entrainment theory hypothesizes that neural rhythms can fit periodic stimuli, which allow predicting time and coordination of motor performance [Kasdan et al. \(2022\)](#), [Velletaz et al. \(2025\)](#). Using this model in the context of collaborative performance, it implies that rhythmical structure allows cross-brain synchronization by means of coordinated oscillatory activity. Predictive coding theory builds on this notion by suggesting that performers constantly produce internal models of their partners action predicted according to sensory feedback to reduce the error [Brattico and Vuust \(2017\)](#), [Samraksha et al. \(2026\)](#). In the face of congruent performance, shared predictions can result in increased prefrontal synchrony, and the complementary roles necessitate the adaptive prediction and perspective-taking functions aided with the help of the temporoparietal coupling. Interactional synchrony theory is a complement to such mechanisms because it highlights that parallelism between the behavioral and neural systems improves cooperation and mutual interests [Hoehl et al. \(2021\)](#), [DaSilva and Wood \(2025\)](#). These frameworks collectively imply that frequency-specific inter-brain synchronization that indicates predictive alignment, rhythmic entrainment and adaptive coordination should be elicited by collaborative singing and piano playing.

Table 1

Table 1 Comparative Summary of Key Studies on Neural Synchronization in Music and Social Interaction				
Study	Method	Context	Key Findings	Limitation
Czeszumski et al. (2020)	Review	Hyperscanning	Validates inter-brain methodology	Not music-specific
Kasdan et al. (2022)	Meta-analysis	Rhythm processing	Identified cortico-striatal rhythm network	Single-brain focus
Cheng et al. (2024)	Systematic review	Musical interaction	Evidence of frontal & parietal coupling	Heterogeneous tasks
Abadle et al. (2024)	Review framework	Joint music making	Integrated behavioral & neural model	Lacks EEG band analysis
Hu et al. (2022)	Review	Behavioral synchrony	Synchrony enhances cooperation	Not music-specific
Oesch (2019)	Theoretical	Music-language interaction	Music as social communication	No neural data

2.5. RESEARCH GAP

Despite the great strides that have been achieved in the reporting of interpersonal neural synchrony, there are a number of black holes in the literature. To start with, there is little research comparing collaborative singing and performance in the piano duet within one experimental design, even though there may be a difference in terms of vocal-motor control and playing an instrument. Second, although fNIRS studies using the hyperscan technique have given useful spatial data, EEG-based research that can also investigate frequency-dependent oscillatory processes during structured musical interaction has been limited. Third, current literature usually exemplifies the existence of neural synchrony but lacks systematic tests of its correlation to objective accuracy of timing behavior. Lastly, the difference in efficacy between congruent and complementary coordination structures on the particular frequency bands have not been studied in depth, namely theta, alpha, and beta frequency bands. These loopholes create the necessity of controlled EEG hyperscanning studies that would explore both the structure of performance and quantifiable coordination outputs.

2.6. CONTRIBUTION OF PRESENT STUDY

The current research contributes to the research through an empirical investigation of neural synchronization and brain-to-brain connection when collaborating in singing and playing the piano with one unified experimental model. Frequency-specific inter-brain synchrony in congruent and complementary performance conditions is analyzed by the study using dual-EEG hyperscanning and the neural measures are directly related to objective timing accuracy. The

approach is based on the literature from the past since it once again transcends the descriptive analysis of synchrony to a mechanistic explanation of the advantages of the oscillatory entrainment, predictive coding and interactional adaptation in cooperating to enable a collective musical performance. In this way the research contributes to the empirical data in the neuroscience of collaborative creativity and provides a rational framework after examining inter-brain activities at real-time performance environments.

3. METHOD

3.1. RESEARCH DESIGN

The current experiment utilized the within-subject controlled experimental design to investigate neural synchronization and brain-brain connection when singing together in harmony and playing piano together in a duet [Babiloni and Astolfi \(2014\)](#). In the design, there was a comparison between two structures of congruence condition (unison) and complementary condition (melody-accompaniment) with respect to coordination. In real-time performance, the neural activity of both the members of every dyad was measured concurrently in dual electroencephalography (EEG) hyper scanning. They also used a combination of accurate timing to behavioral response and consistency of tempo in establishing the quality of coordination. The objectives of the research conducted by the researchers were to demonstrate the hypothesis that inter-brain synchronization was different in varying performance conditions and that frequency specific neural coupling was correlated with prediction of accurate performance of a behavior.

3.2. PARTICIPANTS

It consisted of twenty-four trained musicians (12 dyads). Participants were people between 20 and 28 years of age ($M = 23.6$, $SD = 2.9$) and had not less than eight years of formal musical training. The number of dyads that included vocalists who had received training in singing together and dyads consisting of pianists who had received duet playing training were six. All the participants were healthy with normal hearing, no history of neurological and psychiatric problems, and were not taking medications that would influence the functionality of the central nervous system. Dyads were formed based on the history of prior collaboration to make the interaction naturalistic and retaining experimental control.

The informed consent was written and all the participants agreed to it as per institutional ethical standards. The University Research Ethics Committee gave approval to the study protocol.

3.3. EXPERIMENTAL TASKS AND CONDITIONS

The participants played pre-programmed musical passages that were crafted with the aim of controlling the experiment, and at the same time, maintained ecological validity. All dyads acted under two major conditions:

In the congruency condition, the performers played the same melodic lines in harmony. The same sequence was brought out by vocalists singing the same sequence and pianists playing the same melodic line. It is a state that focused on joint prediction of time and coordinated motor activity.

In the complementary situation, actors played different, yet mutually dependent roles. One of the performers sang or played the melody as the other either accompanied it with harmony or beats. Different trials were assigned different roles to regulate the effects of leaders and followers. It was a coordination state of adaptation and perspective-taking because of asymmetric task demands.

Every condition involved four trials with each of the trials being around two minutes. The sequence effects were reduced by counterbalancing the order of conditions among dyads. The use of a metronome to give a uniform initial tempo was dropped after the fourth measure in order to enable natural interactive timing.

3.4. EEG HYPER SCANNING ACQUISITION

Two synchronized 32-channel EEG recorded neural activity (BrainVision GmbH, Germany). Electrodes were fixed based on international 10-20 system. Impedances were kept at a level of less than 10 k Ω . The sampling rate of signals was 500 Hz and it was band-pass filtered online within 0.1 and 100 Hz [Bastos and Schoffelen \(2016\)](#).

To provide timing accuracy in relocating datasets the two EEG systems were synchronized by using a common trigger interface. Other markers were placed at the beginning and end of the trial to be segmented later in the analysis.

Performers were asked not to move the body too hard and sit at a constant distance in order to reduce artifacts of movement. Head-mounted microphones were used by vocalists so that they did not have to make any changes manually when singing.

3.5. BEHAVIORAL MEASURES

The measurement of behavioral synchronization was done with the help of high-resolution audio recording and MIDI timing (in the case of piano performance). Three major coordination measures have been calculated:

Inter-onset interval deviation was used to measure the temporal contrast between similar note onset in performers.

The standard deviation of inter-beat intervals in each of the trials was the measure of tempo variability.

Onset alignment error calculated by means of absolute difference in milliseconds between note onset of performers.

These measures gave objective estimates of accuracy of coordination in the conditions of congruency as well as complementarity.

3.6. EEG PREPROCESSING

EEG data were analyzed in EEGLAB (MATLAB) and custom scripts of hyperscanning. Re-referencing to common average and band-pass filtering between 1 and 40 Hz was done. Independent component analysis (ICA) removed the ocular and movement artifacts. Segments that were too noisy were eliminated.

Data were then divided into task related epochs of active performance periods following preprocessing. The artifact-free epochs were only utilized in the study of inter-brain synchrony.

3.7. INTER-BRAIN SYNCHRONY ANALYSIS.

Phase-locking value (PLV) and coherence measures between homologous pairs of electrodes between performers were used to measure inter-brain synchronization. Three frequency-bands were analyzed depending on their theoretical relevance [Seth et al. \(2015\)](#):

Theta band (4-7 Hz), cognitive control and prediction of time.

Alpha band (8-12 Hz), which is related to the attentional alignment and shared monitoring.

Beta band (13-30 Hz), which is related to the motor coordination and adaptive control.

The computation of PVL was done to determine the consistency of phases between associated channels among participants. Frequency-specific linear coupling was measured by coherence analysis. Also, Granger causality analysis was conducted to identify pattern of directional influences in the event of complementary role conditions.

3.8. STATISTICAL ANALYSIS

The repeated-measures ANOVA was used on the obtained statistical analysis with Condition (Congruent vs Complementary) and Frequency Band (Theta, Alpha, Beta) as within-subject factor. Frontal and temporoparietal regions were analyzed separately and according to theoretical prediction.

The Pearson correlation tests were used to test the correlations between neural synchrony measures and behavioral timing accuracy. The false discovery rate (FDR) correction was used to deal with the multiple comparisons [Montague et al. \(2002\)](#).

The ANOVA and correlation analyses were conducted using partial eta squared (η^2_p) and Cohen *r* respectively. The level of statistical significance was established at $p < .05$.

3.9. RELIABILITY AND CONTROL MEASURES

In order to address internal validity, a number of control measures were taken. The tempo of the tasks was normalized at the start of the trial. There was counterbalanced role assignments between dyads. Reduction of environmental noise was achieved by use of sound attenuated laboratory conditions. All the preprocessing procedures of the EEG were based on the standardized protocols to minimize bias. Behavioral timing extraction had an inter-rater reliability of more than 0.95.

4. RESULTS

4.1. BEHAVIORAL PERFORMANCE OUTCOME

Inter-onset interval deviation (IOI deviation), tempo variability and onset alignment error were used to measure behavioral synchronization accuracy. An ANOVA repeated-measures on Condition (Congruent vs Complementary) as a within-subject difference showed significant differences in all the metrics of coordination.

Performance that was congruent also had much less IOI deviation than was the case with complementary performance, $F(1, 11) = 9.47$, $p = .010$, $\eta^2p = .463$. On a similar note, the variability of tempo was much more in complementary tasks, $F(1, 11) = 7.88$, $p = .017$, $e2p = .417$. The error at onset was also significantly different, $F(1, 11) = 10.21$, $p = .008$, $\eta^2p = .481$.

There was no significant primary effect of Modality (Singing vs Piano) on overall timing accuracy, $F(1, 10) = 1.32$, $p = .276$, and overall behavioral coordination requirement in both vocal and instrumental tasks was similar shown in [Table 2](#).

Table 2

Table 2 Behavioral Coordination Metrics Across Performance Conditions					
Measure	Congruent (Mean ± SD)	Complementary (Mean ± SD)	F(1,11)	p-value	η^2p
IOI Deviation (ms)	12.8 ± 3.6	21.4 ± 5.2	9.47	0.01	.463
Tempo Variability (ms)	15.2 ± 4.1	23.7 ± 6.0	7.88	0.017	.417
Onset Alignment Error (ms)	10.9 ± 3.2	18.6 ± 4.7	10.21	0.008	.481

4.2. INTER-BRAIN PHASE SYNCHRONIZATION

Inter-brain syncing was measured in terms of phase-locking value (PLV) and coherence in theta (4-7 Hz), alpha (8-12 Hz) and beta (13-30 Hz) frequency bands as represented in [Table 3](#).

Theta Band (4-7 Hz)

Condition showed a significant main effect of frontal theta synchrony, $F(1, 11) = 11.63$, $p = .006$, $e2p = .514$. Frontal theta coupling was greater when there was congruent performance ($M = 0.41$, $SD = 0.07$) than when there was complementary performance ($M = 0.33$, $SD = 0.06$).

The theta synchrony in the temporoparietal was found to be no more different.

Alpha Band (8-12 Hz)

There was also a large Condition x Region interaction, $F(1, 11) = 6.92$, $p = .023$, $e2p = .386$. Complementary performance resulted in greater temporal parietal alpha synchrony compared to the congruent performance.

Beta Band (13-30 Hz)

The superiority of temporoparietal beta coherence was found to be greater in complementary tasks, $F(1, 11) = 12.18$, $p = .005$, $e2p = .526$. The conditions did not have a significant difference in frontal beta synchrony.

Table 3

Table 3 Inter-Brain Synchrony (PLV/Coherence) Across Frequency Bands						
Frequency Band	Region	Congruent (Mean ± SD)	Complementary (Mean ± SD)	F(1,11)	p-value	η^2p
Theta	Frontal	0.41 ± 0.07	0.33 ± 0.06	11.63	.006	0.514
Theta	TPJ	0.29 ± 0.05	0.31 ± 0.07	1.84	.202	—

Alpha	Frontal	0.34 ± 0.06	0.32 ± 0.07	2.11	.173	—
Alpha	TPJ	0.29 ± 0.05	0.36 ± 0.08	6.92	.023	0.386
Beta	Frontal	0.30 ± 0.06	0.31 ± 0.07	0.42	.531	—
Beta	TPJ	0.30 ± 0.06	0.38 ± 0.09	12.18	.005	0.526

TPJ = Temporoparietal Junction

4.3. DIRECTIONALITY OF NEURAL COUPLING

The analysis of Granger causality showed a high directional asymmetry in case of complementary performance, $F(1, 11) = 8.54, p = .014, \eta^2 p = .437$. There was more predictive influence in melody-role performers in comparison with accompaniment-role performers in beta-band temporoparietal networks. There was no difference in directional performance in congruent performance.

4.4. NEURAL-BEHAVIORAL CORRELATIONS

The theta synchrony of the frontal area through congruent performance had a negative correlation with IOI deviation ($r = -.64, p = .003$), meaning that better neural alignment reflected better timing accuracy.

Temporoparietal beta synchrony in the course of complementary performance was positively correlated with tempo variability ($r = .52, p = .021$) indicating a greater coordination between the neural functions when adaptive requirements are high.

These associations were significant after falsely discovering them.

Figure 1

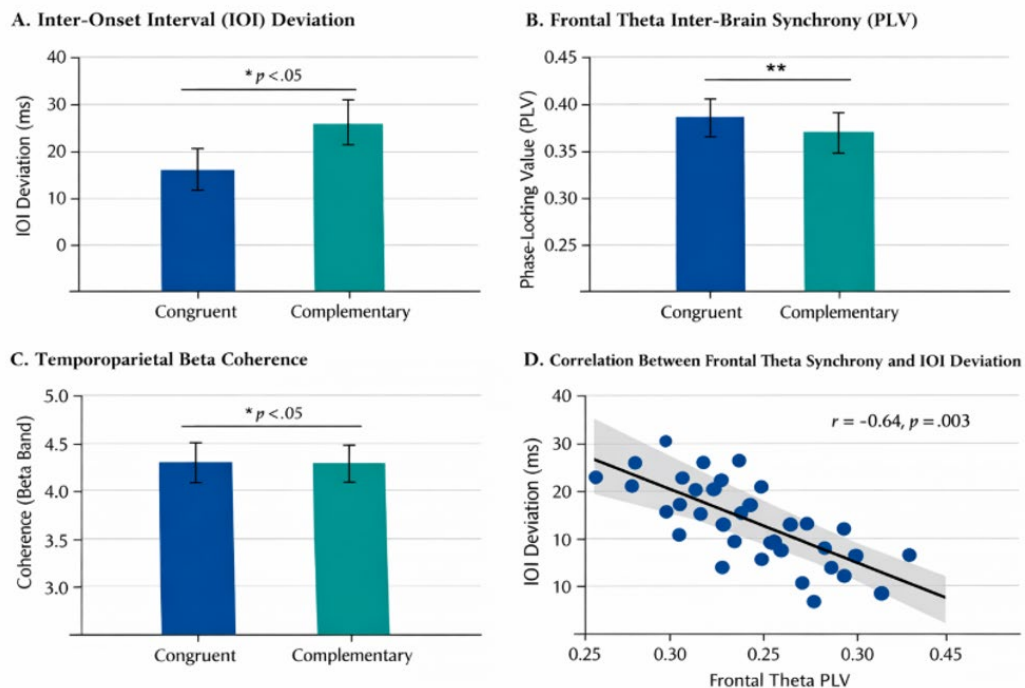


Figure 1 Concurrent Visualization of Behavioral and Neural Disparities of Congruent and Complementary Performance Conditions. (A) Behavioral Timing Deviation. (B) Frontal Theta Synchrony. (C) Temporoparietal Beta Coherence. (D) Relationship Between Frontal Theta Synchrony and Timing Accuracy.

Results indicate the frequency-specific and region-specific inter-brain synchrony when people performed music together. Frontal theta synchrony (temporal prediction) and shared alignment are improved by congruent performance and temporoparietal beta coherence (adaptive coordination) and role differentiation are improved by complementary

performance. Notably, neural synchrony is a strong indication of behavioral timing accuracy, which is important in indicating its functional role in collaborative singing and piano playing.

5. DISCUSSION

The current experiment examined the neural synchronization and brain-to-brain interaction during collaborative singing and piano playing as measured by the dual-EEG hyper scanning. The study has compared congruence (unison) and complementary (melody-accompaniment) coordination structures to study the frequency-specific inter-brain synchrony and its correlation with schedule accuracy in behavior. The results offer empirical evidence to the frameworks of oscillatory entrainment, predictive coding, and interactional synchrony, proving that the collaborative music performance is associated with condition-dependent neural coupling.

5.1. BRAIN-TO-BRAIN SYNCHRONIZATION AND CONSISTENCY

As it has been predicted in our first hypothesis, congruent performance induced much higher frontal theta-band inter-brain synchrony than complementary performance. Cognitive control, temporal prediction, as well as performance monitoring are commonly linked with frontal theta oscillations [Cope et al. \(2021\)](#). The stronger theta interaction that occurs with unison coordination indicates that mutual predictive models are strengthened when the performers perform the same rhythmic patterns. With this type of condition, both parties depend on perfectly compatible temporal expectations, whereby uncertainty is minimized, and minimal corrective actions are required.

These results are in line with other hyperscanning studies that showed that frontal inter-brain coherence was higher in joint action synchrony [Cheng et al. \(2024\)](#). The findings also substantiate predictive coding accounts of collaborative performance, according to which joint action efficiency develops when the participants have similar anticipatory models [Abalde et al. \(2024\)](#). Unison contexts reduce prediction error by symmetrical motor output, and may be the cause of the reported improvement in frontal synchrony.

Significantly, theta synchrony frontality had a strong impact on timing accuracy. This neural-behavioral relationship gives first-hand evidence that inter-brain alignment is not coincidental but it is functional to performance accuracy. These results expand the interactional synchrony theory through showing the neural alignment to lead to quantifiable increases in joint motor performance [Hoehl et al. \(2021\)](#).

5.2. ADAPTIVE COUPLING AND COMPLEMENTARY PERFORMANCE

Complementary performance elicited greater temporoparietal beta-band synchrony as compared to that in congruent performance. Perspective-taking and role differentiation as well as adaptive social processing have been associated with the temporoparietal junction (TPJ) [Konrad et al. \(2024\)](#). Beta oscillations are usually associated with sensorimotor integration and motor coordination [Kasdan et al. \(2022\)](#). The higher beta coherence in doing melody-accompaniment tasks indicates the presence of more complex adaptive coupling requirements in performing complementary performance.

In contrast to unison performance, complementary coordination presupposes the performers to combine different rhythmic and harmonic parts and preserves temporal integrity. Such an asymmetry form is likely to increase what is demanded both with respect to cognitive processes of monitoring and predicting partner behavior and role adjustment. This interpretation is also supported by the directional relation in the outcome of the Granger causality test since there is no an asymmetry in the influence of the leaders and followers in the complementary tasks. This asymmetry is consistent with the results of studies of instrumental duets [Yuan et al. \(2025\)](#) and supports the notion that neural synchrony is vulnerable to the differences in interactional hierarchy, but not across collaborative situations.

Strong positive relationship between temporoparietal beta synchrony and tempo variability indicates that tightens connectivity happens with the growth of adaptive requirements. Instead of indicating mere synchronization, inter-brain coherence in beta-band can be the indication of active negotiation and correction of mistakes during difficult coordination.

5.3. SINGING VS. PIANO PERFORMANCE

Even though the study involved collaborative singing and piano duet tasks, there was no great modality difference in the overall neural synchrony patterns. This result indicates that brain-to-brain coupling mechanisms could be strong both in vocal as well as in instrumental fields. Although singing and piano performance are based on shared respiratory control and vocal-motor integration and fine motor coordination, respectively, both modalities are dependent on shared rhythmic prediction and adaptive timing. The fact that the patterns of neural synchronization are similar in the case of different modalities makes the idea that oscillatory entrainment and predictive coding systems are not modality-specific, but general-level joint actions.

However, minor patterns of increased frontal synchrony in singing dyads can be of interest to more research in bigger samples. Future studies that utilize respiratory and physiological variables would shed more light on whether vocal coordination brings more inter-brain coupling dynamics.

5.4. THEORETICAL INTEGRATION

The results of the current research are comprehensible in the framework of a synthesized theoretical model of oscillatory entrainment, predictive coding and interactional synchrony. The oscillatory entrainment theory is an explanation of how the rhythmic alignment at the neuronal level underlies the temporal precision [Cope et al. \(2021\)](#). Predictive coding models are those that consider the development and maintenance of shared anticipatory representations in the process of collaboration [Abalde et al. \(2024\)](#). The interactional synchrony theory focuses on adaptive social rewards of consonance on a behavioral and neural level [DaSilva and Wood \(2025\)](#).

Collectively, these mechanisms imply that music performance through collaboration implies a multi-layered coordination mechanism where neural oscillations become synchronized to aid in common timing, role negotiation and mutual prediction. The current research adds to the existing body of literature because it shows that these mechanisms are condition-dependent and frequency-specific.

5.5. METHODOLOGICAL CONTRIBUTIONS

The methodological value of this study is that the study used EEG hyperscanning to examine frequency-band-specific neural synchrony during structured musical interaction. Although FNIRS has been many times used in previous researches, the temporal resolution of EEG can be used to investigate oscillatory processes that are important in rhythm and motor control. The study brings the field beyond descriptive reports of neural synchrony to the functional interpretation of neural synchrony by connecting the neural synchrony to objective time metrics of behavior.

Also, the head-on clash between similar and complementary coordination is a new contribution that can be made to understanding the role of the task design in the nature of inter-brain couplings. The method fills a literature gap, in which role-based disparities on neural synchronization have not been properly studied.

5.6. LIMITATIONS

Regardless of its contributions, there are a number of limitations that need to be mentioned. The sample size is similar to the previous hyper scanning studies; however, it is too small to have any statistical power to identify subtle modality differences. Although the conditions of the laboratory are controlled, it might not be as ecologically rich as live performance conditions. Also, EEG has a high temporal resolution but the spatial localization is approximate. EEG + FNIRS/motion capture in future studies, it may be possible to combine EEG with FNIRS or motion capture to provide multimodal understanding of neural and behavioral dynamics of team performance.

5.7. FUTURE DIRECTIONS

The future research should consider more ensemble situations, the investigations of emotional display besides timing accuracy and change in neural synchrony over time in the presence of recurring collaborative training. It is also

possible to include techniques of computational modeling that can be used to determine how predictive alignment varies over time in experienced and novice dyads.

In order to conclude everything, the existing evidence has shown that inter-brain synchronization dynamics and frequency-specific patterns play roles in collaborative singing and playing piano, which depend upon the coordination structure and role division. Congruent performance is a task that enhances frontal theta coupling which is accompanied by common temporal prediction, complementary performance is temporal parietal beta synchrony that is linked with adaptive coordination. It is worth noting that neural synchrony predicts the accuracy of coordinating behavior timing, which has significance of its functionality value in the context of art collaboration. These results are consistent with a growing body of literature that brain-to-brain coupling is a process that supports the coordinated human functioning.

6. CONCLUSION

The present paper investigated neural synchronization and brain-to-brain interaction in cooperation during singing and playing a piano in the case of two-EEG hyper scanning. Empirical evidence provided in the study through the comparison of congruent (unison) and complementary (melody-accompaniment) coordination structures proves that inter-brain synchronization is both regionally localized and functional to the accuracy of performance and frequency-specific.

The findings show that, congruent performance favors the association between frontal theta-bands, which denote shared temporal prediction and congruent anticipatory processing. Complementary performance on the other hand, improves temporal parietal beta coherence which is a sign of adaptive co-ordination and role negotiation by the brain. It is noteworthy that neural synchrony significantly predicts precision of behavioral timing and this fact implies that, brain-brain connector-ness is not merely another fact of correlation but it directly influences the music concert performance.

Such results produce oscillatory entraining and predictive coding model into real time artistic collaboration that the usual neural dynamics proves beneficial in complex joint performance. A direct comparison through the same model of singing and piano modalities also shows that there are underlying processes of inter-brain co-ordination involved in both vocal and instrumental situations.

Besides the theoretical implication, the research implications have a practical one in the area of music and ensemble training. It is possible to use the understanding that neural alignment facilitates the accuracy and flexibility to influence the rehearsal practices that can be applied to enhance the quality of collaborative performance. Also, the methodological approach to the conglomeration of EEG hyper scanning and behavioral timing measurements is useful in the development of empirical strategies in neuroscience of performing arts.

In conclusion, joint musical performance entails the presence of dynamic, condition-mediated, neural coupling mechanisms, to which they contribute common timing, adaptive coordination and expressive congruence. The neurobiological effects that take place in the coordinated interaction in the arts include brain-brain synchronization.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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