INTERBRAIN SYNCHRONY: ON WAVY GROUND

Clay B. Holroyd*

Department of Experimental Psychology Ghent University Henri Dunantlaan 2 9000 Gent, Belgium

*Correspondence: clay.holroyd@ugent.be (C.B. Holroyd)

Keywords:

hyperscanning social neuroscience Replication Crisis EEG gamma oscillations theta oscillations

Abstract: In recent years the study of dynamic, between-brain coupling mechanisms has taken social neuroscience by storm. In particular, interbrain synchrony is a putative neural mechanism said to promote social interactions by enabling the functional integration of multiple brains. In this article, I argue that this research is beset with three pervasive and interrelated problems. First, the field lacks a widely-accepted definition of IBS. Second, IBS wants for theories that can guide the design and interpretation of experiments. Third, a potpourri of tasks and empirical methods permits undue flexibility when testing the hypothesis. These factors synergistically undermine IBS as a theoretical construct. I finish by recommending measures that can address these issues.

Brains in Harmony?

Over the past few decades, the advent of **hyperscanning** (**see Glossary**) techniques [1-3] has provided a powerful new means for investigating the neural mechanisms of social behavior [4-8]. Chief among these mechanisms is a purported phenomenon called interbrain synchrony (IBS), which is said to support social engagement by dynamically coupling the neural activity of pairs [9-11] and groups [12,13] of individuals. One interpretation of this idea holds that neural oscillations occurring along specific frequency bands [14-17] align in **phase** across the brains of people who interact with one another (Figure 1A, Key Figure). This proposal has triggered a wave of enthusiasm, resulting in a recent crush of experiments [2,3,10,11,18] and provocative claims that IBS is, for example, indicative of extended consciousness [19].

Meanwhile, a growing chorus of researchers has been raising concerns about various aspects of IBS research [3,6,8,10,11,18,20-22]. These critiques tend to advocate various housekeeping measures such as a "strategic pruning" of research programs [18], but otherwise see the field as being more or less on track. In contrast, here I argue that the state of affairs is far more alarming: I suggest that this field is repeating the same sorts of errors that researchers made decades ago in work that sparked the **Replication Crisis**, the repercussions of which continue to echo across multiple scientific domains [23,24]. This untenable situation in IBS research has been precipitated by three pervasive and interrelated problems regarding the definitions, theories, and methods associated with research in this domain, which collectively undermine confidence that the phenomenon is real.

A Problem of Definition

The first problem is that "IBS" means different things to different people. Although the formulation depicted in Figure 1A might agree with some researchers' intuitions about the phenomenon, it also permits other forms of interbrain coupling, which sows confusion when such nuances are left unstated. Rather, a strict definition of IBS must differentiate the phenomenon from alternative forms of neural synchrony. From this perspective, IBS can be conceptualized by specifying what it is *not* rather than what it *is*, as I attempt to do in what follows.

First, IBS is not neural entrainment, which occurs when a common external source synchronizes ongoing neural oscillations between brains [25] (Figure 1B). This is an important distinction, because individual stimuli can elicit idiosyncratic yet highly reliable neural responses that are similar across individuals [26]. When they occur in succession, these events can periodically realign the phases of neural oscillations (called **phase reset**) [27,28], thereby maintaining synchrony for extended periods [11]. For example, natural music evokes neural responses that are correlated across individuals [29], so the brains of two people listening to the same song, even if played on different devices in two different

rooms, can synchronize simply due to the common temporal profile of the auditory input. Brain synchrony in this case should be considered an epiphenomenon and does not reflect actual IBS [11,22,30], although some analysis methods such as **intersubject correlation analysis** (ISC) exploit neural entrainment in such situations for other purposes (Box 1).

Second, IBS is not motor-induced neural synchrony (Figure 1C). Humans (and other animals) cannot directly access the brain states of conspecifics, so between-brain synchronization must be mediated by shared behavioral cues [10,20]. Motor-induced neural synchrony occurs when the behavior of one member of a dyad drives the neural activity of both members. Sensory information related to eye gaze [31], speech [32,33] and efference copy of the motor command [34] can reset the phase of neural oscillations, thereby synchronizing neural activity across individuals who are exposed to the same information. Note that this synchrony is the close cousin of neural entrainment: It is immaterial whether the synchronizing information comes from an external stimulus (as from a radio, Figure 1B) or from another person (as from a mouth, Figure 1C), because in both cases any apparent IBS would be incidental to the common input. This point is illustrated by studies in which electroencephalogram (EEG) data [35] and functional magnetic resonance imaging (fMRI) data [36] were recorded from a speaker and from people who later listened to an audio recording of that speaker. Application of ISC revealed that neural representations encoded in high-level cortical association areas aligned across the speaker and the listeners, despite their communications being mediated by an external device.

Third, IBS is not attention-enhanced neural synchrony (Figure 1D). IBS is sometimes inferred from evidence of increased neural synchrony when people interact compared to when they do not interact, even when both states involve the same external stimuli (ruling out neural entrainment as an explanation) and the same behaviors (ruling out motor-induced neural synchrony as an explanation). For instance, more IBS is observed when subjects talk to each other face-to-face compared to back-to-back [37]. Such control conditions, when appropriately designed, are said to provide strong evidence for the phenomenon [10,30]. Nevertheless, greater task engagement can enhance neural processing of stimuli and behavioral cues, which sometimes provides false evidence of IBS [8]. Consider two people listening to the same radio station in two different rooms. IBS might increase during songs that they both enjoy compared to songs that they both find boring, but this would not be a consequence of direct brain-to-brain coupling. The same could be true of people conversing face-to-face compared to back-to-back, where situational factors (such as greater arousal when face-to-face) can up-regulate neural processes involved in motor-induced neural synchrony [13].

The considerations outlined above highlight two key factors underlying IBS. First, the sine qua non of IBS is real-time social interaction. Otherwise, why go through the bother and expense of hyperscanning? Second, IBS does not simply reflect a passive neural response to shared social experiences (Figure 1B-D) [25]. This is why proponents seek to rule out neural

entrainment and related forms of neural synchrony as potential confounds. For example, in a study that recorded EEG between subjects who imitated one another's hand movements, IBS was said to "*not exclusively reflect the execution and perception of similar movements*" [38].

Therefore, to be a meaningful phenomenon, IBS must reflect a process that is distinct from these other forms of neural synchrony. Indeed, many accounts of IBS promise much: namely, that IBS "potentially indicates functional integration across brains" [19]. According to this position, IBS reflects a reciprocal and dynamic interplay between the neural states of sociallyinteracting conspecifics. This view holds that different brains can come together to act jointly as a functional unit, much like modules within an individual brain can coordinate their activities for a superordinate purpose. For example, one hyperscanning study suggested that "brain-to-brain coupling could be the neural signature of cognitive processes underlying cooperation, such as shared intentionality" [39]. In another study, where participants' perceptions of societal threat were manipulated experimentally, the authors concluded concretely that "increased interbrain synchrony in our study reflects a unique interbrain mechanism of the two interacting subjects attempting to coordinate under high societal threat, which cannot be simply identified as 'similar brain activities' among two individuals who are performing the same task" [40]. The common denominator underlying these and related accounts-and what imbibes the idea with its singular appeal-is that IBS actively facilitates social exchanges by establishing a resonant state between brains, albeit one that is also reciprocally mediated by way of those same behaviors [11,22] (Figure 1E, left).

It follows from this logic that IBS exerts a *causal* influence on social behavior (as has been argued previously by others [11,22,30]). What exactly this means is open to debate. Given that most social activities involve simultaneous, reciprocal and ongoing exchanges of information between partners, a modulatory role for IBS would almost certainly conform to a non-linear feedback loop, analogous to the mutual dependence exhibited by coupled pendulums [41]. The precise mechanism underlying all of this awaits specification by theory (see below). Nevertheless, this hypothesis predicts that disrupting IBS should alter the course of the associated social behavior, irrespective of the type of interaction being mediated (Figure 1E, right).

Yet a causal role for IBS in social behavior remains to be demonstrated [11,22,30]. This raises the uncomfortable prospect that all of the previous IBS findings may be no more than epiphenomena of shared environmental and behavioral cues, as opposed to evidence of a functional neural mechanism that furthers social exchanges.

A Problem of Theory

IBS research also lacks broadly accepted theories and models that could be used for generating hypotheses, making predictions, and guiding how empirical results are evaluated [42-44]. This lacuna undoubtedly follows from the absence of a clear definition: it is

challenging to formulate good theories about nebulous concepts. Regardless, the weak theoretical framework has permitted the concept to be operationalized using a sundry assortment of social tasks, recording techniques and analysis methods [45]. Evidence for IBS comes from a wild-west of task paradigms (ranging from studies of simulated tennis [46] to real-life debate [47]); experimental methodologies (mostly EEG, but also the magnetoencephalogram (MEG), fMRI and functional near-infrared spectroscopy (fNIRS)); analysis algorithms (such as **Phase Locking Value**, **Granger causality**, **Partial Directed Coherence**, and **graph theory**); and empirical signatures of IBS (including **delta**, theta, **alpha**, **beta**, and **gamma** EEG frequency bands)[3]. At best, this panoply of experimental techniques makes the job of developing a theory about it all that much harder. At worst, the flexibility afforded by the lack of theory invites practices such as **p-hacking** [48] and **HARKing** [49].

A theory of IBS would impose constraints that rule out whole classes of evidence. In particular, IBS is subject to psychophysical limitations on how information is exchanged between individuals [7,20]. Animals exhibit diverse behaviors occurring at multiple time scales that are supported by a complex interplay of neural processes [50-52]. These behaviors restrict IBS by imposing a low-pass filter [53] or bottleneck [10] that attenuates between-brain communication at higher frequencies. Yet unencumbered by a theoretical framework that constrains interpretation, IBS studies often produce findings at odds with such basic facts, like observations of (high-frequency) gamma-band IBS (Box 2).

At the other extreme, a theory of IBS would expose unremarkable results for what they are, even when these results are real. In particular, social interactions are defined by interindividual coupling of motor behaviors [54], which are themselves mediated by brain mechanisms. It is therefore a truism that the brain activity underlying these behaviors must also be coupled. A case in point is fMRI work that has provided compelling evidence that anterior cingulate cortex (ACC) contributes to a reciprocal process underlying mutual eye gaze [55]. This brain area is also involved in myriad other day-to-day activities, so does the link to ACC reveal a bespoke role for it in social synchrony, or is this another example of its ubiquitous involvement in seemingly every human behavior [56]? A good theory would also make plain which sorts of evidence align with IBS in the first place. For example, spoken language is associated with theta-band neural synchrony, which may be interesting in its own right, but a simple model invoking neural entrainment (or motor-induced neural synchrony) accounts well enough for this phenomenon. What would IBS add to this explanation (Box 3)?

In short, the lack of an overarching theoretical framework has allowed IBS studies to proliferate based on intuitions rather than on a sound mechanistic foundation. It has been argued that such conditions provide a fertile environment for publishing false results [42-45,57].

A Problem of Methods

IBS research is still a relatively young area of study so some growing pains are to be expected. That said, a lack of established norms and practices exacerbates the problems stemming from the absences of a clear definition and a compelling theory of IBS.

The potential for common input from the environment (neural entrainment, Figure 1B) and from the behavior of conspecifics (motor-induced neural synchrony, Figure 1C) to yield spurious between-brain correlations is now well-recognized [1,3,6,11,20-22,25]. Nevertheless, many studies present evidence for IBS using algorithms (such as Partial Directed Coherence and Phase Locking Value) that have been shown to be unreliable for this purpose [25]. Moreover, even what might be considered a gold standard — the **circular correlation coefficient** (Ccor) — is not impervious to error; it is simply *less* susceptible than other measures to Type 1 errors [25].

The confounds associated with neural entrainment and motor-induced neural synchrony are often addressed with better task design. In particular, researchers sometimes show enhanced IBS in an experimental condition involving social interaction compared to a control condition with the same external and behavioral cues but missing the interaction [10,30]. However, a simple difference in task engagement between the conditions, such as elevated arousal when participants make eye contact compared to when they do not [58], can give the spurious appearance of increased IBS. To understand this, consider that alpha oscillations normally increase in amplitude when people close their eyes compared to when their eyes are open. This results in greater alpha-band IBS in the eyes closed condition relative to the eyes open condition, even for dyads composed of randomly-paired individuals who never actually interact [25] (Figure 2). To rule out *this* possibility, researchers sometimes analyze the data using a **shuffling** procedure whereby a control statistic is calculated from data that have been randomly paired across participants (e.g., [59]). But although this procedure is more conservative than not applying any statistical correction at all, it nevertheless falls short of a full permutation analysis that would be needed to demonstrate statistical significance (Box 4).

Finally, even when these hurdles are surmounted, attention to socially-relevant cues can enhance neural processing of those cues, resulting in the spurious appearance of more IBS [8]. In other words, strong evidence of attention-enhanced neural synchrony (Figure 1D) still does not constitute evidence of IBS (Figure 1E).

These caveats indicate that conclusive evidence for IBS is still forthcoming [22]. More concerning, too often these confounds are not even acknowledged by investigators, leaving readers to screen each report for its validity (as has been noted previously [3]).

Concluding Remarks and Future Perspectives

Any of the problems discussed in earlier sections would be vexing enough on their own, but together they synergistically undermine the validity of IBS as a theoretical construct.

Nebulous definitions of IBS undercut efforts to theorize about it, which in turn allows methods to test the idea to proliferate. All of this is a recipe for **confirmation bias** [60] that encourages publication of sweeping, false assertions [45,57].

What can be done? The initial response to the Replication Crisis was to do exactly what the name implies—replicate [23]. One might follow in the footsteps of this and more recent, large-scale replication efforts such as the #EEGManyLabs project [61] by collectively replicating a select set of influential IBS experiments. In other cases, it might be more efficient to reanalyze existing data using more conservative statistical tests (Box 4). That said, the term "Replication Crises" is increasingly viewed, with hindsight, as a misnomer, in that the crisis is believed to have been precipitated less by a lack of statistical power than by a poverty of theory [42-45]. In other words, many of the studies swept up in the crisis were unmoored to begin with. The lesson for IBS research is that there may be little value in revisiting experiments with poorly-operationalized hypotheses.

More important than replication, researchers should propose—and ideally agree on—a working definition of IBS (see "Outstanding Questions"). This definition should specify what kinds of evidence would be diagnostic of the phenomenon; given the considerations discussed here, such evidence must demonstrate that IBS causally facilitates social interactions [11,22,30]. This relatively narrow criterion would disallow evidence obtained using most of the approaches that are currently popular in IBS research (and indeed make the issue of replication moot).

In addition, mechanistic theories of IBS must be developed (e.g., [20,62-64]). These theories should specify boundary conditions beyond which IBS would not be found, and should make differentiating predictions that are unique to each theory [45]. Ideally, the theories would be grounded in a mathematical formalism that describes the dynamics of the process, going beyond pioneering examples of this [65,66] to incorporate slower behavioral dynamics [67] that mediate between-brain coupling. Proof-of-principle could also be demonstrated by instantiating the theory in groups of interacting, socially-attuned robots [68-70].

The functional role of IBS should also be simulated with neurocomputational models. For example, theta cycles are hypothesized to interleave perceptual sampling of the external environment with shifts of attention to new environmental locations [16]; in principle, temporal alignment of these mechanisms across social partners could facilitate their coordinated behavior. Computational simulations also suggest that theta oscillations underlie synchronization of belief states when people communicate with one another [71]. Models of such processes that incorporated IBS would go a long way toward answering the questions raised throughout this article. These studies would also do well to make contact with a nascent literature on the computational neuroscience of social behavior [72].

Finally, the field should develop empirical methods that distinguish IBS from other forms of neural synchrony (Figure 1). Crucially, these methods must demonstrate the causal role of IBS in supporting social behavior, such as recent, creative proposals to use transcranial stimulation [22] and neurofeedback [30,73] for this purpose. Arguably the most promising approach involves animal model experiments, which allow for tight control over experimental variables and for a broader range of empirical measures [22]. For example, different populations of IBS-related neurons in mouse medial frontal cortex separately encode the animal's own behavior vs. the behavior of a conspecific [74]. The causal role for such IBS could be investigated using optogenetic stimulation and other methods [22]. As well, future work should demonstrate whether this synchrony, which so far has been observed for time scales spanning seconds or longer [74,75] (but see [76]), extends to higher frequencies that are important for neural computation such as theta and gamma (Box 2 and Box 3). In the context of human studies, novel techniques that capture rich information about participant behavior, including data about facial expressions, eye, hand and body movements, and physiology [20], should also be developed, together with mathematical and computational methods that quantify the degree of coupling mediated by these behaviors [7,54,77,78].

The Replication Crisis was sparked by a statistical critique [79] of a study that reported evidence for extrasensory perception. Ironically, this was also the subject of what was apparently the first published hyperscanning experiment [80]. Perhaps it is not coincidental that some claims about IBS make it sound like telepathy [20], which similarly calls attention to their implausibility. If IBS exists, then it is a spectacular phenomenon. This is a prize worth setting on solid ground.

FIGURE 1 (KEY FIGURE)

Conceptions of interbrain synchrony. (A) Intuitive formulation of interbrain synchrony (IBS): Neural oscillations are randomly organized across non-interacting individuals (left) and synchronize (phase-align) when the individuals engage socially (right). (B) Neural entrainment. External stimuli (e.g. sounds from a radio) can synchronize neural oscillations across non-interacting individuals. (C) Motor-induced neural synchrony: Stimulus cues associated with motor behavior (spoken communication) can synchronize neural oscillations across non-interacting individuals. (D) Attention-enhanced neural synchrony: Social engagement can increase attention to stimulus cues associated with motor behavior (spoken communication), resulting in enhanced synchronization of neural oscillations across individuals (larger amplitude oscillations relative to motor-induced neural synchrony). (E) Interbrain synchrony: IBS modulates (thick arrows) the social interaction (spoken communication) (left). Perturbing IBS (red X on the right) disrupts the social interaction (upside-down communication icon). For all panels, faces indicate interacting individuals (when facing toward each other) or non-interacting individuals (when facing away from each other). Oscillations represent neural activity over time. Arrows indicate direction of influence/ownership. Oscillations, arrows, and shirts are color-coded according to each individual (red vs. blue). Note that exact phase/amplitude coupling is illustrated for didactic purposes, but IBS only requires that the neural activity be correlated across individuals (i.e., inter-subject coupling [78]).

FIGURE 2

Some IBS methods are unreliable. Some EEG/MEG analysis methods can yield spurious indications of enhanced interbrain synchrony (IBS). For example, alpha oscillations normally increase in amplitude when people close their eyes (right) compared to when their eyes are open (left). Analysis of phase locking value and other measures can indicate more alpha-band IBS in the eyes closed condition relative to the eyes open condition (inset), even for individuals who never actually interact [25]. In the figure, oscillations represent neural activity over time. Arrows indicate direction of influence/ownership. Oscillations, arrows, and shirts are color-coded according to each individual (red vs. blue).

BOX 1: INTERSUBJECT CORRELATION ANALYSIS

Intersubject correlation analysis (ISC) exploits the fact that naturalistic stimuli elicit spatialtemporal patterns of neural activity that are shared across individuals, even in high-level association areas that are relatively removed from sensory cortices, such as brain regions comprising the default mode network (DMN) [81,82]. In a foundational study, the fMRI BOLD response was recorded from participants as they viewed extended film clips; application of ISC revealed that movie scenes with images of faces, places and hands elicited neural activity in corresponding face-, place- and hand-related brain areas with a time course that was common to the different viewers [83]. More recently, it has been observed that when subjects watch animations of ambiguous stories [84] or listen to ambiguous narratives [85], neural representations in the DMN exhibit the greatest similarity in the individuals who interpret the stories most similarly. Neural alignment of association areas is observed even between different listeners when told the same stories in different languages [86].

In general, the amount of attention that viewers pay to naturalistic stimuli predicts the degree of inter-individual neural alignment [87]. For example, relatively engaging movie scenes elicit greater theta-band EEG power, which manifests across subjects as enhanced neural synchrony [88]. Further, when subjects are presented simultaneously with written and spoken narratives, each of which tell a different story, neural activity aligns across readers and listeners according to the story to which they attend [89]. This phenomenon extends to emotional expression: When people emote feelings like joy and anger to their partners via a videotaped recording, their brain states predict that of their partners' [90]. Neural states also become more aligned when individuals listen to political speeches that they self-report as being more powerful (specifically, of "high rhetorical quality") relative to other speeches [91].

Note that ISC reveals prototypical patterns of neural activity that are temporally correlated across people who are exposed to stimuli that share key attributes (e.g., an image of a face, the semantic meaning of a narrative), irrespective of whether the people physically interact or not. In the context of IBS research, this type of synchrony is seen as a confound because it reflects a passive response to, rather than a causal driver of, social interaction.

BOX 2: GAMMA-BAND INTERBRAIN SYNCHRONY IS PROBABLY IMPOSSIBLE

Gamma oscillations (> 30 Hz) are associated with various neurocognitive processes like attention and binding [14]. Gamma-band IBS is often reported (e.g., [38-40,92-100]), but these observations can be questioned. First, the slowest of these oscillations occur with a periodicity of about 30 ms, so brains that interact at this frequency must establish and maintain synchrony with at least 15 ms precision (half a cycle), often for extended periods of time (e.g., seconds) in the absence of any direct line of communication. This is unlikely given that single excitatory post-synaptic potentials last about 10 ms [14]; even different areas within the same brain require a dedicated control system to maintain synchrony with such high temporal fidelity [101]. Second, the relatively slow dynamics of normal behavior impose a low-pass filter [53] or bottleneck [10] that attenuates transmission of high-frequency signals like gamma oscillations. Third, coherence between high-frequency gamma signals can be difficult to assess and interpret even within a single brain [102], so between-brain synchrony of these signals should be even more difficult to evaluate. Fourth, gamma-band analyses are highly susceptible to artifacts [103]. Gamma is especially sensitive to electromyographic activity associated with the face [104], which varies as a function of cognitive demands [105], and with eye movements, including miniature saccades missed by standard artifact detection procedures [106]. Even auditory cues elicit small eye movements that induce gamma artifacts [107].

Not all gamma IBS studies are subject to all of these caveats. For example, gamma power is less sensitive than gamma phase to small differences in timing [93,94], and MEG is less sensitive than EEG to gamma artifacts [94,95]. Nevertheless, most (perhaps all) gamma IBS studies are subject to at least some of these issues. For example, EEG-based gamma IBS has been observed to occur 2-3 s after the eliciting stimulus [40], long after the signals should lose coherence between brains; when participants make eye-contact [98], which would be expected to elicit artifact; and in deep neural sources such as anterior cingulate cortex [92], despite large uncertainties inherent to source localization of EEG signals [108].

Given these caveats it is perhaps prudent to interpret gamma IBS as artifactual until proven otherwise.

BOX 3: THETA AND SPOKEN COMMUNICATION: NEURAL ENTRAINMENT OR IBS?

Theta consists of 4-8 Hz oscillations. When recorded intracranially (usually in animal models), theta oscillations are commonly discussed as a feature of hippocampal processing and hippocampal-cortical communication [17], and when recorded from the human scalp, they often provide a neural index of control processes [15,16]. Because theta is roughly an order of magnitude slower than gamma (Box 2), the biophysical constraints on theta-band IBS are relatively less restrictive. Perhaps for this reason, numerous studies have provided solid evidence that theta oscillations are subject to neural entrainment. The role of theta in spoken communication is illustrative of this relationship [28,32,33].

MEG and EEG studies indicate that the brain segments continuous speech into chunks of approximately 200 ms, i.e., at the theta rhythm [109]. The superior temporal gyrus detects large and rapid changes in the amplitude envelope of the acoustic signal [110], which causes a theta phase reset [111] that parses words into syllables [112]. Interestingly, these signals appear to facilitate cross-modal integration. When participants watch movies, the phases of theta rhythms recorded in visual and auditory cortex are, respectively, sensitive to auditory and visual cues [113]; and when subjects read lips, the unheard auditory speech signals—not the lip movements—entrain oscillations in visual cortex [114]. These speech-related intrabrain coupling mechanisms are also subject to top-down control processes [115]. For example, selective attention to speech in a multi-speaker environment enhances discrimination by theta signals recorded in auditory cortex to the attended voice over other voices (the "cocktail party effect") [116]. Seeing a speaker's face also increases theta entrainment to the speech signal and enhances transfer between brain regions of speech-related information [117].

Yet the question remains whether any of this constitutes strong evidence for IBS. One study questioned whether this evidence is even consistent with neural entrainment, because no theta oscillations were observed before the occurrence of the acoustic signal that caused the putative reset [116]. Tellingly, despite the rich conceptual framework and empirical support for entrainment of theta oscillations by spoken language, most IBS studies of spoken communication use recording methods that are relatively insensitive to theta, like fNIRS [9]. As with IBS research more generally, there is also a relative paucity of theoretically-driven hypotheses about the role of IBS in verbal communication [62].

BOX 4: SHUFFLING VS. PERMUTATION

Imagine an experiment that compared interbrain synchrony (IBS) of 5 dyads (Figure I, pairs connected by solid pink arrows) having face-to-face conversations and the same dyads having conversations back-to-back (e.g., [37]). A t-value determined from this comparison would provide a measure of statistical significance. If the observed t-value (pink dot) were larger than the critical t-value (vertical solid line), then we would conclude that IBS is larger when subjects face each other than when they do not.

Although suggestive, this result could reflect greater neural engagement overall rather than enhanced sensitivity to the partner's voice in particular. To exclude this possibility, researchers sometimes randomly pair each subject's data into new (fictional) dyads (dashed orange arrows), which are used to compute new IBS values and a new t statistic [37,39,59,97,118]. If the t-value for this fictional set of dyads is not statistically significant (orange dot), and the t-value for the actual dyads is statistically significant, then the observed IBS is taken to be real.

The problem with this shuffling procedure is that it depends on the luck of the draw; a different mix of subject pairings (dashed green arrows) could yield a different result, such as a statistically significant t-value even larger than the observed t-value (green dot).

Instead, one could conduct a non-parametric permutation test, which estimates the distribution of the statistic given that the null hypothesis is true (black curve) [119]. This approach entails shuffling the data multiple times (say, 1000) and re-computing the statistic with each shuffle. Significance is declared when the observed t-value is an outlier, usually defined by the upper 5% of the distribution (dashed vertical line). In this hypothetical example, neither the t-static from the observed (pink) dyads nor the shuffled (orange) dyads exceed this criterion, because the estimated distribution exhibits a positive bias.

Many IBS studies compute permutation statistics by randomizing the data with respect to experimental condition [40,55,94,100]. However, fewer studies generate the null distribution by randomizing dyad memberships as prescribed here [63,120] (cf. [37,118]). Further, most EEG studies of IBS variously use shuffling rather than full permutation of dyad members [59,97]; do not indicate where the observed statistic falls within the estimated distribution [31,39]; or do neither shuffling nor full (dyad) permutation. It thus remains possible that these studies show neural entrainment or motor-induced neural synchrony rather than attention-enhanced neural synchrony, to say nothing of IBS (see main text).

GLOSSARY:

Alpha: Electrophysiological oscillations spanning, in humans, frequencies between about 8-12 Hz.

Beta: Electrophysiological oscillations spanning, in humans, frequencies between about 12-30 Hz.

Circular correlation coefficient: A measure of the association between angular variables, which is useful for assessing correlations between phases of neural oscillations.

Confirmation bias: The predisposition to favor evidence supporting one's own hypothesis over evidence contradicting that hypothesis.

Default mode network (DMN): a network of brain areas including the medial prefrontal cortex, precuneus, posterior cingulate cortex and inferior parietal cortex. Although the DMN was first identified because it becomes relatively active when subjects are at rest, it is now understood to play an important role in social behavior and other high-level functions.

Delta: Electrophysiological oscillations spanning, in humans, frequencies between about 1-4 Hz.

Efference copy: Neural information about a motor command processed by brain areas not directly involved in the execution of that command.

Gamma: Electrophysiological oscillations spanning, in humans, frequencies greater than about 30 Hz.

Granger causality: A statistical method for testing whether a given time series is predictive of a second time series.

Graph theory: The mathematical study of structures built from elements (called "nodes") and their pairwise relationships (called "edges").

HARKing: "Hypothesizing After the Results are Known". When experimenters report a posthoc interpretation of their results as an a priori prediction. This is considered bad practice because it violates principles of statistical inference.

Hyperscanning: Experimental techniques that simultaneously record the brain activities of two or more individuals.

Intersubject correlation analysis: A method for analyzing brain activity elicited by naturalistic stimuli and tasks. The method identifies spatio-temporal patterns of neural activity that are statistically reliable across subjects.

P-hacking: A questionable research practice whereby experimenters mine their data for results that support their hypotheses without divulging that these analyses are exploratory.

Partial directed coherence: A statistical measure of brain connectivity that provides a frequency-domain measure of Granger causality.

Phase: The fraction of one cycle of an oscillation relative to the onset of that cycle.

Phase locking value: A measure of phase synchrony between time series that is independent of signal amplitude.

Phase reset: Near-instantaneous change in phase of an ongoing neural oscillation elicited by the occurrence of an internal or external stimulus.

Replication Crisis: Widespread concern throughout multiple branches of science, beginning in the 2010s, that many published and highly-regarded experimental findings fail to replicate. This concern has been especially acute in the social sciences.

Shuffling: As applied in some interbrain synchrony studies, a control analysis whereby the data of dyad members are randomly interchanged across pairs only a single time (in contrast to permutation analysis, which entails interchanging the data across dyads multiple times).

Theta: Electrophysiological oscillations spanning, in humans, frequencies between about 4-8 Hz.

ACKNOWLEDGEMENTS

This work was partly supported by funding from the European Research Council (ERC) under the EU's Horizon 2020 Research and Innovation Programme (grant agreement no. 787307). Thanks to Thomas Colin for feedback on a version of this paper.

DECLARATION OF INTERESTS

The author declares no competing interests in relation to this work.

REFERENCES:

- 1. Hari, R. *et al.* (2015) Centrality of social interaction in human brain function. *Neuron* 88, 181–193
- 2. Mu., Y. *et al.* (2018) Neural mechanisms underlying interpersonal coordination: A review of hyperscanning research. *Soc. Personal. Psychol. Compass* 12, e12421
- 3. Czeszumski, A. *et al.* (2020) Hyperscanning: A valid method to study neural inter-brain underpinnings of social interaction. *Front. Hum. Neurosci.* 14, 39
- 4. Hasson, U. *et al.* (2012) Brain-to-brain coupling: a mechanism for creating and sharing a social world. *Trends Cogn. Sci.* 16, 114–121
- 5. Feldman, R. (2017) The neurobiology of human attachments. Trends Cogn. Sci. 21, 80-99
- 6. Redcay, E. and Schilbach, L. (2019) Using second-person neuroscience to elucidate the mechanisms of social interaction. *Nat. Rev. Neurosci.* 20, 495–505
- 7. Dumas, G. and Fairhurst, M. T. (2021) Reciprocity and alignment: Quantifying coupling in dynamic interactions. *R. Soc. Open Sci.* 8, 210138
- 8. Hoehl, S. *et al.* (2021) Interactional synchrony: Signals, mechanisms and benefits. *Soc. Cogn. Affect. Neurosci.* 16, 5–18
- 9. Kelsen, B. A. *et al.* (2020) What has social neuroscience learned from hyperscanning studies of spoken communication? A systematic review. *Neurosci. Biobehav. Rev.* DOI: 10.1016/j.neubiorev.2020.09.008
- 10. Kingsbury, L. and Hong, W. (2020) A multi-brain framework for social interaction. *Trends Neurosci.* 43, 651–666
- 11. Wass, S. V. *et al.* (2020) Interpersonal neural entrainment during early social interaction. *Trends Cogn. Sci.* 24, 329–342
- 12. Reinero, D. A. *et al.* (2021) Inter-brain synchrony in teams predicts collective performance. *Soc. Cogn. Affect. Neurosci.* 16, 43–57
- 13. Dikker, S. *et al.* (2017) Brain-to-brain synchrony tracks real-world dynamic group interactions in the classroom. *Curr. Biol.* 27, 1375–1380
- 14. Jensen, O. *et al.* (2007) Human gamma-frequency oscillations associated with attention and memory. *Trends Neurosci.* 30, 317–324
- 15. Holroyd, C. B. and Umemoto, A. (2016) The research domain criteria framework: The case for anterior cingulate cortex. *Neurosci. Biobehav. Rev.* 71, 418–443
- Fiebelkorn, I. C. and Kastner, S. (2019) A rhythmic theory of attention. *Trends Cogn. Sci.* 23, 87–101
- 17. Karakas, S. (2020) A review of theta oscillation and its functional correlates. *Int. J. Psychophysiol.* 157, 82–99
- 18. Schirmer, A. *et al.* (2021) Being 'in sync'-is interactional synchrony the key to understanding the social brain?. *Soc. Cogn. Affect. Neurosci.* 16, 1–4

- 19. Valencia, A. L. and Froese, T. (2020) What binds us? Inter-brain neural synchronization and its implications for theories of human consciousness. *Neurosci. Conscious*. 2020, niaa010
- 20. Hamilton, A. (2021) Hyperscanning: Beyond the hype. Neuron 109, 404-407
- 21. Levy, J. *et al.* (2021) The integration of social and neural synchrony: A case for ecologically valid research using MEG neuroimaging. *Soc. Cogn. Affect. Neurosci.* 16, 143–152
- 22. Novembre, G. and Iannetti, G. D. (2021) Hyperscanning alone cannot prove causality. Multibrain stimulation can. *Trends Cogn. Sci.* 25, 96–99
- 23. Open Science Collaboration (2015) PSYCHOLOGY. Estimating the reproducibility of psychological science. *Science* 349, aac4716
- 24. Chivers, T. (2019) A theory in crisis. Nature 576, 200-202
- 25. Burgess, A. P. (2013) On the interpretation of synchronization in EEG hyperscanning studies: A cautionary note. *Front. Hum. Neurosci.* 7, 881
- 26. Hasson, U. *et al.* (2010) Reliability of cortical activity during natural stimulation. *Trends Cogn. Sci.* 14, 40–48
- 27. Lakatos, P. *et al.* (2019) A new unifying account of the roles of neuronal entrainment. *Curr. Biol.* 29, R890–R905
- 28. Obleser, J. and Kayser, C. (2019) Neural entrainment and attentional selection in the listening brain. *Trends Cogn. Sci.* 23, 913–926
- 29. Kaneshiro, B. *et al.* (2020) Natural music evokes correlated EEG responses reflecting temporal structure and beat. *Neuroimage* 214, 116559
- 30. Gvirts Provolovski, H. Z. and Perlmutter, R. (2021) How can we prove the causality of interbrain synchronization? *Front. Hum. Neurosci.* 15, 651949
- 31. Leong, V. *et al.* (2017) Speaker gaze increases information coupling between infant and adult brains. *Proc. Natl. Acad. Sci. U. S. A.* 114, 13290–13295
- 32. Giraud, A. L. and Poeppel, D. (2012) Cortical oscillations and speech processing: Emerging computational principles and operations. *Nat. Neurosci.* 15, 511–517
- 33. Peelle, J. E. and Davis, M. H. (2012) Neural oscillations carry speech rhythm through to comprehension. *Front. Psychol.* 3, 320
- 34. Perez, A. *et al.* (2017) Brain-to-brain entrainment: EEG interbrain synchronization while speaking and listening. *Sci. Rep.* 7, 4190
- 35. Kuhlen, A. K. *et al.* (2012) Content-specific coordination of listeners' to speakers' EEG during communication. *Front. Hum. Neurosci.* 6, 266
- 36. Stephens, G. J. *et al.* (2010) Speaker-listener neural coupling underlies successful communication. *Proc. Natl. Acad. Sci. U. S. A.* 107, 14425–14430
- 37. Jiang, J. *et al.* (2012) Neural synchronization during face-to-face communication. *J. Neurosci.* 32, 16064–16069

- 38. Dumas, G. *et al.* (2010) Inter-brain synchronization during social interaction. *PloS One* 5, e12166
- 39. Barraza, P. *et al.* (2020) Brain-to-brain coupling in the gamma-band as a marker of shared intentionality. *Front. Hum. Neurosci.* 14, 295
- 40. Mu, Y. *et al.* (2017) The role of gamma interbrain synchrony in social coordination when humans face territorial threats. *Soc. Cogn. Affect. Neurosci.* 12, 1614–1623
- 41. Fuchs, A. and Jirsa, V. K., eds (2008) *Coordination: Neural, Behavioral and Social Dynamics.* Springer
- 42. Fiedler, K. (2017) What constitutes strong psychological science? The (neglected) role of diagnosticity and a priori theorizing. *Perspect. Psychol. Sci.* 12, 46–61
- 43. Muthukrishna, M. and Henrich, J. (2019) A problem in theory. *Nat. Hum. Behav.* 3, 221–229
- 44. Oberauer, K. and Lewandowsky, S. (2019) Addressing the theory crisis in psychology. *Psychon. Bull. Rev.* 26, 1596–1618
- 45. Yarkoni, T. (2020).The generalizability crisis. *Behav. Brain Sci.* DOI: 10.1017/S0140525X20001685
- 46. Liu, H. *et al.* (2021) Inter-brain amplitude correlation differentiates cooperation from competition in a motion-sensing sports game. *Soc. Cogn. Affect. Neurosci.* 16, 552–564
- 47. van Vugt, M.K. *et al.* (2020) Inter-brain synchronization in the practice of Tibetan monastic debate. *Mindfulness* 11, 1105–1119
- 48. Simmons, J. P. *et al.* (2011) False-positive psychology: Undisclosed flexibility in data collection and analysis allows presenting anything as significant. *Psychol. Sci.* 22, 1359-1366
- 49. Kerr, N. L. (1998) HARKing: hypothesizing after the results are known. *Pers. Soc. Psychol. Rev.* 2, 196-217
- 50. Kiebel, S. J. *et al.* (2008) A hierarchy of time-scales and the brain. *PLoS Comput. Biol.* 4, e1000209
- 51. Perdikis, D. *et al.* (2011) Time scale hierarchies in the functional organization of complex behaviors. *PLoS Comput. Biol.* 7, e1002198
- 52. Kaplan, H. S. *et al.* (2020) Nested neuronal dynamics orchestrate a behavioral hierarchy across timescales. *Neuron* 105, 562–576
- 53. Clark, A. (2009) Spreading the joy? Why the machinery of consciousness is (probably) still in the head. *Mind* 118, 963-993
- 54. Oullier, O. *et al.* (2008) Social coordination dynamics: Measuring human bonding. *Soc. Neurosci.* 3, 178–192
- 55. Koike, T. *et al.* (2019) What makes eye contact special? Neural substrates of on-line mutual eye-gaze: A hyperscanning fMRI study. *eNeuro* 6, ENEURO.0284-18.2019

- 56. Holroyd, C. B. and Verguts, T. (2021) The best laid plans: Computational principles of anterior cingulate cortex. *Trends Cogn. Sci.* 25, 316–329
- 57. Ioannidis, J. P. (2005) Why most published research findings are false. PLoS Med. 2, e124
- 58. Ishikawa, M. and Itakura, S. (2019) Physiological arousal predicts gaze following in infants. *Proc. Biol. Sci.* 286, 20182746
- 59. Toppi, J. *et al.* (2016) Investigating cooperative behavior in ecological settings: An EEG hyperscanning study. *PloS One* 11, e0154236
- 60. Nickerson, R. S. (1998) Confirmation bias: A ubiquitous phenomenon in many guises. *Rev. Gen. Psychol.* 2, 175-220
- 61. Pavlov, Y. G. *et al.* (2021) #EEGManyLabs: Investigating the replicability of influential EEG experiments. *Cortex* 144, 213–229
- 62. Schoot, L. *et al.* (2016) What can we learn from a two-brain approach to verbal interaction? *Neurosci. Biobehav. Rev.* 68, 454–459
- 63. Mayseless, N. *et al.* (2019) Real-life creative problem solving in teams: fNIRS based hyperscanning study. *Neuroimage* 203, 116161
- 64. Schore, A. N. (2021) The interpersonal neurobiology of intersubjectivity. *Front. Psychol.* 12, 648616
- 65. Dumas, G. *et al.* (2012) Anatomical connectivity influences both intra- and inter-brain synchronizations. *PloS One* 7, e36414
- 66. Zhang, W. and Yartsev, M. M. (2021) A unifying mechanism governing inter-brain neural relationship during social interactions. *bioRxiv* DOI: 10.1101/2021.06.02.446694
- 67. Heggli, O. A. *et al.* (2019) A Kuramoto model of self-other integration across interpersonal synchronization strategies. *PLoS Comput. Biol.* 15, e1007422
- 68. Cross, E. S. *et al.* (2019) From social brains to social robots: Applying neurocognitive insights to human-robot interaction. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 374, 20180024
- 69. Dorigo, M. *et al.* (2020) Reflections on the future of swarm robotics. *Sci. Robot.* 5, eabe4385
- 70. Tejwani, R. *et al.* (2022) Social interactions as recursive MDPs. *Proceedings of the* 5th *Conference on Robot Learning* PMLR 164, 949-958,
- 71. Friston, K. J. *et al.* (2020) Generative models, linguistic communication and active inference. *Neurosci. Biobehav. Rev.* 118, 42–64
- 72. Olsson, A. *et al.* (2020) The neural and computational systems of social learning. *Nat. Rev. Neurosci.* 21, 197–212
- 73. Müller, V. *et al.* (2021) Interacting brains coming in sync through their minds: An interbrain neurofeedback study. *Ann. N. Y. Acad. Sci.* DOI: 10.1111/nyas.14605
- 74. Kingsbury, L. *et al.* (2019) Correlated neural activity and encoding of behavior across brains of socially interacting animals. *Cell* 178, 429–446

- 75. Zhang, W. and Yartsev, M. M. (2019) Correlated neural activity across the brains of socially interacting bats. *Cell* 178, 413–428
- 76. Rose, M. C. *et al.* (2021) Cortical representation of group social communication in bats. *Science* 374, eaba9584
- 77. Fusaroli, R. and Tylén, K. (2016) Investigating conversational dynamics: Interactive alignment, interpersonal synergy, and collective task performance. *Cogn. Sci.* 40, 145–171
- 78. Hasson, U. and Frith, C. D. (2016) Mirroring and beyond: Coupled dynamics as a generalized framework for modelling social interactions. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 371, 20150366
- 79. Wagenmakers, E. J. *et al.* (2011) Why psychologists must change the way they analyze their data: the case of psi: Comment on Bem (2011). *J. Pers. Soc. Psychol.* 100, 426–432
- 80. Duane, T. D. and Behrendt, T. (1965) Extrasensory electroencephalographic induction between identical twins. *Science* 150, 367
- 81. Nastase, S. A. *et al.* (2019) Measuring shared responses across subjects using intersubject correlation. *Soc. Cogn. Affect. Neurosci.* 14, 667–685
- 82. Yeshurun, Y. *et al.* (2021) The default mode network: Where the idiosyncratic self meets the shared social world. *Nat. Rev. Neurosci.* 22, 181–19
- 83. Hasson, U. et al. (2004) Intersubject synchronization of cortical activity during natural vision. *Science* 303, 1634–1640
- 84. Nguyen, M. *et al.* (2019) Shared understanding of narratives is correlated with shared neural responses. *Neuroimage* 184, 161–170
- 85. Yeshurun, Y. et al. (2017) Same story, different story. Psychol. Sci. 28, 307-319
- 86. Honey, C. J. *et al.* (2012) Not lost in translation: Neural responses shared across languages. *J. Neurosci.* 32, 15277–15283
- 87. Ki, J. J. *et al.* (2016) Attention strongly modulates reliability of neural responses to naturalistic narrative stimuli. *J. Neurosci.* 36, 3092–3101
- 88. Dmochowski, J. P. *et al.* (2012) Correlated components of ongoing EEG point to emotionally laden attention a possible marker of engagement? *Front. Hum. Neurosci.* 6, 112
- 89. Regev, M. *et al.* (2019) Propagation of information along the cortical hierarchy as a function of attention while reading and listening to stories. *Cereb. Cortex* 29, 4017–4034
- 90. Anders, S. *et al.* (2011) Flow of affective information between communicating brains. *Neuroimage* 54, 439–446
- 91. Schmälzle, R. *et al.* (2015) Engaged listeners: Shared neural processing of powerful political speeches. *Soc. Cogn. Affect. Neurosci.* 10, 1137–1143
- 92. Astolfi, L. *et al.* (2010) Neuroelectrical hyperscanning measures simultaneous brain activity in humans. *Brain Topogr.* 23, 243–256

- 93. Kinreich, S. *et al.* (2017) Brain-to-brain synchrony during naturalistic social interactions. *Sci. Rep.* 7, 17060
- 94. Levy, J. *et al.* (2017) Perception of social synchrony induces mother-child gamma coupling in the social brain. *Soc. Cogn. Affect. Neurosci.* 12, 1036–1046
- 95. Ahn, S. *et al.* (2018) Interbrain phase synchronization during turn-taking verbal interaction-a hyperscanning study using simultaneous EEG/MEG. *Hum. Brain Mapp.* 39, 171–188
- 96. Li, J. *et al.* (2020) Inter-brain synchronization is weakened by the power to reject offers in bilateral bargaining games. *SSRN* DOI: http://dx.doi.org/10.2139/ssrn.3617843
- 97. Djalovski, A. *et al.* (2021) Human attachments shape interbrain synchrony toward efficient performance of social goals. *Neuroimage* 226, 117600
- 98. Luft, C. *et al.* (2021) Social synchronisation of brain activity by eye-contact. *Res Sq.* DOI: 10.21203/rs.3.rs-654192/v1
- 99. Richard, C. *et al.* (2021) Elevated inter-brain coherence between subjects with concordant stances during discussion of social issues. *Front. Hum. Neurosci.* 15, 611886
- 100. Zhou, X. *et al.* (2021) Mortality threat mitigates interpersonal competition: An EEGbased hyperscanning study. *Soc. Cogn. Affect. Neurosci.* 16, 621–631
- 101. Verguts, T. (2017) Binding by random bursts: A computational model of cognitive control. *J. Cogn. Neurosci.* 29, 1103–1118
- 102. Buzsáki, G. and Schomburg, E. W. (2015) What does gamma coherence tell us about inter-regional neural communication? *Nat. Neurosci.* 18, 484–489
- 103. Nottage, J. F. and Horder, J. (2015) State-of-the-art analysis of high-frequency (gamma range) electroencephalography in humans. *Neuropsychobiology* 72, 219–228
- 104. Whitham, E. M. *et al.* (2007) Scalp electrical recording during paralysis: Quantitative evidence that EEG frequencies above 20 Hz are contaminated by EMG. *Clin. Neurophysiol.* 118, 1877–1888
- 105. Whitham, E. M. *et al.* (2008) Thinking activates EMG in scalp electrical recordings. *Clin. Neurophysiol.* 119, 1166–1175
- 106. Yuval-Greenberg, S. *et al.* (2008) Transient induced gamma-band response in EEG as a manifestation of miniature saccades. *Neuron* 58, 429–441
- Yuval-Greenberg, S. and Deouell, L. Y. (2011) Scalp-recorded induced gamma-band responses to auditory stimulation and its correlations with saccadic muscle-activity. *Brain Topogr.* 24, 30–39
- 108. Michel, C. M. and He, B. (2019) EEG source localization. *Handb. Clin. Neurol.* 160, 85– 101
- 109. Luo, H. and Poeppel, D. (2007) Phase patterns of neuronal responses reliably discriminate speech in human auditory cortex. *Neuron* 54, 1001–1010

- 110. Oganian, Y. and Chang, E. F. (2019) A speech envelope landmark for syllable encoding in human superior temporal gyrus. *Sci. Adv.* 5, eaay6279
- 111. Yeung, N. *et al.* (2004) Detection of synchronized oscillations in the electroencephalogram: An evaluation of methods. *Psychophysiology* 41, 822–832
- 112. Doelling, K. B. *et al.* (2014) Acoustic landmarks drive delta-theta oscillations to enable speech comprehension by facilitating perceptual parsing. *Neuroimage* 85, 761–768
- 113. Luo, H. *et al.* (2010) Auditory cortex tracks both auditory and visual stimulus dynamics using low-frequency neuronal phase modulation. *PLoS Biol.* 8, e1000445
- 114. Hauswald, A. *et al.* (2018) A visual cortical network for deriving phonological information from intelligible lip movements. *Curr. Biol.* 28, 1453–1459
- 115. Park, H. *et al.* (2015) Frontal top-down signals increase coupling of auditory lowfrequency oscillations to continuous speech in human listeners. *Curr. Biol.* 25, 1649– 1653
- 116. Kerlin, J. R. *et al.* (2010) Attentional gain control of ongoing cortical speech representations in a "cocktail party". *J. Neurosci.* 30, 620–628
- 117. Giordano, B. L. *et al.* (2017) Contributions of local speech encoding and functional connectivity to audio-visual speech perception. *eLife* 6, e24763
- 118. Osaka, N. *et al.* (2015) How two brains make one synchronized mind in the inferior frontal cortex: fNIRS-based hyperscanning during cooperative singing. *Front. Psychol.* 6, 1811
- 119. Nichols, T. E. and Holmes, A. P. (2002) Nonparametric permutation tests for functional neuroimaging: A primer with examples. *Hum. Brain Mapp.* 15, 1–25
- Bilek, E. *et al.* (2015) Information flow between interacting human brains:
 Identification, validation, and relationship to social expertise. *Proc. Natl. Acad. Sci. U. S. A.* 112, 5207–5212

OUTSTANDING QUESTIONS

- IBS can be defined as a neural mechanism that promotes social interactions by enabling functional integration of multiple brains. This definition meets two criteria that are arguably essential for IBS, that is: IBS 1) requires hyperscanning for its empirical verification, and 2) is not reducible to other forms of neural synchrony (i.e., neural entrainment, motor-induced neural synchrony, and attention-enhanced neural synchrony). Are there other definitions if IBS that could meet these criteria, and if so, what would be their formulation?
- Invasive experiments in animal models and non-invasive transcranial stimulation and neurofeedback experiments in humans provide exciting new avenues to investigate the causal factors underlying IBS. How can these methods be improved? Are there other methods that could serve this purpose?
- Although many EEG studies assume IBS to be an oscillatory phenomenon, this assumption raises multiple questions. Do slower fMRI and fNIRS signals reflect the same oscillatory mechanism as faster EEG and MEG signals do? Are fast IBS oscillations (i.e., above 30 Hz) curtailed by the slower periodicities associated with natural behaviors? How can oscillatory synchronization be maintained for extended periods of time? And does IBS reflect aperiodic brain-to-brain coupling in addition to oscillatory synchrony?
- A hallmark of IBS research is the wide variety of experimental tasks used to investigate it. Does IBS occur for all social activities or for only certain kinds?
- As of this writing, no formal mathematical or computational framework adequately describes the neurocognitive mechanism that produces IBS. What form would such a model take?
- Robots are increasingly used to model social interactions, both with humans and with other robots. Can IBS be instantiated in interacting robots as proof-of-principle?

HIGHLIGHTS

- Interbrain synchrony is a putative neural mechanism said to promote social interactions by enabling the functional integration of multiple brains. Research on this topic has skyrocketed in recent years.
- However, the field lacks a widely-accepted definition of interbrain synchrony.
- Interbrain synchrony wants for theories that can guide the design and interpretation of experiments.
- A plethora of empirical methods permit evidence consistent with the idea to accumulate without providing means to falsify it.
- These problems conspire to undermine the construct validity of the phenomenon. However, steps can be taken to address these issues.



Figure 1 (Key Figure)



Figure 2

