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Running head: Hyperscanning studies of spoken communication

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Highlights

- Emergence of synchrony identified in verbal communication hyperscanning studies
- Identifies knowledge sharing, turn-taking, and naturalistic discussion paradigms
- Alignment predominantly occurred in the frontal and temporo-parietal areas
- Second-person neuroscience assists our understanding of interpersonal communication
- Suggest new experimental conditions and deep learning data analysis techniques

Abstract

A growing body of literature examining the neurocognitive processes of interpersonal linguistic interaction indicates the emergence of neural alignment as participants engage in oral communication. However, questions have arisen whether the study results can be interpreted beyond observations of cortical functionality and extended to the mutual understanding between communicators. This review presents evidence from electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) hyperscanning studies of interbrain synchrony (IBS) in which participants communicated via spoken language. The studies are classified into: knowledge sharing; turn-taking speech co-ordination; cooperation, problem-solving and creativity; and naturalistic discussion paradigms according to the type of interaction specified in each study. Alignment predominantly occurred in the frontal and temporo-parietal areas, which may reflect activation of the mirror and mentalizing systems. We argue that the literature presents a significant contribution to advancing our understanding of IBS and mutual understanding between communicators. We end with suggestions for future research, including analytical approaches and experimental conditions and hypothesize that brain-inspired neural networks are promising techniques for better understanding of IBS through hyperscanning.

Key words: hyperscanning; oral communication; social interaction; interbrain synchrony (IBS)

1. Introduction

Being ‘in sync’ or ‘on the same wavelength’ are idioms commonly used to describe feelings of social harmony or agreement with others. In recent years, cognitive neuroscientists have begun to explore the cognitive processes activated during social interactions, such as spoken communication, and examine the cortical functionality and connectivity underlying social cognition (see Redcay and Schilbach, 2019, for a review). This emerging research area, termed ‘second-person’ or ‘two-brain’ neuroscience, is based upon the assumption that engagement in social interaction, overlaps but differs from observation of social interaction (named ‘third-person’ neuroscience). Early two-brain studies investigated situations in which participants engaged in imitation, cooperation, and competition tasks (e.g., Astolfi et al., 2010; Astolfi et al., 2011; Cui et al, 2010, Dumas et al., 2010; Montague et al, 2002). Over time the number of studies has proliferated and the experimental paradigms employed have increased in diversity and complexity to examine functional connectivity while interacting through complex strategies requiring elements of cooperation, competition, and deception (e.g., Balconi et al., 2017; Balconi and Vanutelli, 2017, Toppi et al., 2016), to producing and receiving language in an array of ecological settings, including educational, creativity and problem-solving scenarios (e.g., Antonenko et al., 2019; 2018; Dikker et al., 2017; Mayseless et al., 2019; Xue et al., 2018).

In addition to this, the second-person approach has been extended to investigations of the social interactions occurring during counselling sessions and in role plays of workplace annual performance reviews (Balconi et al., 2020; Zhang et al., 2018). Other recent research has suggested the application to situations where communication is unsuccessful; for example, for those with neurological disorders (e.g., autism spectrum disorder, ASD, schizophrenia, borderline personality) and who may be receiving psychotherapy, neurofeedback, or other clinical interventions (Pan and Cheng, 2020; Wang et al., 2020). From this growing body of literature it has become apparent that the cognitive processes engaged during social interaction share a degree of functional connectivity resulting from the dynamic patterns of entrainment stemming from collective mental processes (Fedorenko and Thompson-Shill, 2014; Redcay and Schilbach, 2019).

One of the central concepts emerging from the second-person neuroscience approach has been the premise of interbrain synchrony (IBS) resulting from the harmonization of brain signals between people interacting in socially-mediated settings. Measurement of IBS is performed via neuroimaging techniques, and the degree of functional connectivity or alignment is estimated through computation of dynamic phase coherence between cerebral activities (Babiloni and Astolfi, 2014; Balconi et al., 2017; Konvalinka and Roepstorff, 2012). In general, IBS is thought to depend upon a number of factors, including the type of social activity, setting and significance of the interaction, and nature of the relationship between partners, and neural regions commonly displaying evidence of coupling are the temporal-parietal and prefrontal areas associated with social cognition, mirror and mentalizing systems, and the language network (Fedorenko and Thompson-Schill, 2014; Gvirts and Perlmutter, 2020; Redcay and Schilbach, 2019). This review focuses on IBS reported in two-person neuroscience studies of spoken communication.

Language is a fundamental element of human social interaction, with reciprocal communication dependent upon dynamic mutual interactions between people (Markova et al., 2019; Berwick et al., 2013). Speech production and reception, especially at lower levels where acoustic signal formation and processing occur, were initially thought to concern separate cortical areas, with speaking predominantly employing Broca's area in the left prefrontal cortex, and listening utilizing the left temporal region known as Wernicke's area. Currently, the prevailing understanding of the functional anatomy of speech processing presents a dual-stream model with a left-dominant dorsal stream mapping acoustic signals to articulatory networks in the frontal region and a bilaterally organized ventral steam processing comprehension of speech signals (Hickok and Poeppel, 2007). Building upon this, the cognitive architecture underlying discourse is believed to be constructed around a network of functionally connected neural localities which actuate during utterance production and reception (Fedorenko and Thompson-Schill, 2014). Overlap in the neural regions used during speaker-listener interaction leads to a coupling of these areas during oral communication, often including a delay, as the signal passes from producer to receiver. Extending this beyond individual brains, construction of meaning between interlocutors requires more than merely acoustic signal production, reception, and processing, but involves entering into dynamic conceptual alignment to overcome ambiguity of connotation and become involved in episodes of reciprocal understanding (Schoot et al., 2016; Stolk et al., 2016).

Research shows alignment of speech rhythm, rate and syntax assist the transmission of information; however, for situational alignment to occur during communication, interlocutors are required to have successfully constructed analogous conceptual models of the matter under discussion (Menenti et al., 2012; Schoot et al., 2019). Accordingly, as people communicate, not only do they constantly modify their behavior and speech in response to their continuously changing conversation, they also repeatedly update their expectations and predictions of their conversation companions (Friston and Frith, 2015b). As such, effective communication represents a dynamic process of alignment at differing degrees of linguistic and extra-linguistic representations (Schoot et al., 2016). While the precise mechanism of alignment is not fully understood, several possible mechanisms have been proposed.

The interactive linguistic alignment theory (Pickering and Garrod, 2014) hypothesizes that while communicating, speech production and comprehension align, such that the discoursal processes – lexical, semantic, and syntactic – required to communicate become dependent upon related brain networks (Menenti et al., 2011). As a result, linguistic alignment during spoken interaction is sustained by comparable neural patterns (Pérez et al., 2019). The idea that speech comprehension and production recruits similar brain networks is supported by overlap in areas implicated in semantic, lexical, and syntactic processing (Menenti et al., 2011, 2012). For example, networks including auditory and left inferior frontal cortexes are involved in both primary sensory and motor aspects of speech, yet only motor cortex activity is observed while speaking (Menenti et al., 2011). That is, although speaking and listening mutually employ linguistic elements of the language system, listening does not entail sizeable motor system involvement.

Schoot et al. (2016) propose a generative theoretical model adapted from Friston and Frith's (2015a, 2015b) predictive coding framework, where brain signals of interlocutors may dynamically align at differing levels of representation. That is, when people engage in episodes of spoken communication, shared interpersonal coupling of neural oscillations occurs beyond the speech-auditory envelope as the joint attention required for successful comprehension of discourse is established among those parties involved (Friston and Frith, 2015a; Schoot et al., 2016). Therefore, IBS may occur at different levels according to the dynamics of the interbrain neural coupling. That is, synchrony may occur at the linguistic processing level (low-level) through speech-auditory envelope alignment as well as at the extra-linguistic level (high-level) through reciprocal interpretation of the situation being discussed enabling modification and adaptation of the shared conceptual space to achieve mutual understanding (Schoot et al., 2016; Stolk et al., 2016).

Taken together, construction of meaning between interlocutors requires more than merely acoustic signal production, reception, and processing. Rather, it involves entering into dynamic conceptual alignment as ambiguity of connotation is overcome and episodes of reciprocal understanding are shared (Schoot et al., 2016). To date, research in social interaction and communication has focused on interactive brain activity, exploring the functional equivalence and temporal phase harmonization between communicators, such as IBS, coupling, alignment, or entrainment (Czeszumski et al., 2020; Pérez et al., 2017; Redcay and Schilbach, 2019). Research methods have extended from traditional methods, focusing on individual brain activity, to hyperscanning that aims to measure brain activity of multiple brains simultaneously. Hyperscanning permits more authentic estimations of social interactions in second-person neuroscience, compared to single-person studies (Mayseless et al., 2019; Redcay and Schilbach, 2019), by allowing study of interbrain activity patterns across interacting participants (Montague et al., 2002).

Dual simultaneous recording of brainwaves can be acquired by a variety of neural scanning/imaging techniques, including electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), and functional magnetic resonance imaging (fMRI). Each measure has its own advantages and disadvantages. EEG measures brain electrical signals – primarily extracellular post-synaptic potentials from pyramidal cells – at millisecond intervals (Luck, 2005), with low cost, convenience in recording and high temporal resolution. In addition, negligible auditory noise caused by EEG machinery (i.e., unlike that from magnetic resonance scanners) allows individuals to communicate in a natural continuous stream more easily. Although EEG offers some indication of regional activation, low spatial resolution limits the degree to which specific areas of neural activity can be precisely localized. Functional near-infrared spectroscopy (fNIRS) offers high spatial resolution recordings based on oxy- and deoxy- hemoglobin concentrations in surface neural regions. However, as with EEG, fNIRS is limited in providing information on subcortical regions. It is also limited to region of interest studies, rather than investigation of global scalp parameters.

fMRI has higher spatial resolution, allowing more precise identification of regional activation from cortical to subcortical areas (Mu et al., 2018; Wang et al., 2018). However, given limitations of fMRI in temporal resolution and the types of activities feasibly performed within the confines of the scanner, more naturalistic experimental data collection from two-person studies is not currently possible (Koike et al., 2015; Mu et al., 2018; Wang et al., 2018).

Of the neuroimaging techniques that have been used in dual-setting research, EEG and fNIRS are currently the most commonly utilized methods in ecological settings, given advantages in temporal resolution, logistics, feasibility and cost (Babiloni and Astolfi, 2014). Therefore, the present review primarily focused on EEG and fNIRS studies.

Several systematic reviews on hyperscanning have been published (e.g., Babiloni and Astolfi, 2014; Czeszumski et al., 2020; Dumas et al., 2011; Konvalinka and Roepstorff, 2012; Wang et al., 2018). However, given that these studies do not focus on hyperscanning during language production and reception, and that hyperscanning research on verbal communication has been increasing in recent years, a more specific review in this area is warranted. Thus, the aim of the present systematic review is to assess whether hyperscanning research can inform about social interaction using spoken language and evaluate the extent to which it can inform our knowledge of biological mechanisms underpinning mutual understanding between individuals (Konvalinka and Roepstorff, 2012; Schoot et al., 2016). With evidence from the emerging second-person neuroscience literature suggesting a link between greater neural synchrony and closeness between people in social interaction (e.g. Redcay & Schilbach, 2019), we hypothesized that IBS represents an interpersonal neural marker of successful communication.

2. Search method and inclusion criteria

PubMed and Scopus databases were searched on May 11, 2020, employing the search parameters (hyperscanning OR interbrain synchronization) AND (social interaction OR social communication), with the result of 149 studies found. In order to gather relevant published studies, the search was conducted independently by two researchers according to preferred reporting items for systematic reviews and meta-analysis (PRISMA) guidelines (Moher et al., 2009) who appraised the studies based on the inclusion criteria: (1) hyperscanning study of IBS; (2) utilizing EEG or fNIRS neural oscillation recordings; (3) participants engaged in interaction requiring verbal communication (either as a one-way monolog, two-way dialog, or multi-person discussion); and (4) study reports results from original research conducted on healthy adults. Retrieved studies were screened according to their title, abstract, and key words, and further searches through analysis of references sections from relevant manuscripts were conducted via Google Scholar. Any divergence in selection for inclusion was resolved through discussion and further reading of the articles.

The final list was approved by all authors. Figure 1 shows the flow diagram representing study selection.

(Please insert Figure 1)

3. Results

Twenty-nine studies were identified and included in this review (Figure 2). They comprised studies from Argentina, China, Israel, Italy, Japan, South Korea, and the United States of America. The majority have used fNIRS equipment, with only nine studies using EEG. Participant languages in order of most common were Chinese, English, Japanese, Spanish, Hebrew and Italian, including two studies allowing language combinations Japanese/English and Spanish/English. Multiple paradigms were used for measuring verbal communication in social interactions including classroom, cooperative, creative, face-to-face, eye contact, first and second language, educational, puzzle solving, and group discussion settings. For example, Dikker et al. (2017) examined a combination of teacher-learner and learner-learner naturalistic interactions during lecture, video, and classroom discussion situations, Fishburn et al. (2018) observed neural alignment while participants completed Tangram puzzles requiring cooperation and creativity under a condition of shared intentionality, while Xue et al. (2018) assessed cortical synchrony of pairs engaged in cooperative tasks based on their creativity combinations. Based on the nature of experimental paradigms, research articles were classified into four categories: knowledge sharing; turn-taking speech coordination; cooperation, problem-solving and creativity; and naturalistic discussion.

(Please insert Figure 2)

Knowledge sharing presented dynamic social interactions between teachers and learners engaged in either monolog or dialog in an educational environment. This often includes continuous transmission and feedback of information with one participant playing the transmitter/instructor role and sharing information or a narrative with another participant (who may or may not be able to engage in questioning) playing the receiver/learner role; turn-taking speech coordination studies typically included participants in pairs, with one as speaker and the other as listener, coordinating their oral communication to complete a task; cooperation, problem-solving, and creativity paradigm commonly required participants to collaborate in order to complete an experimental task or activity that entailed finding solutions or original answers; and naturalistic discussion refers to conversations in real- or quasi-real- world situations generally free of restrictions imposed by other paradigms. It must be acknowledged that in some cases overlap occurred as researchers employed combinations of paradigms to best evaluate multifaceted hypotheses. Figure 3 shows representations of the four types of experimental paradigm.

(Please insert Figure 3)

Studies included in this review commonly employed wavelet transform coherence (WTC) and phase locking value (PLV) measures of synchrony to analyze phase coherence of neural oscillations recorded following brain activation (e.g., Jiang et al., 2012; Pan et al., 2018; Pérez et al., 2019), with some also conducting Granger causality analysis (GCA) in order to determine directionality (e.g., Ahn et al., 2018; Pan et al., 2018). In addition to determining alignment following WTC, Pan et al. (2020) applied machine learning techniques for classification of IBS according to experimental conditions.

3.1 Knowledge sharing

Of ten studies assessing the brain activity involved in knowledge sharing, three were carried out using EEG, while the rest were performed with fNIRS (Table 1). The cortical regions activated and exhibiting IBS while sharing knowledge include frontal (Holper et al., 2013; Liu et al., 2019; Nozawa et al., 2019; Pan et al., 2018), temporal-parietal (Zheng et al., 2018), and frontal and temporal-parietal (Bevilacqua et al., 2019; Dikker et al., 2017; Pan et al., 2020; Pérez et al., 2017) areas. In a classroom study by Dikker et al. (2017), IBS emerged from averaged neural activity over a variety of cortical regions between students which was greatest during interactive class discussion compared to lecture, reading, and video conditions. Furthermore, alpha coherence was highest in dyads that engaged in mutual eye gaze before class discussions compared to other dyads, and student IBS was a reliable predictor of both social dynamics and student class engagement. A noteworthy finding in a teacher-student knowledge-sharing format described by Zheng et al. (2018) was that of time-lagged IBS in the temporal parietal junction (TPJ) of the teacher and anterior superior temporal cortex (aSTC) of the student which was conveyed as a neural marker of effective instruction. Nevertheless, Liu et al. (2019) found IBS in the left prefrontal cortex (PFC) and not in the right TPJ (rTPJ) when comparing face-to-face and computer-mediated communication conditions. In a context of participants engaged in prior physical synchrony, Nozawa et al. (2019) reported that IBS in the PFC region between teacher and learner was enhanced and positively associated with teacher learner rapport. Finally, neural alignment regarding alpha-band wave activity was detected for listeners in the frontal region and speakers in the central region and with respect to the theta band in the temporal region for the listener and frontal region for the speaker (Pérez et al., 2017).

(Insert Table 1 here)

3.2 Turn-taking speech coordination

Four studies investigated IBS during turn-taking speech coordination and reported different findings, with three of the four using EEG (Table 2). In an early study of speech coordination, Kawasaki et al. (2013) showed increased IBS in alpha and theta bands in the lateral parietal and temporal regions for the human-to-human communication condition compared to the frontal region for the human-computer communication task and reasoned this as showing periods of speech rhythm synchronization. However, Nozawa et al. (2016) highlighted coupling concentrated in frontal regions. Contrasting interactive and non-interactive conditions, Hirsch et al. (2018) detected changes in hemodynamic signals and observed IBS in the superior temporal gyrus (STG; responsible for auditory processing, language, and social cognition) and the sub-central area (active during verbal semantic analysis – thus playing a role in interpreting meaning from syntactic structures). IBS overlapped with Wernicke's (STG), but not Broca's areas.

(Insert Table 2 here)

3.3. Cooperation, problem-solving, and creativity

The effects of cooperation, problem-solving, and creativity in relation to IBS have been popular topics of study in ecological settings (Antonenko et al., 2019; Fishburn et al., 2018; Lu and Hao, 2019; Lu et al., 2019a, 2019b; Lu et al., 2020; Mayseless et al., 2019). Seven studies employed these experimental paradigms (Table 3), and all but one used fNIRS. IBS was predominantly identified either in the frontal (Fishburn et al., 2018; Lu et al., 2019a; Lu and Hao, 2019; Lu et al., 2020) or both the frontal and the temporal-parietal regions (Antonenko et al., 2019; Lu et al., 2019b; Mayseless et al., 2019; Xue et al., 2018).

Fishburn et al. (2018) reported IBS in the PFC for triads cooperatively solving creative Tangram puzzles under the condition of shared intentionality. In a series of studies, Lu and Hao (2019) and Lu et al. (2019a, 2019b, 2020) broadly supported Fishburn et al.'s findings of synchrony in the frontal regions, i.e., the dorsolateral prefrontal cortex (DLPFC), with additional alignment in the temporal and parietal regions during cooperation (Lu et al., 2019b), particularly for female-female partners (Lu et al., 2020). In contrast, compared to a control condition requiring only cooperation, Mayseless et al. (2019) found IBS between asymmetric cortical locations, namely the anterior PFC/DLPFC and TPJ regions, during creative task design. Their study indicated increased IBS in locations connecting cognitive control with the mirror neuron system (MNS) and metalizing system (MTS). In a study focusing on participants paired according to similar creativity levels, Xue et al. (2018) discovered that IBS in the prefrontal (right DLPFC) and the right TPJ areas was greater for low-creativity pairs, compared to those with high creativity, likely reflecting a mechanism to offset limitations in creativity.

(Insert Table 3 here)

3.4 Naturalistic discussion

Eight studies took place in naturalistic settings (Table 4), with five employing fNIRS. IBS was predominantly identified in frontal (Balconi et al., 2020; Jiang et al., 2012; Lu et al., 2019a; Pérez et al., 2019) and temporal-parietal regions (Dai et al., 2018; Jiang et al., 2015; Kinreich et al., 2017; Zhang et al., 2018). In one of the pioneering hyperscanning studies of verbal communication, Jiang et al. (2012) reported significantly increased IBS in the left inferior frontal cortex (IFC) region for those engaged in face-to-face dialog compared to none for monologue and/or back-to-back states. Kinreich et al. (2017) included oral communication between dyads partnered as couples or strangers, with the results showing positive correlations between neural alignment and affirmative emotions and social gaze in couples, and length of social gaze and affirmative emotions in strangers, irrespective of verbal/non-verbal interaction or conversation content. In one of few studies investigating IBS whilst conversing in first and second languages, Pérez et al. (2019) discovered more concentrated IBS in the alpha band in fronto-central areas in the native language and more distributed IBS in the foreign language, pointing to differential IBS according to language code used for verbal exchanges. Moreover, the naturalistic paradigm has been extended to a counselling simulation, with IBS between counselor and client in the rTPJ (Zhang et al., 2018), and recently in a workplace role play, where neural alignment was found in frontal and frontopolar regions between manager and employee during an annual performance review (Balconi et al., 2020).

(Insert Table 4 here)

4. Discussion

This review has found persuasive evidence of interbrain synchrony between communicators engaged in verbal communication. Although studies display variability reflecting the distinctions inherent in each experimental design and the regions of interest assessed, frontal areas exhibited heightened stimulation during episodes of language production, possibly associated with increased working memory load and attentional interaction, as did temporal parietal regions, which are commonly implicated in connection with auditory processing and social interaction (e.g., Ahn et al., 2018; Dikker et al., 2017; Gvirts and Perlmutter, 2020; Mayseless et al., 2019; Xue et al., 2018). Alpha wave activity, asymmetric patterns of entrainment, and the significance of eye contact on face-to-face communication and collaboration are also discussed.

The findings suggest that learning that occurs through social interaction goes beyond merely transmitting information to include recognizing emotional expressions (Carr et al., 2003; Gallese et al., 2004), facilitating communication (Holper et al., 2013; Pan et al., 2018), and developing rapport (Nozawa et al., 2019). Knowledge sharing via verbal communication stimulates entrainment at both the brain-to-speech envelope level and the brain-to-brain level (Dumas et al., 2010; Pérez et al., 2017), with face-to-face exchanges likely facilitating social and neural alignment (Bevilaqua et al., 2019; Liu et al., 2019). An example of this is the INS observed in the left PFC in Liu et al. (2019) which is interpreted as indicating the interactional nature of common representations of information between teacher and student during a dynamic interpersonal learning process requiring shared negotiation of understanding.

Similarly, turn-taking verbal interactions focus on speech rhythms involving interlocutors not only engaging in the content and context of the discourse, but also coordinating duration, interval, rate, and timing of their interaction (Kawasaki et al., 2013). Thus, the activation witnessed in the fronto-temporal and centro-parietal locations (Ahn et al., 2018; Nozawa et al., 2016), and the presence of alpha band suppression during interactive conditions (Ahn et al., 2018; Kawasaki et al. 2013) have been reported, suggesting that taking turns requires interlocutors to exert a considerable amount of working memory capacity to harmonize their conversation. These studies are notable for incorporation of alternative measures of phase synchronization as they attempt to decipher patterns of brainwave alignment particular to the detailed coordination, timing, and speech rhythms inherent in turn-taking tasks.

Interestingly, asymmetric connections in neural synchrony found in cooperative and naturalistic discussion settings were similar to those shown in turn-taking studies, particularly between frontal and parietal regions (Ahn et al., 2018; Mayseless et al., 2019; Pérez et al., 2019). This suggests consistency in the complex dynamics of both cognition and coordination present during real-world social interaction and experimental conditions, with both requiring communication of additional linguistic information in the presence of interlocutors (Schoot et al., 2019). Moreover, these highlighted cortical regions have been associated with the theory of mind, a precursor of which is joint attention, and which is considered essential to understanding others' mental states and intentions as we adapt during communicative social interaction with others (Dumas et al., 2011).

In addition to involvement of the amygdala, orbital frontal cortex, medial prefrontal cortex, and temporal-parietal junction in social interaction, the MNS and MTS have also been implicated depending upon cognitive and emotional demands (Liu and Pelowski, 2014; Redcay and Schilbach, 2019). Both systems are employed to predict and recognize others' communicative signals and engage in effective communication (Mainieri et al., 2013;

Minagawa et al., 2018). The MNS is involved in cognitive functions essential to social interaction, such as mutual gaze, imitation and gestures, along with goal setting (Koike et al., 2019; Sperduti et al., 2014), while the MTS connects with the cognitive processes of personal orientation and intention awareness required for co-regulation of reciprocal engagement (Sperduti et al., 2014). Activation of prefrontal and temporal-parietal neural regions observed during social interactions suggests the MNS and MTS, respectively, are initiated during episodes of IBS arising from spoken communication. The IBS present in the left IFC during face-to-face communication in Jiang et al. (2015) is thought to represent inception of the MNS and decoded as an indication of alignment of expressions and gestures, while activation of the MTS during IBS reported in the TPJ region and theta/alpha amplitude modulation by Kawasaki et al. (2013) was interpreted as showing commonality among social cognition and social interaction mechanisms. In line with this, Gvirts and Perlmutter (2019) recently hypothesized that social attunement between interacting peers arises from synchrony mainly between the TPJ and PFC areas, representing a system of mutual shared attention. However, although mirror and mentalizing systems are thought to play complementary roles during social encounters and neural coupling, interaction between the two remains little understood (Mayseless et al., 2019; Schilbach et al., 2013; Sperduti et al., 2014).

Alpha-wave suppression was the most commonly reported phase activity, particularly during turn-taking, which might reflect the short-term memory and social coordination related to joint attention and information processing required as interlocutors coordinate their timing and rhythm. Observation of alpha band inhibition and excitation may be interpreted as part of neuronal activation during the course of information processing (Klimesch, 2012). It is argued that alpha-band oscillations represent basic cognitive processes resulting from their roles in inhibition and timing which enable selective access of knowledge and semantic orientation in time, space, and context (Klimesch, 2012). Thus, reports of suppression as participants engaged in oral narratives and naturalistic discussions may be viewed as reflecting both sensorimotor functions and coordination across neural regions during auditory reception processing and articulatory response preparation in addition to formation of joint attention as participants harmonize their contributions and role (speaker-listener) transitions during conversations to optimize dynamic social relationships.

Interpersonal coherence likely arises from both lower-level speech-to-brain entrainment and higher-level connectivity of the shared communicative process as information is transmitted in the form of oral language from speaker to listener (Pérez et al., 2017). Similarities in neural localities exhibiting IBS among the reviewed studies, which are conducted in different language and environmental contexts, including first and second languages, at first glance corresponds with the notion of a common neural foundation for the computation of human language that shares related neuroanatomical structures (Berwick et al., 2013). However, while acknowledging that even though the IBS demonstrated in studies with oral narratives points to similarities in neural functionality during the production and comprehension of verbal language, it is conceded that due to the existence of IBS during speaking and listening occurring in conjunction and concurrently with the brain-to-speech synchronization, the neural regions identified as markers of speech and comprehension may need to be revisited to take account of this alignment (Pérez et al., 2017).

With respect to these concerns, asymmetric patterns of entrainment have been observed between interlocutors depending upon their role in interpersonal communication, such as turn-taking interaction (Ahn et al., 2018), leader-follower (Jiang et al., 2015), first and second language use (Pérez et al., 2019), or due to multiple neural regions employed during speaking and listening (Pérez et al., 2017). In response to the prospect of asymmetric alignment depending upon language choice, Pérez et al. (2019) examined neural to speech signal alignment in first (Spanish) and foreign languages (English) and found higher coherence of affiliation between the brain phase and the more proficient language. Interbrain coupling in the alpha band was also found for native and foreign language; however, the strength of this is higher for the first language compared to the second. Furthermore, the neural regions highlighted through significant entrainment varied across languages and conversant role as speaker or listener. In general, native entrainment occurred predominantly in fronto-central regions, while the foreign language condition recorded more distributed alignment (fronto-, centro-, temporo-, and parietal- regions). Indeed, studies of language switching have reported activation of the anterior cingulate cortex (ACC) and DLPFC as speakers disengage from one language to engage in another (Blanco-Elorrieta et al., 2018). Furthermore, these results may indicate differences in the functional connections required for speech and comprehension while handling distinctive phonological structures and connect with the belief that the cognitive architecture of language likely requires engagement of assemblies of neural areas, including core and peripheral cortical regions, which co-activate depending on the specific language task performed (Fedorenko and Thompson-Schill, 2014). It may also support findings of shared neuroanatomy during production and processing at higher-level linguistic representations associated with meaning, yet greater separation at lower-level linguistic representations related to acoustic production and reception (Pérez et al., 2017; Pickering and Garrod, 2014; Silbert et al., 2014).

The importance of eye contact during face-to-face interaction emerged as a factor modulating IBS in knowledge sharing and naturalistic discussion paradigms (Dai et al., 2018; Dikker et al., 2017; Jiang, 2012; Kinreich et al., 2017; Liu et al., 2019). The implication of shared gaze relates to the non-verbal social aspect of communication, and in educational contexts signposting the efficient transfer of knowledge occurring under conditions representing greater interpersonal entrainment or bonding, thus pointing to pedagogical benefits of incorporating opportunities for teacher-student rapport, interaction, and pair and group discussion during class to promote learning environments (Dikker et al., 2017). Moreover, eye-to-eye contact has also been associated with cortical activity in areas responsible for speech production, articulatory function, and speech reception (Hirsch et al., 2017). Recent evidence suggests the significance of eye contact as an expression of interlocutors' attentional and emotional states and an important indicator of attention and instinctive form of interpersonal synchronization (Koike et al., 2019). In fact, speaker gaze is believed to be wired into humans through information transfer between infants and adults (Leong et al., 2017). Nevertheless, some studies have also found that, regardless of the presence of eye contact or not, brain waves synchronized as interlocutors verbally transmitted auditory signals in turn-taking sharing of information (Ahn et al., 2018; Pérez et al., 2017, 2019). Therefore, the significance of shared gaze is likely context dependent and requires future investigation to extricate the precise connections and interactions depending upon communication scenarios.

Beyond interpersonal entrainment through joint speech-rhythm stimuli, successful communication requires processing verbal utterances which entails shared attention and cognitive processing as speakers and listeners engage in mutual negotiation of linguistic and contextual cues as they attempt to achieve reciprocal comprehension (Pérez et al., 2015, 2017, 2019). This connects with the theme of cooperation/collaboration which arose in several ecological studies entailing creative and/or problem-solving scenarios engaging two or more participants. Other than speaker-listener joint-attention and coordination, these experimental setups required higher cognitive functioning to complete shared tasks and indicated IBS in prefrontal and temporo-parietal regions (e.g., Fishburn et al., 2018; Lu et al., 2020; Mayseless et al., 2019; Xue et al., 2018). In one example, Xue et al. (2018), examined combinations of pairs with respect to creativity while solving and presenting their solutions to problems. Under the condition of shared intentionality, they only found IBS in the PFC and rTPJ in low-low pairs, which they suggest provides evidence that these pairs leverage mutual understanding and cooperation to overcome their inherent weakness and generate synergy leading to enhanced performance. Activation of IBS in the PFC suggests collaborators develop a mutual interpretation of information as the PFC, particularly the left PFC, is associated with the MTS and assimilating information and comprehension, thus illustrating its crucial role during cognitive, problem solving, emotional, social and creative endeavors where deep mutual understanding is essential.

Therefore, we reason that hyperscanning research has extended knowledge beyond merely observing cortical functionality, but helped shed light on the shared cognitive and neural processes underlying human communication and understanding. As such, the reviewed studies have implications not only for spoken social communication in a broad sense, but also for teaching and learning with respect to the transfer and retention of knowledge. First, effective teaching requires transfer of knowledge from educator to learner, which is more likely to occur when sender and receiver develop rapport, and may be indicated by higher IBS. Therefore, IBS could be a marker for improved likelihood of teaching efficacy (Liu et al., 2019). Second, classroom activities and configurations fostering face-to-face communication and eye contact may be one method to improve IBS and social interaction, and increase engagement in education (Dikker et al., 2017). Mediating this with attention to prior knowledge may further improve interpersonal synchrony, yet digital- and computer-mediated communication settings may require modified courses of action (Liu et al., 2019).

Regarding group composition, little evidence had been found for effects of acquaintance and gender on IBS and communication (Nozawa et al., 2016), yet the emergence of recent research suggests heightened IBS of females may be representative of their enhanced behavioral interaction, attention, and consideration of partner during creative problem solving (Lu et al., 2020).

5. Limitations and suggestions for future research

Concern has been raised about differentiating IBS from synchrony arising from artefactual synchrony related to physiological and movement signals. A number of analysis techniques and experimental methods have been used to account for this and separate the origin of the synchronization among participants' brain waves including regression analysis, examining shallow and deep signals (Nozawa et al., 2016), and establishing environments limiting motion, gestures and facial expressions (Pérez et al., 2017). Accordingly, the studies included in this review expressed measures to account for physiological artefacts and noise in the recorded signals through filtering and use of normalization techniques, such as wavelet transformations. Furthermore, as speaking, which is most likely to cause artifacts, rarely occurs in unison among communicators, it is unlikely a source of synchrony of phase oscillations (Nozawa et al., 2016). Additionally, the use of false discovery rate (FDR) statistical procedures to control for type I errors in small sample sizes may lead to an underestimation of the expected proportion of falsely rejected null hypotheses. This point leads to the issue of small sample size and lack of studies replicating the experimental conditions in different populations, countries, and cohorts to determine whether the results hold across age, gender, cultures, and linguistic groups.

The authors duly acknowledge that this review excludes inclusion of fMRI studies of IBS during spoken interaction. One reason for this relates to lower utilization of fMRI in experiments of interaction among interlocutors due to restrictions of activities feasibly performed within the confines of the scanner constraining experimental data collection from two- or multi-person studies in ecological settings (Koike et al., 2015; Mu et al., 2018; Wang et al., 2018). Nevertheless, Spiegelhalder et al. (2014) offers a notable exception regarding leveraging fMRI to compare voxel clusters in a live verbal communication setting and reports on IBS associated with speech production and auditory regions. Moreover, the auditory cortex was activated during speech-related brain activity, suggesting speakers may listen to themselves, while the primary visual cortex was initiated when engaging in dialog, including imagining one's life events, and is thought to represent either attention to instructional text or visual imagery. Therefore, despite restrictions related to their experimental design and equipment, their study revealed evidence of neural coupling similar to that found in experiments employing other neuroimaging techniques.

Furthermore, although IBS may enhance mutual understanding during verbal communication, it has yet to be shown that IBS is a requirement for shared comprehension (Pérez et al., 2019). This relates to issues regarding the directionality of estimated synchronization estimates. Consequently, some studies have incorporated GCA and autoregressive methods to model causal relationships among communicators, though further research is required (Ahn et al., 2018). Finally, to date, no standard computational models exist to analyze the spatio-temporal dynamics of hyperscanning data. Many studies select different time periods during verbal communication to investigate neural synchrony and primarily employ traditional statistical methods, such as analysis of variance and correlation techniques, to compare alignment and assess associations in different locations and conditions (e.g., Dikker et al., 2017; Jiang et al., 2012; Lu et al., 2019). Therefore, the extent to which we can recognize patterns and interpret the spatio-temporal dynamics from analyses of neural coherence and episodes of entrainment during social verbal communication remain incomplete. To this end, recent research by Pan et al. (2020) successfully utilized machine learning to classify brain-to-brain coupling in contrasting instructional conditions.

To further advance and deepen the literature on IBS during verbal communication, future research recommendations include:

1. Analysis of speech on phonological, morphological, syntactic, and semantic levels to investigate whether type and form of linguistic content, such as semantic ambiguity (MacGregor et al., 2020), are associated with IBS, as may acoustic analysis on the importance of motor and cognitive auditory signal production and processing.
2. Investigation of participants from different language groups and cultural backgrounds to analyze processes of oral communication in a broader context and improve the generalizability of hyperscanning during verbal communication. In addition, expanding research into foreign language contexts may offer insights into contrasting neural activations and configurations underlying successful interpersonal communication in a host of new ecologically valid linguistic settings.
3. Manipulation of experimental conditions for closer examination of the MNS-MTS interface (Schilbach et al., 2013) may offer insight into their interplay during social communication.
4. The findings of these hyperscanning studies could have important clinical implications and offer insights into deficits or dysfunction occurring during social

communication; for example, training people with speech impairments using neurofeedback (Crum, 2019; Pan and Cheng, 2020; Wang et al., 2020).

5. Apart from Bevilacqua et al. (2019) and Dikker et al. (2017), the majority of studies focused on analyzing data from experiments conducted at one time. As such, incorporating longitudinal study designs to examine the evolution of IBS between participants in response to a variety of conditions may provide important insights into the progression of IBS.
6. Emerging virtual and augmented reality technologies may offer opportunities to implement imaginative experimental conditions and incorporate creative social and linguistic scenarios (Czeszumski et al., 2020).
7. Recently developed neuromorphic computing techniques suited to spatio-temporal data and specialized deep learning methods for data visualization of cortical connectivity (Kasabov et al., 2016; Doborjeh et al., 2018, 2019) represent promising future approaches. For example, the evolving connectivity of multiple subjects before and after IBS can be measured and visualized in a brain-inspired spiking neural network (SNN) models such as NeuCube (Kasabov, 2014, 2018), to trace and understand the dynamics and effects of language communication.

6. Summary and conclusion

This review examined queries raised by previous scholars regarding what can be learned from hyperscanning studies of spoken communication and reported on the major findings of neuroscience research covering different types of human social communication via spoken language and categorized the findings into three distinct variants of study paradigm: knowledge sharing, turn-taking conversation, and naturalistic discussion. We conclude that hyperscanning research investigating IBS during episodes of spoken communication has advanced our understanding of interpersonal synchrony through linking theoretically-inspired experimental frameworks with empirical data in a variety of contexts. Finally, by addressing pertinent questions surrounding IBS in social communication via verbal language and employing innovative analysis techniques, future studies will proceed from a solid base to further explore the boundaries of this exciting and fruitful field of research into human understanding.

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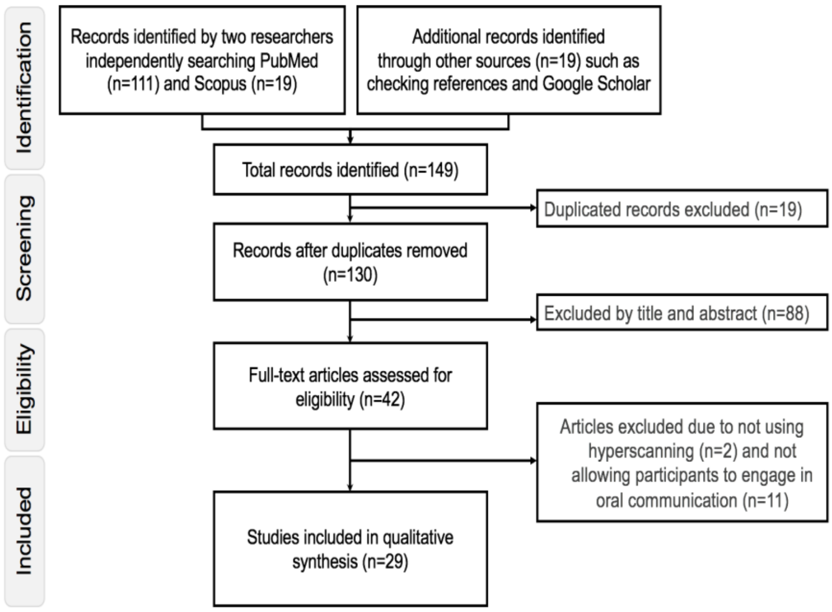

Figure 1: Study selection procedure flow diagram

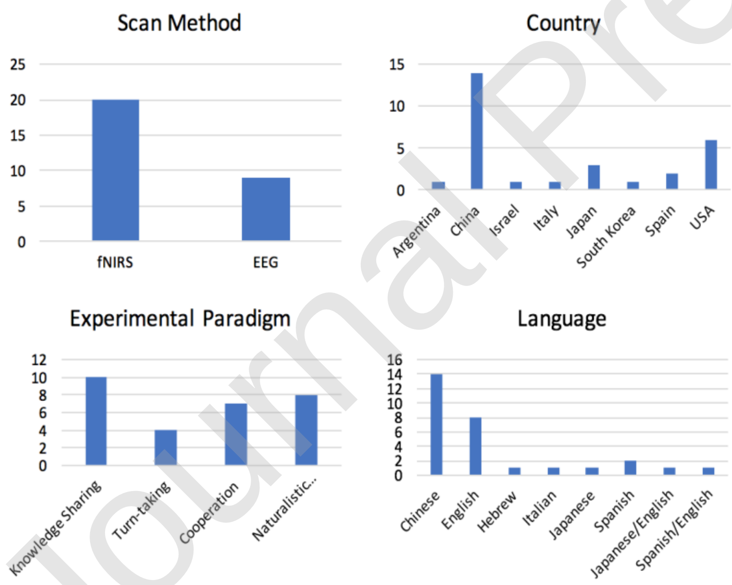

Figure 2: Included studies according to scan method, country, experimental paradigm and language.

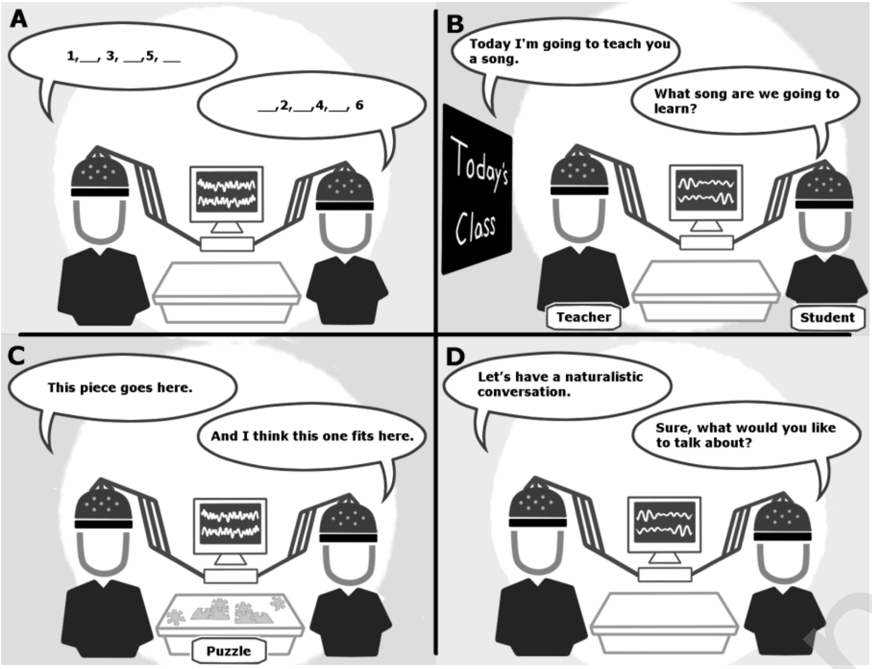

Figure 3. Experimental design communication methods: (A) Turn-taking; (B) Knowledge-sharing; (C) Cooperation, problem-solving, and creativity; (D) Naturalistic discussion.

Table 1. Knowledge sharing paradigm hyperscanning studies

Study	Country (Language)	Scan method/ Channels	Aim	Participants/age	Method	Phase analysis/IBS regions	Conclusions
Holper et al., 2013	Argentina (Spanish)	fNIRS 4 channels	Investigate teacher student interaction using Socratic dialog.	n=44, 5 pairs excluded, 17 pairs (70% female) all right-handed except for one left-handed. Range 18-74 years	Pairs performed Socratic dialog (interaction) and Meletos reading (read specific roles).	Linear transform Prefrontal IBS during Meno and Melotos dialogs.	Positive correlation for teacher-student blood flow dynamics and transfer of knowledge for both conditions. Successful educational dialogs leading to transmission of knowledge require teacher-student alignment.
Dikker et al., 2017	USA (English)	EEG 14 channel (wireless)	Compare IBS over different conditions in naturalistic classroom setting. Investigate teacher-student and student-student IBS.	n=12, students in naturalistic high school classroom setting. 17-18 years	Over 8-week period students brain waves recorded for ‘lecture’, ‘reading’, ‘video’, and ‘discussion’ conditions.	Spectral coherence, TI TI averaged across frontal, temporo-parietal and occipital locations higher during discussion and video. Alpha coherence strongest after mutual eye gaze.	Synchronization of brain waves linked to engagement in class and social dynamics, suggesting brain-to-brain coherence is a neural marker for dynamic social interactions likely arising from shared attention mechanisms during class.
Pérez et al., 2017	Spain (Spanish)	EEG 32 channels	Investigate whether IBS occurs when pairs exchange verbal narratives.	n=30 (14 female), 15 pairs of right handed age- and gender- matched Spanish participants who had not met prior. M=23.18, SD=3.64 years	Exchanged oral narratives as either listener or speaker without visual contact.	PLV IBS mainly frontal in alpha band for listener and central for speaker; in theta band mainly frontal for speaker and temporal for listener.	IBS patterns showed interbrain entrainment during exchange of oral narratives. Interactive situational process and speech-to-brain mechanisms mediated inter-person neural coherence and reveal IBS beyond that of simple auditory processing.
Pan et al., 2018	China (Chinese)	fNIRS 44 channels	Test involvement theory through examining learner-instructor interaction during learning of a song.	n=24 female students and a music instructor. M=20.58, SD=2.15 years	Students learned a song under two conditions: interactions involving part (PL; higher interaction) and whole learning (WL; lower interaction). Social interaction measured with fNIRS focusing on teacher-student synchronization.	WTC; GCA IBS detected in bilateral IFC for PL group but not for WL group.	Teacher-learner IBS in IFC increased during PL, particularly when learner concentrating on instructor’s voice and interactive process. Instructor’s brain signal predicted that of learner. IBS neural indicator of social learning suggesting importance of learner involvement in learning process.
Zheng et al., 2018	China (Chinese)	fNIRS 10 channels	Test Prediction-transmission hypothesis neural processes during teacher-learner knowledge transfer.	n=60 students (30 female), 4 teachers (2 female, 2 male). Students: M=23, SD=2.3 years Teachers: M=25, SD=2.4 years	Examined teacher-learner knowledge transmission under three teaching styles: lecture, interactive and video.	WTC Time-lagged IBS increase from teacher rTPJ to student aSTC.	Student brain blood flow activity following that of teacher lead to better teaching results associated with time-lagged IBS between rTPJ of instructors and aSTC of students. IBS could mark teaching outcome quality at early stage of the teaching process and play important role in effective instruction.
Bevilacqua et al., 2019	USA (English)	EEG 14 channels (wireless)	Compare IBS during naturalistic classroom teaching conditions.	n=12 (seven female, five male) high school in dynamic, real-world classroom using lectures and videos over six class session. 16-18 years	Measured outcomes of different teaching styles through content retention of either lectures or videos.	Spectral coherence, TI Occipital, frontal, parietal IBS.	IBS higher under condition of videos than lectures. Student engagement and teacher likeability influenced teacher-student coherence during lectures. Retention of content associated with teacher-student closeness ratings rather than IBS.
Liu et al., 2019	China (Chinese)	fNIRS 46 channels	Test teaching effect with and without prior knowledge under FTF and CMC conditions.	n=84 (32 female) formed 42 right-handed dyads, one of pair designated teacher and one student, randomly assigned FTF or CMC. 8 dyads excluded. 17 FTF and 17 CMC pairs. M=21, SD=2.3 years	IBS calculated for different task blocks.	WTC IBS enhancement was detected in the left PFC; no IBS found in rTPJ.	Increased task-related IBS in left PFC for FTF condition with prior knowledge. Cumulative IBS predicted teaching effectiveness in FTF prior knowledge condition. Teacher-student interaction and test scores mediated by IBS, with prefrontal IBS a possible neural marker of interaction.
Nozawa et al., 2019	Japan (Japanese and English)	fNIRS 2 channels	Examine whether physical synchrony pre-empts neural synchrony.	n=64 (18 females) formed 32 right-handed same sex pairs who had not met before.	Rhythmic arm movement assessment to appraise physical synchrony followed by teacher-learner vocabulary scenario.	WTC Prior physical synchrony enriched IBS in lateral PFC.	Evidence that prior physical synchrony improved the teacher-learner relationship and fostered later prefrontal cortex IBS. Physical synchrony may lead

				M=21.5, SD=1.5 years			to higher degree of social bonding during educational communication.
Pan et al., 2020	China (Chinese)	fNIRS 46 channels	Compare instructor-learner neural alignment during scaffolding and explanation-based teaching methods.	n=48 right-handed, all-female formed 24 dyads comprised of an instructor (trained in instruction and familiar with graduate-level psychology) and a learner (non-psychology major). M=21.46, SD=2.75 years	Dyads undertook a conceptual learning task requiring mastery of two sets of materials explaining four psychological terms related to the concepts reinforcement and transfer.	WTC Modulatory effects detected during scaffolding instructional technique in PFC and STC	Instructor-learner IBS occurred during interactive scaffolding instructional technique compared to explanation-based learning and co-varied with learning outcomes. IBS may present a dynamic pedagogically informative evaluation of learning related to instructor-learner interaction.
Zheng et al., 2020	China (Chinese)	fNIRS 10 channels	Examine association between social interaction and affiliative bonding.	n=60 students (30 female), 4 teachers (2 female; 2 male). Students: M=23, SD=2.3 years Teachers: M=25, SD=2.4 years	Students allocated into three groups according to experimental procedures (turn-taking, lecturing, and video) and randomly assigned to one of teachers.	WTC IBS after social interaction in right SMC of teacher-student (CH16-10) in resting state after turn-taking teaching mode.	IBS during teaching partially mediates association with IBS increment in resting state after teaching and strength of social bond between teacher and student. In addition, role assignment and social interaction required for affiliative bond. IBS supports social bonding and interaction mediates bonding process.

Notes: functional near-infrared spectroscopy (fNIRS); interbrain synchrony (IBS); electroencephalography (EEG); total interdependence (TI); phase-locking value (PLV); part learning (PL); whole learning (WL); wavelet transform coherence (WTC); Granger-causality analysis (GCA); inferior frontal cortex (IFC); right temporal-parietal junction (rTPJ); anterior superior temporal cortex (aSTC); face-to-face (F2F); computer mediated communication (CMC); prefrontal cortex (PFC); sensorimotor cortex (SMC).

Table 2. Turn-taking paradigm hyperscanning studies

Study	Country (Language)	Scan method	Aim	Participants/configuration	Method	Phase analysis/IBS regions	Conclusions
Kawasaki et al. (2013)	Japan (English)	EEG 27 channels	Address whether IBS occurs between two subjects when speech rhythms align.	n=20 right-handed pairs (F-F=9, M-M=7, F-M=4), of which 14 pairs were acquainted and 6 weren't. 1 F-F pair excluded. M=21.57, SD=0.84 years	Speech rhythm synchronization during alternating speech task speaking English alphabet sequentially in human-human (H-H) and human-machine (H-M) modes.	Cross correlation Theta/alpha amplitudes, temporal and lateral-parietal alignment for H-H mode, and frontal region for H-M mode. Beta activity higher for H-M task.	Higher likelihood of speech rhythm synchronization in H-H communication compared to H-M. Alignment in theta and alpha waves in temporal and lateral-parietal regions. IBS improved following H-H mode, implying IBS connected to speech alignment between subjects.
Nozawa et al. (2016)	Japan (Japanese)	fNIRS 1 channel (wireless, continuous wave)	Examine IBS in frontopolar region during a social communication task.	n=48 (female=20); 12 teams of 4, right-handed, mostly acquainted members. M=21.9 years	Teams engaged in communication via a cooperative word-chain game requiring no specific background knowledge	WBMR Brain coherence in frontopolar region	Social communication lead to enhanced frontopolar IBS, which was not impacted by gender nor acquaintance. Multiparty social interactions without fixed roles for interlocutors possibly leads to distribution of cognitive functions across multiple bands.
Ahn et al. (2018)	South Korea (English)	EEG/MEG 19/146 channels	Investigate turn-taking verbal interaction based on number counting with three conditions – interacting, speaking, and listening – without visual input.	n=10 (male=9) M=23.9, SD=3.3 years	Performed turn-taking interactions counting numbers consecutively and non-turn taking speaking and listening with partner at another site hyperscanned via online connection. Repeated 6 times for a total of 18 trials. Electrodes placed on left hemisphere because its known role in MNS and language processing.	WPLI Verbal interacting task for EEG alpha: left fronto-temporal and right centro-parietal regions registered synchrony for pairwise T3, F7, C4, and P4 channels and between left temporal (T3 and F7) and right centro-parietal (C4 and P4) areas.	Found significant IBS in phase and oscillations (EEG – alpha and MEG – alpha/gamma) during verbal turn-taking cooperation compared to the non-interactive control tasks. Suggests alpha suppression related to the important role of short-term working memory in turn-taking verbal interaction.
Hirsch et al. (2018)	USA (English)	fNIRS 42 channels	Investigate interactive brain hypothesis during speaking and listening. Predict dynamic alignment of regions associated with language.	n=62 unacquainted or casually acquainted, mostly right-handed (57% female) adults formed pairs. 4 dyads excluded due to data collection issues (n=54). M=24, SD=6.1 years	Participants performed object naming task and alternated speaker and listener roles under interactive (allowed dialog) and non-interactive (monolog) conditions.	WTC, PPI Brain activity associated with the STG (part of Wernicke's area) and SCA increased during interaction compared to non-interaction condition. No significant result for Broca's area.	Significant IBS of neural signals in STG and SCA show dedicated pathway of between-brain coherence for interaction relating to listening, but not for speaking. Supports interactive brain hypothesis through IBS during exchange of information using language as the means of communication.

Notes: Electroencephalography (EEG); interbrain synchrony (IBS); female-female (F-F); male-male (M-M); female-male (F-M); human-human (H-H); human-machine (H-M); wavelet-based motion artifact reduction (WBMR); magnetoencephalography (MEG); mirror neuron system (MNS); weighted phase lag index (WPLI); functional near-infrared spectroscopy (fNIRS); psychophysiological interaction (PPI); superior temporal gyrus (STG); subcentral area (SCA).

Table 3. Cooperation, problem-solving, and creativity paradigm hyperscanning studies

Study	Country (language)	Scan method	Aim	Participants/configuration/ age	Method	Phase analysis/IBS regions	Conclusions
Fishburn et al., 2018	USA (English)	fNIRS 18 channels split over 3 participants	Investigate PFC synchrony of multiple individuals communicating while problem solving during shared intentionality.	n=60 (female=37), 20 non-family, non-intimate, college student triads (F-F=11, M-M=5, F-M=4). Side-by-side, so eye contact minimal. Due to equipment error, data for one triad not included (n=57). M=19.73, SD=1.02 years	Completed Tangram puzzles requiring spatial and geometric aptitude under 4 conditions: 'together active' 2 students completed puzzle; 'together passive' third member only watched; 'apart' individually completed the same puzzles; 'movie' watched videos of a pair completing Tangrams.	Autoregressive model; robust correlation coefficient Increase in IBS in PFC region.	Higher IBS for 'together active' than peak connection for other conditions. IBS during completing task in pairs compared to control conditions and neural activity of one partner predicted that of the other but not of those in another partner set completing the same puzzle. Suggests shared intentionality of the exchange leads to IBS beyond that of solely social exchanges previously studied.
Xue et al., 2018	China (Chinese)	fNIRS 42 channels	Observe IBS in PFC and rTPJ as indicators of cooperation and creativity between paired participants.	n=60 participants (female=43) formed dyads consisting of high-high, high-low, and low-low creativity individuals. M=20, SD=2.13 years	Pairs sitting face-to-face were required to solve creativity problems and report the solutions they had generated.	WTC Increased IBS observed in rDLPFC for low-low dyads compared to other pairings, and rTPJ for low-low dyads compared to high-low pairing.	Low-low dyad IBS in rDLPFC and rTPJ positively correlated with cooperative behavior and creative performance. Inherent weakness of low-creativity pairs may be offset by the interaction process representing mutual understanding and cooperation during creative problem solving.
Antonenko et al., 2019	USA (English)	EEG 9 channels (wireless)	Explore neural synchrony of two-person teams engaged in collaborative problem-solving task.	n=80 (female=40) heterogeneous dyads of right-handed college students. 18-24 years	Student dyads given problems under two conditions: epistemic (pre-structured learning steps) and social (structure learner interactions) scripts.	PLV IBS in alpha band frontal and parietal regions in the epistemic script condition.	Results of IBS suggest epistemic scripts may work as better scaffolds for collaborative problem solving where the learning objective is to define and solve the problem as opposed to retaining specific knowledge.
Lu & Hao, 2019	China (Chinese)	fNIRS 22 channels	Explore situations in which IBS occurs and examine its course over time by comparing cooperative interaction versus similar task hypotheses.	n=44 (female=40) unacquainted participants arranged in 22 pairs, each dyad joined by a confederate, 1 group omitted due to low signal/noise ratio. M=20.66, SD=2.29	Teams of three discussed RPP and took turns reporting ideas generated during brainstorming with confederate reporting pre-prepared ideas. Participants cooperatively created and reported new ideas, whereas confederate retrieved and reported task-related information.	WTC Real-participant dyads showed increased IBS in PFC and bilateral DLPFC which increased over time compared to real-confederate dyads.	Increase in IBS and cooperation over time in real-participant pairs represents an indicator of collaborative engagement in interpersonal interaction which is not displayed for real-confederate pairs conducting a similar task requiring retrieval of information from memory.
Lu et al., 2019b	China (Chinese)	fNIRS 46 channels	Study effect of cooperation and competition on creativity and whether IBS predicts cooperative mode, particularly under creative condition.	n=104 (female=64) formed 52 dyads, data from 1 pair missing M=21, SD=1.52 years	Undertook AUT (n=25) or OCT (n=26) tasks under conditions of cooperation or competition.	WTC Increased IBS in rDLPFC and rTPJ for dyads in AUT/ cooperation compared to other conditions. Stronger IBS between rDLPFC and rTPJ in AUT/cooperation compared to competition mode.	Increased IBS in rDLPFC and rTPJ regions predicted cooperative behavior. Findings suggest enhanced IBS may underlie the positive performance effects of cooperation compared with competition in tasks requiring group creativity.
Mayseless et al., 2019	USA (English)	fNIRS 8 channels	Assess cooperation, communication and creative thinking in a dynamic team situation.	n=56 (female=27) resulting in 28 dyads (9 M-M, 8 F-F, 8 F-M), 3 dyads excluded due to data noise issues M=32.09, SD=6.25 years	FTF problem solving: creative design (product to motivate people to vote) thinking session for 10-minutes and cooperative (control) 3D model building (airplane) session for 10-minutes. Focused on left hemisphere.	WTC For differences between creative task and cooperative task IBS found for pairs aPFC-pSTG, aPFC-TPJ, IFG-pSTG.	IBS in regions involving cognitive control system connected to MNS and MTS in dyads achieving innovation during creative design tasks. Creative cooperation related to IBS between aPFC-TPJ. Declining IBS over time may reflect partners becoming more comfortable with each other.
Lu et al., 2020	China (Chinese)	fNIRS 46 channels	Study effect of gender composition on interaction pattern while pairs generate creative ideas.	n=136 (female=77) formed unacquainted F-F, F-M, and M-M dyads, 2 dyads omitted owing to not following instructions M=21.23, SD=2.91 years	Participants conducted creative (AUT) and memory-retrieval (OCT) tasks and took turns reporting ideas after brainstorming session.	WTC Higher IBS in rPPC during AUT and OCT tasks for F-F pairings, which was positively correlated with creative performance.	Females are more likely to interact, pay attention, consider partner's perspective, and depend upon one another while solving creative problems. The gender distinction may result from heightened IBS in rPPC.

Notes: functional near-infrared spectroscopy (fNIRS); prefrontal cortex (PFC); female-female (F-F); male-male (M-M); female-male (F-M); interbrain synchrony (IBS); right temporal-parietal junction (rTPJ); wavelet transform coherence (WTC); right dorsolateral prefrontal cortex (rDLPFC); realistic presented problem (RPP); prefrontal cortex (PFC); alternative uses task (AUT); object characteristic task (OCT); anterior prefrontal cortex (aPFC); posterior superior temporal gyrus (pSTG); inferior frontal gyrus (IFG); temporal-parietal junction (TPJ); mirror neuron system (MNS); mentalizing system (MTS); right posterior parietal cortex (rPPC).

Table 4. Naturalistic discussion paradigm hyperscanning studies

Study	Country (language)	Scan method	Aim	Participants/configuration/ age	Method	Phase analysis/IBS regions	Conclusions
Jiang et al. (2012)	China (Chinese)	fNIRS 20 channels each within one system	Compare face-to-face (F2F) and other forms of communication in left frontal, temporal and parietal cortices	n=20, 10 pairs of participants (F-F=6 and M-M=4) M=23, SD=2 years	Partners discussed topics under 4 conditions including F2F dialog, F2F monologue, B2B dialog, and B2B monologue.	WTC IBS in left IFC during F2F dialog condition compared to resting and B2B dialog.	IBS arose as result of direct interactions relating to integration of multi-modal sensory information in dialog. Implies special neural features absent in other forms of communication and inter-brain coherence may underlie successful F2F dialog.
Jiang et al. (2015)	China (Chinese)	fNIRS 10 channels	Test hypothesis that Leader-Follower (LF) pairs will have higher INS than follower-follower (FF) pairs	n=36, divided into 12 (all female=6, all male=6) unacquainted same-sex teams of 3. 1 female team excluded due to data collection failure. M=22, SD=2 years	Teams given topic and engage in leaderless group discussion for 5 minutes. In final one minute one member chosen to report on the team's discussion.	WTC, GCA Higher in left TPJ for LF than FF groups.	Left TPJ, important in social mentalizing, activity higher in LF pairs than FF pairs and for LF pairs where communication was leader initiated compared to follower initiated. Leader emergence characterized by high degree of IBS between leader and follower and that quality supersedes frequency of communication.
Kinreich et al. (2017)	Israel (Hebrew)	EEG 32 channels	Compare natural M-F interactions and IBS in romantic couples and strangers with respect to verbal and non-verbal behaviors.	n=104 in 52 heterosexual M-F pairs; 3 dyads excluded; couples=24 pairs, strangers=25 pairs Couples: M=25, SD=4.1 years Strangers: M=24, SD=3.6 years	Partners grouped as 'couples' or 'strangers' planned a fun day out while seated facing each other at a 45-degree angle.	Stockwell transform, Spearman correlation Synchrony in temporal-parietal structures and gamma rhythms.	IBS higher in couples indicating a link to the degree of social interconnectedness of partners. Synchrony correlated with social gaze and positive affect in couples, length of social gaze and positive social affect in strangers, and independent of verbal/non-verbal interaction and conversation content.
Dai et al. (2018)	China (Chinese)	fNIRS 11 channels each (within one system)	Assess neural mechanism for selectively tuning into target speaker during multiple speaker conversation.	n=66 right-handed adults split into non-acquainted 3-member teams. Data from 1 group unusable: 21 groups (n=63; M-M=11 and F-F=10) conducted F2F and B2B natural discussions. M=23, SD=2 years	Two tasks: (1) speaker spoke to listener while other speaker silent; (2) two speakers spoke to listener simultaneously, though listener only attended to one speaker. This was conducted in F2F and B2B configurations.	WTC IBS between listener and speaker in left TPJ.	Increased IBS between the listener and the attended speaker in left TPJ compared with between the listener and the unattended speaker across various multi-speaker situations. Increased IBS precedes verbal responses and is independent of brain-to-speech coherence suggesting IBS underlies speaker-listener selection through neural prediction of content.
Zhang et al. (2018)	China (Chinese)	fNIRS 46 channels	Investigate IBS and working alliances during psychological counselling and chatting.	n=34 (female=29) right-handed, with no prior psychiatric illness, college students in dyads and 3 female counsellors. Two excluded due to not finishing task. Clients: M=21.1 years Counselors: M= 30.0 years	Students divided into two conditions – counselling and chatting in a F2F interaction.	WTC Higher IBS in rTPJ during counselling session compared to chatting. IBS in PFC insignificant.	Higher working alliances and IBS of counselling group related to the bond that formed between the counsellor and client. Result may pertain to mentalizing and understanding with IBS contributing to a positive relationship.
Lu et al. (2019a)	China (Chinese)	fNIRS 22 channels	Assess effect of feedback on group creative performance.	n=118 (female=102) typically unknown participants formed 59 brainstorming pairs to join with a false participant (evaluator) and assigned to positive, negative, and no feedback (control) conditions. M=20.72, SD=2.47 years	Teams assigned positive, negative, and no (control) feedback conditions before brainstorming a realistic presented problem (RPP). False participant gave only positive, negative, and no feedback in relation to respective condition. Participants took turns to report ideas.	WTC Stronger IBS in FPC and bilateral DLPFC for positive and negative feedback conditions. IBS increment covaried with creative performance in positive condition.	Positive feedback supported interpersonal interaction, negative feedback inhibited creative performance, and no feedback aided collective flexibility. IBS likely reflects underlying interpersonal neural correlates between partners and willingness to restrain one's own self-interest to understand and process their partner's ideas in positive condition.
Pérez et al. (2019)	Spain (Spanish/English)	EEG 27 channels	Record neural responses of concomitant participants during verbal interaction in Spanish (L1) and English (L2).	n=60 (female=40) in dyads M=22.5, SD=2.7 years	Alternate speaking and listening roles in Spanish and English.	Hilbert transform, circular correlation Alpha band: fronto-central areas in L1 (i.e., 5 electrode pairs); spread more evenly in L2 (i.e., 9 electrode pairs). Theta and beta bands: no significant results.	IBS related to verbal information exchanges related to linguistic alignment, joint attention, and brain-to-speech entrainment, along with language-specific neural functions. Synchrony of neural activations and their spatial dimensions may vary according to the language code used.

Balconi et al., (2020)	Italy (Italian)	EEG 16 channels	Investigate manager-employee synchrony during simulated annual performance review in the presence or absence of a quantitative rating.	n=22 (male=84%), 11 leaders, 11 employees in dyads. M=43.88, SD=7.65	Participants role-played an employee performance review with rating (quantitative) and no rating conditions.	Partial correlation Increased alignment (delta frequency) in frontopolar and frontal locations between leader and employee in no rating condition as compared to the rating condition.	Neurophysiological effects suggest shared purpose and understanding induces empathic alignment during interaction. Significant improvements in coordination and communication can be gained from increased interpersonal engagement.

Notes: functional near-infrared spectroscopy (fNIRS); face-to-face (F2F); female-female (F-F); male-male (M-M); back-to-back (B2B); wavelet transform coherence (WTC); interbrain synchronization (IBS); inferior frontal cortex (IFC); leader-follower (LF); follower-follower (FF); Granger-causality analysis (GCA); temporal-parietal junction (TPJ); electroencephalography (EEG); realistic presented problem (RPP); frontopolar cortex (FPC); dorsolateral prefrontal cortex (DLPFC); first language (L1); second language (L2).

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