Inter-brain Synchronization: Mechanisms, Influencing Factors, and Functions

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Abstract

By simultaneously recording brain signals from multiple individuals during social interaction, hyperscanning studies have commonly observed inter-brain synchronization (IBS) of neural activity signals. Through common representation and mutual prediction mechanisms, indirect factors such as similar sensory inputs, motor outputs, and attentional arousal between individuals, as well as inter-individual information transmission activities, drive the emergence of IBS. Among these, the mirror neuron system, mentalizing system, and mutual attention-interbrain synchronization-reward circuit play important roles. The strength of IBS is modulated by interaction type and intensity, task context, interpersonal relationships, and individual characteristics and states. IBS may have functional significance in interpersonal motor coordination, language communication, and establishing social bonds. Future research could further investigate the relationship between "common representation" and "mutual prediction" mechanisms, interpersonal "desynchronization", cross-brain plasticity, and the similarities and differences among various interaction forms.

Full Text

The Mechanisms, Influencing Factors, and Functions of Inter-Brain Synchronization

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Abstract: By simultaneously recording brain signals from multiple individuals during social interaction, hyperscanning studies have consistently observed inter-brain synchronization (IBS)—the temporal coupling of neural activity between interacting individuals. IBS is driven by both indirect factors such as shared sensory inputs, motor outputs, and attentional arousal, as well as direct information transfer between individuals, operating through co-representation and mutual prediction mechanisms. The mirror neuron system, mentalizing system, and the mutual attention-synchronization-reward loop play crucial roles in these processes. The strength of IBS is modulated by interaction type and intensity, task context, interpersonal relationships, and individual characteristics and states. IBS may serve functional roles in interpersonal motor coordination, language communication, and social bonding formation. Future research should further investigate the relationship between "co-representation" and "mutual prediction" mechanisms, interpersonal "de-synchronization," cross-brain plasticity, and comparisons across different interaction modalities.

Keywords: interpersonal interaction, inter-brain synchronization, co-representation, predictive coding

Frequent communication and interaction with others represent a defining characteristic that distinguishes human society from other species' ways of life and serves as a key driver of human cognitive abilities and brain evolution. Over recent decades, social cognitive neuroscience has made significant progress in understanding how individual brains process social information and engage in interpersonal interaction. However, social interaction involves a complex nonlinear system composed of coordinated activities between two or more individuals, making it difficult to infer its mechanisms through simple superposition of effects generated by isolated brains (Konvalinka & Roepstorff, 2012). In recent years, researchers have employed hyperscanning technology to simultaneously record brain activity from multiple individuals and analyze inter-brain synchronization, providing novel insights into the neural mechanisms of social interaction. This research area has grown rapidly (Figure 1 [Figure 1: see original paper]). Current literature has summarized and reviewed analytical methods for inter-brain synchronization (Burgess, 2013; Xu et al., 2024), research paradigms, and empirical findings (Czeszumski et al., 2020; Czeszumski et al., 2022; Li et al., 2018). Nevertheless, theoretical explanations regarding the generation mechanisms and functional significance of inter-brain synchronization remain relatively vague. This article summarizes the definition and measurement approaches of inter-brain synchronization, the driving factors, cognitive mechanisms, and neural underpinnings of IBS generation, and analyzes key variables influencing IBS as

well as its potential functional significance. Based on this synthesis, we identify current limitations and propose directions for future research.

Figure 1. Recent developments in hyperscanning research. Data were obtained from the following databases: Web of Science, PubMed, PsycINFO, PsycARTICLES, Psychology and Behavioral Sciences Collection, and ProQuest. Search keywords included: inter-brain coupling, inter-brain coherence, inter-brain connectivity, inter-brain correlation, inter-brain synchronization, interpersonal brain synchronization, hyperscanning. Total number of articles: 744.

2.1 The Meaning of Inter-Brain Synchronization

Interpersonal synchronization is a ubiquitous phenomenon in human society, encompassing four types: behavioral synchronization, emotional synchronization, cognitive synchronization, and physiological synchronization. Physiological synchronization can be further subdivided into autonomic nervous system synchronization, inter-brain synchronization, and hormonal system synchronization (Mayo & Gordon, 2020). Through behavioral observation and experimentation, researchers have extensively investigated behavioral, emotional, and cognitive synchronization between individuals, achieving relatively deep understanding of their mechanisms and functional significance. Only recently, with the application of hyperscanning technology, has inter-brain synchronization begun to be systematically examined.

Inter-brain synchronization (IBS) generally refers to the correlation or synchronization of brain activity patterns between individuals during interaction, representing a covariation phenomenon of neural activity across individuals (Valencia & Froese, 2020). Some scholars have proposed a stricter definition, arguing that only inter-individual correlated or synchronized neural activity that emerges during real-time interaction and has causal influence on behavior should be termed IBS (Holroyd, 2022). However, given the difficulty in establishing causal links between IBS and behavior, most current literature reports IBS in its broader sense, a convention we follow in this article.

A term frequently used interchangeably with IBS is inter-brain coupling (IBC), which refers to neural processes that exhibit regular relationships between the brains of information senders and receivers. This includes correlations (i.e., neural alignment) or complementary activities, as well as other regular transformations and dynamic interactions that influence and constrain the neural responses of both senders and receivers (Hasson & Frith, 2016). Currently, the hyperscanning field does not strictly distinguish between inter-brain synchronization and coupling; therefore, these terms appear alternately in this article with identical meanings.

From a temporal perspective, interpersonal synchronization can be categorized as trend synchronization, concurrent synchronization, or lagged synchronization. Trend synchronization refers to correlations in behavior, neural activity, or physiology between individuals over extended periods. Concurrent synchro-

nization denotes correlations occurring within the same time window. Lagged synchronization occurs when one individual's measurements correlate with another's measurements from a previous time point (Sened et al., 2022). Most hyperscanning studies currently focus on concurrent or lagged synchronization. Additionally, from a phase perspective, interpersonal synchronization can be classified as in-phase synchrony or anti-phase synchrony. In-phase synchrony indicates positive correlations between individuals' measurements, whereas anti-phase synchrony means that when one participant's measure increases, the other's decreases simultaneously (Sened et al., 2022). Due to the complexity of factors causing anti-phase synchrony, most current research focuses on in-phase synchronization.

2.2 Measurement of IBS

At the data level, IBS reflects the correlation or similarity between two (or more) signals. Consequently, its measurement methods are fundamentally similar to those used for examining relationships between signals from different brain regions within an individual. Based on differences in the type of information utilized, IBS metrics can be divided into time-domain and frequency-domain categories. According to the directionality of information flow between brains, IBS can be classified as directed or undirected connectivity. Beyond these distinctions, different IBS metrics also vary in their underlying statistical principles. Integrating these classification criteria, current IBS measurement methods in the literature can be categorized into five classes (Hakim et al., 2023).

The first class comprises inter-subject correlation (ISC) metrics, which reflect the covariance of brain signal amplitude or power over time between participants. Common methods include Pearson correlation, cross-correlation, and partial correlation. These indices describe symmetric, linear relationships between signals. For nonlinear covariation relationships, Spearman correlation or dynamic time warping methods can be employed. ISC analysis is applicable to various neuroimaging data types.

The second class involves regression analysis. In regression approaches, generalized linear models (GLM) are typically used to model an individual's brain activity based on others' brain activity and additional data. Compared to ISC methods, regression analysis offers greater flexibility by allowing the inclusion of multimodal data. For example, brain signals from others that appear synchronously, with lag, or in anticipation can be included as predictor variables. Additionally, external environmental variables that occur in real-time during interaction, such as sounds and facial expressions, can be incorporated as predictors. In multi-person interaction tasks, brain signals from multiple participants can be included as predictor variables to examine associations between a target participant's brain activity and the group. Due to the diversity of independent variables, this analytical approach is also termed xGLM (Hamilton, 2021). Regression analysis is applicable to various neuroimaging data types.

The third class of IBS metrics is coherence analysis, which aims to measure the similarity in power density between two signals within specific frequency bands. This method is suitable for signals with high temporal resolution and operates under the assumption that different frequency bands in neural signals reflect distinct cognitive functions. Therefore, coherence in specific frequencies between interacting individuals' neural signals suggests their joint engagement in certain cognitive functions. The most commonly used method in this category is wavelet transform coherence (WTC), which can estimate the dynamic evolution of frequency-domain relationships between two signals over time and is frequently applied in functional near-infrared spectroscopy (fNIRS) data analysis.

The fourth class is phase synchrony, which, similar to coherence analysis, focuses on specific frequency bands but disregards amplitude differences between signals. A commonly used metric for phase synchrony is the phase-locked value (PLV), which reflects the consistency of phase differences between two signals over time. Notably, phase synchronization can arise from four physical mechanisms: (1) mutual influence between two oscillators (reciprocal synchronization); (2) both oscillators being driven by identical external factors; (3) one oscillator driving another; and (4) "coincidence," where two oscillators happen to oscillate at the same frequency (Burgess, 2013). Only in cases 1 and 3 does genuine information transfer exist between the two oscillators, representing the phenomenon of interest in hyperscanning research. Phase synchrony is commonly used to analyze EEG signals.

The fifth class comprises causality analysis methods, which are suitable for analyzing time series data and can reflect the directionality of information flow—for example, from the information sender's brain to the receiver's brain. Causality analysis methods are based on two premises: (1) causes precede effects, and (2) knowledge of causes improves prediction of effects (Hakim et al., 2023). Commonly used methods include Granger Causality (GC), partial directed coherence (PDC), and Transfer Entropy (TE). As a model-free method, TE is particularly suitable for detecting both linear and nonlinear coupling relationships (Ursino et al., 2020; Wang & Chen, 2020). It should be noted that these methods essentially reveal directional predictive relationships between variables and do not necessarily imply biological or physical causality. These methods require relatively long time series and are commonly used to analyze EEG signals or fNIRS data with high temporal resolution.

3.1 Classification of IBS Driving Factors

Inter-brain synchronization is defined as a phenomenon that emerges specifically in interactive contexts. However, based on the measurement methods described above, it is possible to observe high correlations between individuals' brain signals even without genuine information exchange or interaction (Burgess, 2013; Holroyd, 2022). According to whether information transfer exists between individuals, IBS generation can be divided into two scenarios.

The first scenario involves no genuine information transfer between individuals; IBS emerges solely due to shared driving factors. This includes three types of driving factors: (1) Similar neural responses produced by identical sensory stimulation. Research shows that when individuals receive external periodic stimuli, particularly rhythmic sensory information, the stimulus rhythm adjusts the phase of neural oscillations, gradually synchronizing neuronal ensemble activity and aligning it with the external stimulus phase (i.e., phase locking) (Burgess, 2013; Calderone et al., 2014). This process is called neural entrainment (Nozaradan et al., 2011). Through this mechanism, even if different individuals are not directly interacting or even in the same physical space, they will exhibit strong inter-brain signal synchronization as long as they receive sensory inputs with common temporal characteristics (Wass et al., 2020). (2) Inter-brain signal synchronization produced through common motor output. To elicit group communication and interaction, researchers often require participants to perform explicit tasks, such as button-pressing tasks based on specific rhythms. Studies show that when executing identical or similar simple action sequences—such as synchronized stepping (Miles et al., 2009) or arm flexion (Miles et al., 2011)—individuals exhibit significant coherence in power density within specific frequency bands. (3) Inter-brain signal synchronization arising from shared enhancement of attention and arousal. Attention forms the foundation of social cognition. Overall enhancement of attention and arousal places groups in similar psychological states, producing covariance in signal amplitude or power over time (Gvirts & Perlmutter, 2019). Research using inter-subject correlation (ISC) has found that when groups receive identical external stimuli, higher-arousal stimuli elicit stronger ISC compared to "boring" stimuli (Schmälzle et al., 2015). Additionally, psychiatric and clinical research has found that individuals with attention-related deficits exhibit abnormal synchronization during social interaction (Fitzpatrick et al., 2016).

The second scenario involves real-time information transfer between individuals that evokes inter-brain neural synchronization through shared psychological processes. Based on the direction of information transfer, this can be divided into two categories: (1) Unidirectional information transfer in one-to-one or one-to-many contexts. Typical paradigms include "leader-follower" (Jiang et al., 2015; Kurihara et al., 2024) and "speaker-audience" (Zheng et al., 2020) scenarios. In leader-follower situations, the "leader" possesses more information about the task or bears greater responsibility, while the "follower" lacks information and must rely on the leader's guidance to achieve individual or group goals, thereby enabling information transfer and communication. Using coherence analysis and other metrics, synchronization of brain signals within specific frequency bands can be demonstrated. Even without explicit task goals—for example, in simple playing, speaking, and listening—information output and automatic reception still exist between individuals. However, because followers have weaker goal orientation, synchronization in specific frequency bands is often at lower levels (Kourtis et al., 2014). (2) Bidirectional information transfer between individuals. In this context, groups typically share common task goals, requiring

real-time, bidirectional information exchange. Common tasks include group cooperation (Li, Mayseless, et al., 2021), intergroup conflict (Yang, Zhang, et al., 2020), group performance enhancement (Xie et al., 2023), persuasion and conformity (Li et al., 2023), and intragroup games (Tang et al., 2016). In these tasks, individuals must not only express their own thoughts or actions to others but also adjust their behavior in real-time based on feedback from others' speech, facial micro-expressions, and body movements, thereby achieving bidirectional information transfer.

3.2 Cognitive Mechanisms of IBS Generation

At the cognitive level, two major theories currently explain the generation mechanisms of inter-brain synchronization.

3.2.1 Co-Representation Theory   Regardless of whether information flow is unidirectional or bidirectional, the emergence of IBS requires that different individuals' mental systems form shared representations of the situation (Hasson et al., 2012; Jiang et al., 2021; Shamay-Tsoory et al., 2019). In social interaction, the objects of co-representation include both shared external objects, events, or actions and the internal mental activities of the agents themselves. These representations exist at different hierarchical levels, including primary perceptual-motor representations, intermediate cognitive layers (e.g., semantic concepts, world knowledge, joint attention), higher-level social-cognitive representations (e.g., intentions, attitudes, beliefs), and emotional state representations. The brain regions where IBS emerges are closely related to the content of co-representations established during the task. For example, meta-analyses have revealed that IBS during action synchronization tasks commonly appears in brain regions related to motor control (parietal lobe, prefrontal cortex) (Czeszumski et al., 2022). During verbal communication tasks, IBS frequently emerges in brain regions associated with phonological, syntactic, and semantic processing (Liu et al., 2019; Liu et al., 2020). When pathways for establishing co-representation are blocked—for instance, when a listener cannot comprehend the speaker's language—IBS is substantially reduced (Liu et al., 2021; Novembre et al., 2016).

3.2.2 Mutual Prediction Theory   In social interaction, forming shared mental representations is insufficient for smooth interpersonal interaction; mutual prediction between individuals is also required. According to predictive coding theory, the human brain continuously generates predictions based on prior experience. When incoming sensory information about oneself and the environment differs from predictions, prediction errors occur. To reduce these errors, the brain takes action to change incoming sensory information or update predictions (Shamay-Tsoory et al., 2019; Spratling, 2017). Hamilton (2021) extended predictive coding theory to interpersonal interaction contexts, proposing the mutual prediction theory. According to this theory, an individual's brain encodes information about its own behavior (Aself) and encodes information about others'

behavior through predictive mechanisms (Aother). Simultaneously, the interaction partner's brain also encodes information about its own behavior (Bself) and predicts and encodes information about the other's behavior (Bother). When predictions are relatively accurate, the results of Aself + Aother are similar to those of Bself + Bother, causing these two individuals' brains to exhibit similar overall neural activity. This theory has been well-validated in animal experiments (Kingsbury et al., 2019).

3.3 Neurophysiological Basis of IBS

Meta-analyses of hyperscanning studies indicate that multiple brain regions—including the prefrontal cortex, parietal lobe, temporal lobe, and precentral gyrus—participate in social interaction and exhibit IBS (Czeszumski et al., 2020; Wang et al., 2018; Zhao et al., 2024; Zhou et al., 2019). Based on the potential functions of these brain regions, they can be divided into three systems.

(1) **Mirror Neuron System.** Mirror neurons are primarily distributed in the ventral premotor cortex, posterior inferior frontal gyrus, rostral inferior parietal lobule, and superior temporal gyrus. The mirror neuron system is characterized by similar activation patterns specific to particular actions that occur both when an individual executes an action and when observing others execute similar actions (Iacoboni & Dapretto, 2006). Inter-individual synchronization of the mirror neuron system typically appears in tasks involving body movements (e.g., hand-clapping or button-pressing) and plays an important role in action imitation and coordination (Lu et al., 2023; Ménoret et al., 2014).

(2) **Mentalizing System.** In social interaction, while the mirror neuron system is primarily responsible for action simulation and coordination, the mentalizing system is responsible for inferring others' intentions in the absence of explicit motor information input (Begliomini et al., 2017; Van Overwalle & Baetens, 2009). The mentalizing system includes the medial prefrontal cortex, temporoparietal junction (TPJ), precuneus, posterior cingulate cortex, and temporal pole (Van Overwalle & Baetens, 2009). The prefrontal cortex is responsible for planning, management, information integration, and other higher-order functions, while the TPJ is responsible for more complex cognitive processes such as perspective-taking. Inter-subject synchronization in the mentalizing system, manifested as covariance in brain signal amplitude or power over time or similarity in power density within specific frequency bands, typically emerges in interaction tasks involving higher-level social cognition, such as face-to-face verbal communication (Jiang et al., 2015; Kinreich et al., 2017), persuasion (Li et al., 2023), and intergroup conflict (Yang, Zhang, et al., 2020).

(3) **Mutual Attention-Synchronization-Reward Loop.** In real life, we are typically surrounded by multiple people. Why do we selectively synchronize with specific individuals? Some researchers propose that neural

and behavioral synchronization with others may be related to potential benefits obtained through alignment during interaction (Gvirts & Perlmutter, 2019; Shamay-Tsoory et al., 2019), such as achieving intimacy or facilitating task success. According to the "loop of mutual attention, synchronization, and reward" proposed by Gvirts and Perlmutter (2019), inter-brain neural synchronization in the mutual attention system promotes social alignment between individuals in behavior, emotion, or cognition, which in turn activates the reward system. As feedback, reward system activation and social consistency further enhance IBS. This model can explain the modulatory effect of oxytocin on inter-brain synchronization during social interaction tasks (Mu et al., 2016).

3.4 Summary

The generation mechanism of inter-brain synchronization—how two (or more) independent brains establish connections—represents a core question that hyperscanning researchers must address. We have analyzed and summarized current understanding of this issue from three perspectives: driving factors, cognitive mechanisms, and neurophysiological foundations. However, the relationships among these factors and mechanisms remain unclear. For example, under what circumstances does the "mutual prediction" mechanism play a primary role in the emergence of IBS? Does IBS generated through the "co-representation" mechanism primarily rely on the mirror neuron system, while IBS generated through the "mutual prediction" mechanism mainly depends on the mentalizing system? Furthermore, the ultimate goal of investigating IBS generation mechanisms is to understand its role in interpersonal communication and interaction. However, current empirical research exploring how IBS establishes associations with behavior remains relatively scarce.

4. Influencing Factors of IBS

The previous sections summarized the cognitive mechanisms and neural foundations associated with IBS phenomena. When does IBS emerge, and what factors modulate it? By analyzing empirical studies, we have broadly categorized factors influencing IBS into four types, which we discuss in turn (see Table 1).

Table 1. Influencing Factors of IBS

Category	Description
Interaction Type and Intensity	Types: verbal communication, non-verbal communication, body movements; Intensity: low, medium, high
Task Context	Cooperation, competition, independence, task rewards

Category	Description
Interpersonal Relationships	Attachment relationships, group identity, cultural background
Individual Traits and States	Gender, age, personality, empathy, attention, emotion, motivation

4.1 Interaction Type and Intensity

The type and intensity of social interaction significantly influence both the brain regions (or neural oscillation frequencies) where IBS emerges and its strength. Based on interaction content, current hyperscanning research involves three types: verbal communication, non-verbal communication (e.g., smiling, eye contact), and body movements. Interaction types can also be distinguished based on spontaneity, reciprocity, and multimodality. Interaction intensity can be understood as the subjectively perceived degree of interpersonal connection, influenced by subjective engagement in the interaction task. Different interaction types and activities within the same type vary in interaction intensity. For example, dialogue involves stronger interaction than eye contact, which in turn is more interactive than averted gaze (Farroni et al., 2002). Interaction task type importantly influences the brain regions where IBS emerges (Zhao et al., 2024), while interaction intensity further affects IBS strength. For instance, compared to back-to-back conditions, face-to-face verbal communication produces higher cross-brain coherence in the left inferior frontal cortex (Jiang et al., 2012). Among romantic couples, touch elicits higher cross-brain coherence than verbal communication in sensorimotor and mentalizing systems (Long et al., 2020). One EEG study found that body movement and smiling during interaction evoked gamma-band inter-brain synchronization, while eye contact evoked beta-band synchronization (Koul et al., 2023).

4.2 Task Context

Social-cognitive tasks can be divided into cooperative, independent, and competitive contexts, each affecting IBS differently. Compared to independent or competitive tasks, cooperative tasks typically produce stronger IBS (Nguyen et al., 2021; Reindl et al., 2018; Reindl et al., 2022), and IBS strength positively correlates with team performance. This result also indirectly confirms the important role of effective information transfer (Reveille et al., 2024). However, significant inter-brain synchronization is not observed under competitive conditions. For example, in button-pressing tasks requiring participants to respond faster than their partners (Cui et al., 2012) or in computer ping-pong games where participants control paddles competitively (Sinha et al., 2016; Susnoschi Luca et al., 2021), no significant IBS was found among participants. The strength of IBS during interaction is also influenced by task reward mechanisms, as corresponding task rewards can affect IBS by influencing individual motivation. Researchers have found that when monetary rewards for cooperative success

are higher, both the frequency of cooperation and IBS (phase-locking values for alpha and theta bands) increase (Hu et al., 2018). In summary, when participants share aligned task goals and interests, they adopt similar processing strategies, more easily understand each other's intentions, and categorize each other as in-group members, thereby enhancing cooperative performance and strengthening IBS; the opposite occurs under competitive conditions.

4.3 Interpersonal Relationships

Interpersonal relationships among group members during interaction can also modulate IBS, primarily by regulating its strength. Research shows that during cooperative tasks, IBS between romantic partners is consistently higher than that between friends or strangers, manifesting as higher wavelet coherence in the right superior frontal gyrus; IBS between friends is also stronger than between strangers (Pan et al., 2016). Additionally, mother-child dyads show higher coherence than stranger dyads in the dorsolateral prefrontal cortex and prefrontal cortex (Reindl et al., 2018). These phenomena may result from well-established attachment relationships between partners, friends, and mother-child pairs (Zhou et al., 2019). Group membership also influences IBS. In gaming contexts, people tend to show more synchronization with in-group members than out-group members (Astolfi et al., 2010; Yang, Zhang, et al., 2020). In motor synchronization tasks, same-race partners show stronger cross-brain correlations than different-race partners (Gamliel et al., 2021). Collectively, these studies reveal that whether in experimentally arranged cooperative scenarios or pairings between familiar group members, the common feature is that participants share aligned positions and belong to the same in-group, consequently producing stronger IBS.

4.4 Individual Traits and States

Individual traits—including personality, gender, age, and empathy—and momentary mood states during experiments also influence IBS strength. Research shows that participants' extraversion and agreeableness, as measured by the Big Five Inventory, positively correlate with inter-brain wavelet coherence in the right and left inferior frontal gyri, respectively, indicating stronger neural coupling (Zhang et al., 2021). Regarding gender, current research has focused primarily on the effects of gender composition. In cooperative button-pressing tasks, researchers found that mixed-gender dyads showed stronger prefrontal inter-brain coherence than same-gender dyads (Cheng et al., 2015). However, other studies have reported inconsistent or even opposite findings (Baker et al., 2016; Li, Chen, et al., 2021), suggesting that IBS strength may be modulated by multiple factors. Furthermore, researchers using linear regression analysis have found that individuals with stronger empathy abilities are more likely to develop neural coupling with partners in the inferior frontal gyrus and posterior superior temporal sulcus during cooperative tasks, as individual empathy scores positively predict inter-brain synchronization (Liu et al., 2017). Beyond

trait factors, individuals' attentional, emotional, and motivational states during interaction also affect IBS strength. Compared to positive emotions, negative emotions can elicit stronger IBS; moreover, regardless of valence, emotional arousal positively correlates with IBS (Nummenmaa et al., 2012; Nummenmaa et al., 2014). This aligns with the earlier proposition that arousal constitutes one of the primary driving factors of IBS.

4.5 Summary

In summary, we have identified several key factors closely associated with inter-brain synchronization: interaction type and intensity, task context, interpersonal relationships, and individual traits and states. In essence, IBS is more likely to emerge between in-group members during cooperative tasks with strong interactivity. Beyond these factors, numerous other variables in social interaction (e.g., stimulus characteristics, interaction medium, cultural background) may also influence IBS, but they were not included in this discussion due to limited empirical research. How do these factors influence IBS? Integrating current understanding of IBS generation mechanisms, we propose the following possibilities: (1) In social contexts, stimulus characteristics (bottom-up factors such as intensity and novelty) and task goals (top-down factors) drive joint attention between individuals. Tasks requiring cooperation and strong interactivity drive higher degrees of joint attention, resulting in stronger IBS. (2) After information filtering by the attentional system, individuals process and represent situations based on their own memory systems. Individuals with closer interpersonal relationships have more similar past experiences, leading to higher similarity in their representations of task situations and consequently more synchronized inter-brain activity. (3) According to the "mutual attention-synchronization-reward loop" theory (Gvirts & Perlmutter, 2019), inter-brain synchronization in the mutual attention system promotes social alignment between individuals in behavior, emotion, or cognition, which in turn activates the reward system. For identical stimuli, individuals differing in personality, gender, empathy, and other traits may exhibit different degrees of reward system activation, thereby influencing their inter-brain synchronization with others. These hypotheses await empirical testing.

5. Potential Functions of IBS

As a ubiquitous phenomenon in social interaction, what role does inter-brain synchronization play in interpersonal communication and interaction? Some researchers argue that IBS is merely an epiphenomenon resulting from simultaneous external stimulation driving different individuals' brains, lacking substantive function in most cases (Holroyd, 2022). However, by analyzing evidence from neuromodulation and neurofeedback experiments, brain-behavior correlation analyses, and studies of special populations, we contend that IBS indeed possesses important functional significance in promoting motor coordination, verbal communication, and social bonding.

5.1 Facilitating Interpersonal Motor Coordination

Numerous studies have observed significant IBS between participants during interpersonal coordinated movements (e.g., hand-clapping, button-pressing). Is this phenomenon merely a consequence of shared motor output? A recent study used transcranial electrical stimulation to simultaneously increase neural excitability in the prefrontal cortex and right inferior frontal gyrus of dyads performing coordinated button-pressing tasks while recording their brain activity with fNIRS. Results showed that compared to pre-intervention trials, both during and after stimulation, dyads exhibited higher prefrontal cortex signal correlations and improved coordination on the button-pressing task. These effects were absent in control groups receiving sham stimulation (Lu et al., 2023). Other researchers have also found that increasing inter-brain synchronization through neuromodulation techniques enhances spontaneous behavioral synchronization in subsequent tapping and song-learning tasks (Novembre et al., 2017; Pan et al., 2021). These results provide causal evidence that inter-brain synchronization promotes motor coordination.

Animal studies have also played important roles in revealing the functional significance of IBS. Zhang and Yartsev (2019) used wireless electrophysiology to record real-time neural activity, including local field potentials (LFP) and single-neuron spiking, in bats during natural social interaction. They found that neural synchronization increased before bats began interacting, suggesting that such synchronization may be a prerequisite for behavioral coordination. We speculate that IBS promotes motor coordination primarily through predictive coding mechanisms. Stronger IBS implies that individuals form shared representations in encoding external stimuli, action preparation, and attention, thereby enabling more accurate predictions of others.

5.2 Facilitating Verbal Communication

Language constitutes the primary means of human social interaction. According to the "interactive alignment" theory of dialogue, successful verbal communication is built upon representational alignment. Representations requiring alignment include not only linguistic features such as phonology, semantics, and syntax but also situation models (Pickering & Garrod, 2006). Pickering and Garrod (2006) further divided verbal communication into three levels—interactive language processing, mutual understanding, and relationship construction and maintenance—and proposed that different levels of interpersonal communication are associated with different patterns of inter-brain synchronization. Consistent with these views, researchers have found that during both unidirectional and bidirectional verbal communication, listeners and speakers exhibit significant ISC in the amplitude changes of blood oxygen signals in language-processing brain regions (e.g., temporal lobe, inferior frontal gyrus) and brain regions related to situation model construction (default mode network). Moreover, stronger neural coupling is associated with better listener comprehension of the speaker (Liu et al., 2021; Stephens et al., 2010). Is inter-brain synchro-

nization during spoken communication merely a result of both speaker and listener receiving identical auditory input? One EEG study using multiple linear regression analysis found that even after controlling for brain-to-sound synchronization effects, significant phase synchronization remained between speakers and listeners in the posterior temporal lobe, parietal cortex, and motor cortex (Pérez et al., 2017). This result indicates that inter-brain synchronization during verbal communication is related to spontaneous cognitive activity rather than being a passive consequence of identical sensory input.

Research on individuals with social communication disorders further suggests the function of IBS in interpersonal communication. Autism spectrum disorder, characterized by deficits in social interaction and communication involving difficulties in understanding others' intentions and behaviors, has been studied using fNIRS. Researchers assessed IBS between autistic children and their parents during cooperative tasks using coherence as a metric. They found that autism severity was highly correlated with reduced IBS; children with more severe autism showed less IBS increase during social interaction with parents, particularly in the medial prefrontal cortex (Wang et al., 2022). However, these studies currently provide only correlational evidence; experimental results demonstrating that IBS intervention affects verbal communication outcomes are still lacking.

5.3 Facilitating Social Bonding and Prosocial Behavior

Interpersonal synchronization is considered an evolutionarily based mechanism that enhances social bonds, cohesion, and group identity (Launay et al., 2016). As a neural marker of behavioral synchronization, inter-brain synchronization may play an important role in this process (Muller et al., 2021). Researchers using neurofeedback technology to allow participants to voluntarily increase inter-brain synchronization subsequently measured their prosocial experiences. They found that enhanced IBS was associated with stronger prosocial experiences exhibited after the experiment. Similar effects have been found in pigeon neurofeedback experiments (Yang, Zhang, et al., 2020). Beyond neurofeedback approaches, altering IBS through cooperative tasks can also induce subsequent behavioral changes. In one fNIRS study, two groups of participants completed either a cooperative or independent button-pressing task, followed by a prosocial tendency test. Analysis revealed that compared to the independent group, dyads in the cooperative condition showed stronger coherence in the left frontal region, and their prosocial scores were also higher. Within the cooperative group, the strength of inter-brain synchronization during button-pressing positively predicted subsequent prosocial scores (Hu et al., 2017). The link between IBS and prosocial behavior may be related to the "mutual attention-synchronization-reward loop." According to this hypothesis, inter-brain neural synchronization in the mutual attention system promotes social alignment between individuals in behavior, emotion, or cognition, which in turn activates the reward system, releasing dopamine and oxytocin (Gvirts & Perlmutter, 2019). This process may generate more positive experiences and produce motivation for prosocial

behavior.

5.4 Summary

Results from studies using neuromodulation or neurofeedback methods to alter IBS and subsequently change behavior provide strong evidence for the functional significance of IBS. It should be noted that although these findings refute the view that "inter-brain synchronization is merely a byproduct of behavior," they do not imply that IBS is unaffected by behavior. We propose that IBS and behavior may have a reciprocal causal relationship: inter-brain synchronization promotes motor coordination, verbal communication, and social bonding, while these behavioral outcomes in turn facilitate the continued development of these behaviors. Future research should clarify the specific mechanisms through which IBS influences behavior. We suggest that three possibilities warrant further investigation: IBS may promote interpersonal motor coordination through "predictive coding" mechanisms, facilitate language communication through "interactive alignment" mechanisms, and promote prosocial behavior through "reward feedback" mechanisms. Additionally, many studies have found significant positive correlations between IBS and behavioral performance during interaction, while individuals with deficits in social interaction and communication skills exhibit abnormal IBS. Although these studies cannot establish causal relationships between IBS and specific behaviors, they demonstrate that IBS can serve as an objective neural marker of effective communication and social interaction. Based on this, future research could expand the application value of IBS in assessing interpersonal relationships, evaluating social function in atypical individuals, and lie detection.

6. Summary and Outlook

Using hyperscanning technology, numerous researchers have observed covariation patterns in brain activity between interacting individuals, a phenomenon collectively termed inter-brain synchronization (IBS). Based on whether information transfer exists between individuals, IBS generation can be divided into two scenarios. In the first scenario, no genuine information transfer occurs between individuals; IBS emerges solely due to shared driving factors, including identical sensory input, common motor output, or shared enhancement of attention and arousal. In the second scenario, real-time information transfer exists between individuals, evoking IBS through shared psychological processes, including unidirectional (one-to-one or one-to-many) and bidirectional information transfer. Regardless of scenario, IBS generation depends on interacting individuals forming shared psychological representations of the situation. Mutual prediction mechanisms also cause interacting individuals to exhibit similar neural activity. At the neural level, IBS emergence is closely related to the functions of the mirror neuron system and the mentalizing system (including the medial prefrontal cortex and temporoparietal junction). Additionally, according to the "mutual attention-synchronization-reward loop" hypothesis, the reward sys-

tem modulates IBS (Gvirts & Perlmutter, 2019). IBS strength is influenced by four factors: interaction type and intensity, task context, interpersonal relationships, and individual traits and states. Regarding IBS functional significance, controversy remains. Some researchers argue that in most cases, inter-brain synchronization is merely an epiphenomenon occurring when different individuals' brains encode similar sensory information or are in similar psychological states (Holroyd, 2022). By analyzing intervention studies using neuromodulation or neurofeedback techniques, brain-behavior correlation analyses, and research on special populations, we propose that IBS may have functional significance for interpersonal motor coordination, verbal communication, and social bonding formation.

Despite progressive deepening of understanding of inter-brain synchronization over the past two decades, at least two major issues remain: (1) Different researchers employ diverse IBS measurement metrics lacking standardization. Different metrics have different physiological meanings, and the associated cognitive processes may also differ substantially. In fact, for the same data, different metrics may lead to different or even opposite conclusions. For example, two signals may have similar amplitudes but opposite phases at specific frequencies. To more accurately understand inter-brain synchronization, future researchers should justify their choice of specific metrics or replicate results using different measurement methods. (2) Current understanding of the specific process of "how different brains establish connections" remains shallow. In physical space, different individuals' brains are independent. For independent brains to exhibit statistical covariation or mutual constraint relationships, external environmental factors and internal psychological processes must serve as mediators. The third section of this article listed some driving factors, but the specific processes through which these factors operate and the relationships between variables remain poorly understood. Future research could collect multimodal data— including voice, movement, facial expressions, heart rate, and respiration—and use regression or causality analyses to reveal how different individuals' brain signals achieve synchronization or mutual constraint through these variables. Additionally, combining "single-brain" and "dual-brain" analyses could help infer how intra-individual implicit cognitive processes influence inter-brain synchronization.

Future research could further investigate inter-brain synchronization in several directions:

(1) **What is the relationship between "co-representation" and "mutual prediction" in social interaction?** These two mechanisms represent primary explanations for how individuals effectively interact and generate inter-brain synchronization. However, their relationship remains unclear. We speculate that co-representation may be an important prerequisite for mutual prediction: the more similar an individual's mental representation is to others', the more accurate their predictions of others will be. Accurate predictions, in turn, promote behavioral coordination

between individuals, leading to deeper levels of co-representation. Therefore, "co-representation" and "mutual prediction" may be two mechanisms that mutually reinforce each other in the dynamics of interpersonal interaction. To explore this question, future researchers could design sustained interaction scenarios, such as meaningful in-depth conversations, and infer individuals' prediction accuracy of others through behavioral or verbal responses. Then, by analyzing IBS in relevant brain regions, they could infer the degree of co-representation individuals establish with others and examine the dynamic relationship between IBS and prediction accuracy.

(2) **In complex social interactions, beyond "entering synchronization," individuals also need to "de-synchronize."** What factors drive people to "de-synchronize," what is its functional significance, and how do individuals flexibly switch between "synchronization" and "de-synchronization" states? Behavioral research shows that synchronization in action is not always beneficial for task completion; rather, lower interpersonal synchronization allows for more flexible interpersonal organization and facilitates problem-solving (Mayo & Gordon, 2020). Recent hyperscanning research indicates that the brains of interacting individuals are not always in a stable state of strong synchronization but instead exhibit complex patterns of state changes (Li, Mayseless, et al., 2021). However, research on the patterns governing changes in inter-brain synchronization strength, their driving factors, and relationships with behavior remains limited. Notably, many factors can cause "de-synchronization" or "non-synchronization," including absence of factors driving "entering synchronization" (as listed in Section 3.1), attentional lapses, different processing strategies, and individual neurophysiological differences. Among these, the truly interesting case is when individuals actively adjust their states to adapt to social situational demands, thereby causing "de-synchronization." Additionally, examining inter-brain "synchronization" and "de-synchronization" requires consideration of temporal scale. At long-term and macro-system levels, interpersonal synchronization may benefit behavior, while at short-term and micro-levels, "de-synchronization" may be more advantageous.

(3) **"Post-interaction inter-brain coupling" and "cross-brain plasticity."** The vast majority of current research focuses on inter-brain synchronization that occurs during tasks. A few studies have found that inter-individual neural synchronization persists briefly after social interaction ends, a phenomenon termed "post-interaction inter-brain coupling" (Khalil et al., 2022). Shamay-Tsoory et al. (2019) found that the strength of post-interaction neural coupling between individuals could predict self-reported motivation for future connection with that person. The authors propose that post-interaction inter-brain coupling may reflect individuals' preparation for future social relationships and represent a potential mechanism for social relationship development. After social interaction, social cues are consolidated, and representations of interaction partners' actions

may remain active in memory, facilitating future interpersonal relationship development. Some researchers have also proposed the novel concept of "inter-brain plasticity," referring to the process whereby repeated exposure to high inter-brain synchronization leads to lasting changes in individuals' overall synchronization capacity (Shamay-Tsoory, 2022). This concept provides a novel and valuable perspective for understanding the neural basis of interpersonal interaction and the functional significance of inter-brain synchronization. However, whether "post-interaction inter-brain coupling" represents a genuine sustained effect of interaction or is caused by other factors (noise) that co-occur with inter-brain coupling requires further investigation. Moreover, if it is a genuine neural plasticity phenomenon, "post-interaction inter-brain coupling" must be accompanied by structural changes in the nervous system. Future research could investigate post-interaction changes in brain microstructure and the relationships between structural changes, inter-brain synchronization, and subsequent behavior.

(4) **Similarities and differences in cognitive and neural mechanisms across different interpersonal interaction forms.** Based on the number of participants and interaction structure, interpersonal interaction forms can be categorized as "one-to-one," "one-to-many," and "many-to-many." Different interaction forms involve obvious differences in information processing modes, behavioral responses, and dynamic characteristics of information flow (Yang, Li, et al., 2020). However, current hyperscanning research primarily focuses on "one-to-one" interaction contexts. Even in "one-to-many" contexts (e.g., teacher-student interaction), researchers mainly analyze data following a "one-to-one" approach. Future research could, guided by social-cognitive models, compare similarities and differences in intra-individual brain activity patterns and inter-individual neural synchronization patterns across different interaction forms. Such findings would help reveal how the brain dynamically and flexibly modulates its activity patterns across different social contexts.

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