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Inter-brain Synchrony in the Social World: A Family Resemblance Model

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Abstract

Interbrain synchrony (IBS) is a phenomenon that occurs when two or more people interact, and neural activity across their brains synchronize. The variety of scenarios in which IBS is observed suggests that the extent of synchronization, the brain regions involved, and the social contexts in which the interaction occurs are uniquely combined in each instance of IBS. A review of recent literature reveals that IBS has been generally examined based on the particular social contexts in which it is measured, but a conceptual model that cuts across these different contexts is lacking. I believe it is appropriate and necessary to work out a model of IBS that accounts for the subtlety and variability of the various factors related to IBS at the behavioral, neural, and social levels. An effective conceptual model for IBS will allow us to apply and expand our knowledge of the phenomenon to novel situations and provide a deeper understanding of what role IBS plays in human behavior. I propose a *family resemblances*-based model of IBS in which members of a particular category are held together by overlapping subsets of similarities rather than a single common characteristic that all members of a category share. In this review, I discuss how this model can help clarify the variety of commonly reviewed social constructs in which IBS is observed and conclude by identifying areas for future research that would help deepen our understanding of neural and behavioral synchrony.

Introduction

Social interactions involve complex decision-making and mental calculations that are shaped by dynamic, mutual feedback between participants[1]. When two people interact, neural activity can synchronize between multiple brains. *Synchrony* can refer to temporal alignment of individual neurons' firing rates, to overall activity in a given brain region, or network activity increasing or decreasing in a synchronous manner. Interbrain synchrony (IBS) refers to the alignment of neural oscillations occurring across specific frequency bands across the brains of people. [2–4]. The existence of IBS has been proven by experimental methodologies including the use of the electroencephalogram (EEG), magnetoencephalogram (MEG), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and empirical signatures of IBS (including delta, theta, alpha, beta, and gamma EEG frequency bands) [5]. The simultaneous measurement of brain activity using the above methodologies allows for the examination of IBS within a time scale[6–9]. The existence of the phenomenon of IBS has become a foundational mystery in the nascent field of social neuroscience. It is important to distinguish between IBS generated by exposure to a common external stimulus and IBS that is generated concomitant with social interactions. The former has been studied extensively in the context of vision[10], audition[11], and recall of shared stimuli[12]. The present paper focuses on the latter[13,14], and the discussion centers around the aspects of social interaction that are directly related to the observed IBS.

Research on IBS in the past has typically focused on social interaction paradigms that can lack real-world validity[15]. Recently the field has moved in the direction of naturalistic social interaction scenarios. For example, parent-child dyads[16], teacher-student dyads[17] and teammate dyads[18] have been studied and in each case, synchronous neural activity has been observed. The brain region where the IBS occurs[19,20], the intensity of the IBS[21,22], and the extent of cooperation and productivity of the dyad in a particular task[18] were among the aspects of neural synchrony studied. In the context of one person, brain activity can tell us the where, when, and what of the neural underpinnings of cognition and behavior. If this activity is synchronous in multiple brains during an interactive behavior, it acquires a broader significance.

Behavioral synchrony refers to the act of keeping together in time with others during social interactions and group activities such as music making and dance[11,23]. Behavioral synchrony has been researched in the past[24] and some hypotheses for its purpose and relevance have emerged, including its role in mentalizing[23], creative problem solving in teams[18], development of social competence and emotional regulation in children[25], coordination during instrument playing[26], promoting prosocial behavior[27] and theory of mind[28]. One reason why behavioral synchrony is so well-studied compared to neural synchrony is that behavioral synchrony is easier to measure and observe. While neural

synchrony is seen in many of these contexts, the specific relationship between the two is not well understood.

IBS is hypothesized to facilitate social interaction and yet even in real-world interactive domains, the cognitive demands for each situation can be quite different. For example, a one-on-one parent-child interaction may make high demands on attention and emotional processing, whereas in the case of several children, the children's focus might be on sibling competition, rather than attending to the parent. A consensus on the functional significance of neural synchrony requires finding commonalities across these various social scenarios. It is necessary to work out a model of IBS that both accounts for the subtlety and variability at the behavioral level and unifies them in such a way that we can understand the purpose of neural synchrony in the human brain. I expect that this model will span social contexts and potentially group members of different dyads within the same family of behaviors. Such a model will assist in helping us understand the various drivers of IBS in more detail and how IBS facilitates various types of interactions.

Current Models of Interbrain Synchrony

Several models have been put forward to explain IBS. One of note concerns the idea that phase synchronization across brains is potentially the basis of the formation of an extended consciousness[29], and could be responsible for subjective reports of social connectedness, engagement, and cooperativeness, as well as experiences of social cohesion and "self-other" merging. The extended consciousness concept is a controversial one, and is rejected by, among others, the proponents of the Integrated Information Theory[30], one of the leading models of consciousness. The Integrated information theory postulates that the brain functions via direct, anatomical connections, rather than regional phase synchronization.

A model that focuses on IBS as it relates to human attachments and its development across the lifespan has been proposed by Ruth Feldman[31]. In this model, synchronous interactions experienced during early sensitive periods are expressed in later attachments throughout life. IBS, then, is correlated with the intensity of the attachment, facilitated by coordinated oscillations. This synchrony is observed in the alpha and gamma bands during parent-child interaction, while gamma band synchrony specifically in temporal cortex is seen in romantic partners, as well as in the mentalizing network during interactions between strangers. Another attachment-oriented view suggests that IBS is a key factor in allostasis (i.e., the brain as a resource regulator that applies anticipatory predictions to foresee, prioritize, and deliver resources to fulfil survival-related needs), which functions to ensure optimal and efficient pursuit of social goals[32].

An area of ongoing research that is related to the IBS discussion concerns the mirror neuron system (MNS). The MNS system remains an influential concept since the phenomenon was first discovered in 1992[33].

It has recently been suggested that mirror neurons may support social coordination mechanisms, including those that exhibit synchronous activity[34]. There is some evidence[18] that IBS in Superior Temporal Gyrus and Inferior Frontal Gyrus increased during cooperative tasks, and these are key nodes within the mirror neuron system. Future work is needed to determine exactly how mirror neuron mechanisms and synchronous activity may interact to support social cognition.

Significance of Dyads in the Context of IBS

In order to understand the role and utility of neural synchrony, it is important to determine how the various forms of IBS that have been observed and studied are unified, and whether there are clear distinctions between different kinds of IBS at the level of the brain, behavior, or social interaction. That is perhaps the biggest stumbling block that researchers have encountered—the lack of a clear and defining taxonomy of IBS that is directly related to other observable phenomena.

While the location in the brain where IBS occurs is important, a distinction needs to be drawn between synchronous processes that undergird all general-purpose functions (e.g. attention or working memory) and those that undergird task-specific processes. Processes that have to do with the specific task at hand are those that are the most interesting to social neuroscientists because it may be that they play a role in anticipating and predicting another person's behavior as much as they are about guiding an individual's behavior. Understanding the cognitive functions required by different social contexts is essential for a common thread that can help us build a taxonomy of IBS.

Competition and Cooperation Can Provide Conceptual Unity

Student-teacher and teammate dyads are among the most frequently studied contexts in social neuroscience. A detailed examination into competitive versus cooperative teacher-student pairs[16,35] and teammate pair[19,36] show many similarities. Cooperative pairs had greater activity in dlPFC (dorsolateral prefrontal cortex, associated with executive function) and TPJ (temporoparietal junction, associated with theory of mind) whereas competitive pairs did not (see Figure 1). Even though teachers and students compared with child or adult teammates appear to occupy dissimilar social situations, the neural underpinnings of the core modes of interaction (i.e., cooperation and competition) are the same. These commonalities are perhaps the basis for a possible taxonomy, rather than our narrative description of who the people are and what roles they are playing. Depending on whether a parent and child are completing a task individually or together, there can be an enormous difference in IBS. It has been suggested that the style of interaction (e.g. cooperative versus competitive), sex differences, etc. are all factors that can affect synchrony

[16,21,37]. Similarly, teacher-student interactions are characterized by synchrony in PFC, serving mentalizing functions that facilitate teachers and students connecting[38–41]. In fact, expert teachers show greater IBS in PFC compared with novice teachers. In a study of interacting teammates, Mayseless et al. observed that the most successful pairs weren't necessarily the most synchronous[18]. This was because the partners were trying to adapt and cooperate which in turn lowered their potential creative ability (while cooperating, partners had to compromise with regards to creative decisions which regulated their combined creative ability). In these teams that showed greater cooperation the IBS spiked in bilateral dorsolateral PFC and bilateral temporo-parietal junction (TPJ). It was observed that cooperation can evoke strong IBS in right DLPFC and right TPJ between the individuals engaged in tasks demanding creative thinking [42].

Cooperation, in all contexts, relies on similar brain regions[16,35]. Dorsolateral prefrontal cortex is involved in the inference of social status and its regulation[43], and TPJ is involved in understanding people's mental state and for reorienting attention[20]. When cooperation is happening there will be activity in these regions. This further supports the idea of a taxonomy that uses higher-level social functions as the discriminating factor between varieties of IBS.

Common Factors Underly IBS but Situational Complexities Remain

In this review of the different types of dyads used to study IBS, we see similarities in the brain regions that show the most activity during tasks performed as a pair or a group. We note that a spike in activity levels in bilateral dorsolateral PFC and bilateral TPJ occurs for fathers and mothers in parent child dyads[16,35], interacting teammates[18], and teacher-student dyads too[44] (see Figure 1). It is generally accepted that the extent of cooperation is a factor that drives the intensity (strength of the activity in the brain) of the IBS[21,45–48]. However, what is not known is the extent to which other factors such as ingroup versus intergroup dyads[49], sex differences[37], dispositional attitudes[50], and the effect of increasing familiarity with a teammate[18] have on the intensity of IBS[45]. Future work is needed to understand the relationship between these psychological complexities and IBS.

A Family-Resemblances Model for IBS Categorization

The range of similarities and differences between IBS studied in different types of dyads underscores the need for some kind of unifying model to explain the commonalities and differences that are observed. Social context is clearly an influence, and similarities among teammates, familiarity or comfort with parents or teachers, and many other factors

influence the observed IBS, though it is not currently possible to link together the cognitive similarities and behavioral differences.

An alternative to using the social context to categorize IBS is a *family resemblances*-based model. The principle of family resemblance-based categories suggests that members of a category are held together by overlapping subsets of similarities rather than a single common characteristic that all members of a category share. The related concept of graded membership suggests that category members may range from "most prototypical" when they share the most overlap in features with other members to less prototypical where fewer features overlap[51].

This model allows us to examine IBS driven by substantially different social constructs, and that may involve a large number of unique characteristics that may not be shared with other category members. As seen in Table 1, IBS occurs in a wide range of brain regions and social contexts, and while there are commonalities (e.g. cooperation or competition), there is no single unifying through-line.

Using the family resemblance model, dyads can be grouped into two categories: "Low intensity IBS" (shaded) and "High intensity IBS" (Table 1). Note that the dyads that are categorized into the "Low intensity IBS" category do not share the exact same location for synchrony in the brain. It may be that members of the low intensity and high intensity categories of IBS are fundamentally more closely related to other members of their own category than they are to members of the other category. In addition to the intensity level they share in many instances functional specialization and are aligned on where they appear in the cooperative/competitive axis. Pure cooperation in social settings seems to drive higher IBS[21,35,47] while a mix of cooperation and competition seems to drive lower IBS[16,19] across all social contexts.

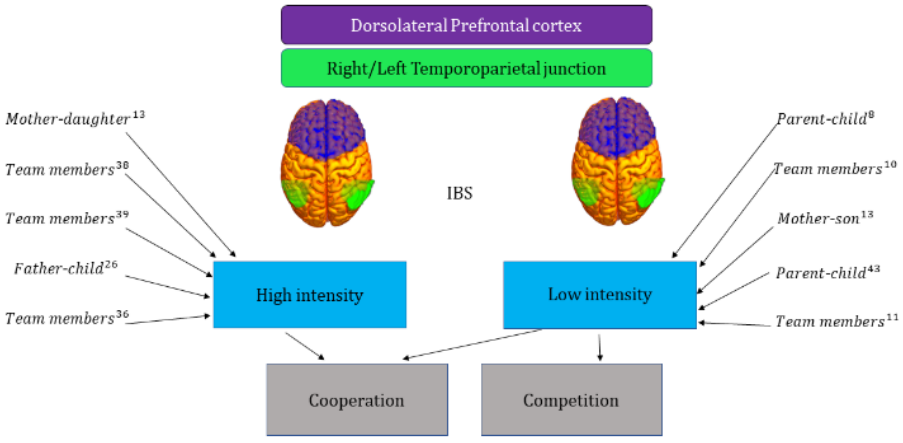

FIGURE 1. Showing papers that describe cases of high and low IBS and the brain regions that are affected.

		Location on the brain where activity is observed				Behavior exhibited by the dyad	
IBS Intensity	Dyads	Right PFC	Right TPJ	Dorso lateral PFC	Left TPJ	Competitive	Cooperative
High	Team members[47]		X				X
	Parent-child[52]			X			X
	Mother-child[21]	X					X
	Father-child[35]			X	X		X
	Team members[48]				X		X
	Team members[45]	X	X	X	X		X
	Team members[46]	X	X		X		X
	Team members [42]		X	X			X
Low*	Parent- child[16]			X	X	X	X
	Team members[18]	X	X		X	X	X
	Mother- son[21]	X		X		X	X
	Parent-child[52]			X		X	
	Team members[19]	X		X		X	X

FIGURE 2. Examination of IBS in different dyads with respect to their behavioral characteristics and area in the brain where activity is observed. *Majority of the Low IBS dyads exhibit competitive behavior with cooperation to an extent.

Conclusion

Much of the current literature on IBS is focused on dyads in specific social contexts. Social context is important insofar as it dictates the cognitive requirements for the participants, but it is not the single defining characteristic of IBS and is perhaps not best suited as a basis for a unifying taxonomy. I examined two opposed factors (competition and cooperation)

that are at play in the variety of social contexts where IBS has been observed. Clearly there are additional factors at play. For example, threat processing has been shown to reduce activity in PFC, perhaps due to more instinctual or reflexive processes 'taking over' for higher cognition[53]. Any cognitive process that necessarily undergirds a behavior is a source for an explanatory theme that cuts across social context. And yet, the demands of each context require that this process will look different in each instance.

The hypothesis of this review is that IBS intensity is an important characteristic of IBS and that it can be used to build a taxonomy based on the intensity of IBS in PFC and TPJ. Cooperation and competition may drive IBS in some regions and attenuate IBS in others, depending on the needs of the task. Importantly, one mode can attenuate another. Competition might reduce IBS in a cooperation-driven interaction, and vice versa. A family resemblances model allows us to group widely varying dyads and social scenarios together, even though the specific behavioral instantiations might be different. Building a taxonomy around intensity of IBS, rather than trying to force a fit between different social contexts, helps to identify the features of IBS that are common to a wide range of different social situations. Even though the underlying processes are not necessarily identical, relaxing the requirements for what counts as a 'similar' process facilitates a loose agglomeration of related cognitive processes that can help clarify what IBS is and what purpose it serves.

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