ISSN 2616-5783 Vol.6, Issue 3: 114-117, DOI: 10.25236/AJHSS.2023.060318

Experimental studies on inter-brain neural synchronization in economic behavior

Lina Lu

School of Economics and Management, Southwest Petroleum University, Chengdu, China

Abstract: *Developments in Neuroeconomics have motivated researchers to explore human cognition and behavior at the cerebral-neural level, and the rise of hyperscanning technology has allowed exploring the human social brain in a more ecologically efficient way. In recent years, experimental studies on hyperscanning of economic behavior have contributed substantial evidence. This paper reviews the literature on inter-brain synchronization and sorts out experimental studies of inter-brain synchronization in different economic behaviors. Finally, this paper draws a conclusion of the research in this area and puts forward an outlook.*

Keywords: *Inter-brain synchronization, Experimental studies, Behavioral economics, Neuroeconomics*

1. Introduction

The study of economic behavior is inseparable from the study of human behavior, which is determined by the brain. Therefore, exploring the generation and formation mechanisms of human cognition and behavior at the neurological level can provide a deeper understanding of individual behavior.The breakthrough and development of Neuroimaging technology at the end of the 20th century inspired many management researchers to explore the causal relationship between the human brain and its decision-making behavior, which promoted the development of interdisciplinary disciplines such as cognitive neuroscience, Neuroeconomics and Neuromanagement.

Due to the complexity of social interactions and technical limitations, early studies of the neural mechanisms of human behavior were mainly conducted at the single-brain level, i.e., single-subject laboratory studies.Although these studies identified a series of key brain regions that constitute the "social brain" hypothesis and provided valuable information on the neural mechanisms of social interaction, single-brain studies are extremely limited because they ignore the fact that social interaction itself is a continuous, real-time dynamic process and the brain states of both interacting parties are constantly adjusted during the interaction.In the last decade, the rapid development and application of hyperscanning technology has met this need. Hyperscanning techniques allow the study of inter-brain neural synchronization between two or more interacting brains and, therefore, provide a more realistic estimation of human social interaction behavior[1-3].

2. Literature review on inter-brain neural synchronization

2.1. Hyperscanning

Hyperscanning is a technique that enables the simultaneous recording of brain activity of two or more interacting subjects (Koike et al., 2015). Montague et al. (2002) first introduced the concept of hyperscanning. They explored the underlying brain mechanisms of deception by using two functional magnetic resonance imaging (fMRI) devices to simultaneously record the brain activity of two subjects engaging in the Deception Game. Since then, a series of hyperscanning studies based on electroencephalography (EEG) (Babiloni et al., 2006), functional near-infrared imaging (fNIRS) (Funane et al., 2011), and magnetoencephalography (MEG) have emerged. The emergence of hyperscanning has bridged the gap in single-brain studies by enabling the simultaneous study of dual or multiple brain activities during interactions, and further revealing the brain mechanisms behind socially interactive behaviors by analyzing the relationship between behavior and inter-brain activity synchrony. Inter-Brains Synchronization (IBS), the most commonly used index in hyperscanning studies, measures the inter-brain neural coupling between interacting players, or the correlation between inter-brain cortical activity over time in a specific time window (Hasson et al., 2012). The stronger the inter-brain synchronization,

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the more the brain activity of the interacting players tend to be identical [4-8].

2.2. Inter-brain synchronization

Inter-brain synchronization, also known as Hyperconnectivity, i.e., functional connectivity between two brains, is a generalization of functional connectivity within a single brain. Functional connectivity is measured by calculating correlations between brain regions (e.g., phase-locked values and partially directed coherence), which can measure the collaboration between brain regions and the functional connectivity between brain regions in the resting or task state. Synchronization refers to the existence of mutual collaboration mechanisms between different brain regions during the performance of a specified task, and brain regions with a higher degree of collaboration may discharge simultaneously. In social interaction, if the brain areas between two interacting subjects have simultaneous discharge, it can be assumed that these two brain areas have collaborative mechanisms during social interaction, i.e., there is inter-brain synchronization.

3. Experimental studies on inter-brain neural synchronization in economic behavior

3.1. Experimental studies on inter-brain neural synchronization based on game model

3.1.1. Trust Game

In order to investigate the inter-brain synchronization of human trust behavior, King-Casas et al. (2005) conducted an fMRI hyperscanning experiment adopting the Trust Game. In this experimental design, a player (the Investor) must determine how much of the endowment to invest in a partner (the Trustee). This portion of the investment is multiplied by specific parameters and then given to the Trustee, who has to determine how much of gains to return to the Investor. They found that the reciprocity exhibited by a player strongly predicted the future trust exhibited by their partner. Tomlin et al. (2006) investigated the effect of social distance on inter-brain synchronization in the Trust Game. They recruited two groups of subjects, one in which the subjects knew each other and the other in which the subjects were strangers to each other. A comparative analysis of the two groups of subjects showed that in the Trust Game, the cingulate gyrus is activated in different ways when individuals make decisions, and there are significant differences in neural activity depending on social distance. Based on Tomlin et al. (2006), Chiu et al. (2008) used a fMRI hyperscanning experiment to investigate the differences in neural activity between patients with Autism Spectrum Disorder (ASD) and normal controls in the Trust Game. The results showed that patients with ASD lacked neural activation patterns in the cingulate cortex, but had normal responses in the cingulate cortex when shown a partner's decisions.

3.1.2. Prisoner's dilemma game

Another paradigm often applied to the investigation of brain decision-making processes is known as the Prisoner's Dilemma (PD). Such a paradigm is similar to the Trust Game, with the difference that both players simultaneously choose whether to trust each other without knowledge of partner's choice. The PD was adopted using EEG hyperscanning by the research group of Babiloni and colleagues (Babiloni et al 2007; Astolfi et al., 2009, 2011; De Vico Fallani et al.,2010). They investigated the brain activity of 52 subjects engaged in the PD game. In repeated PD, each player have two possible choices: betrayal and cooperation. Each player makes his own choice without knowing his partner's choice. The outcome of the game depends on the combination of choices. If both players cooperate, they both win some money; if only one player cooperates, the betrayer gains an advantage; if both players betray, they both lose. Inter-brain synchronization was estimated using EEG hyperscanning data based on Partial Directional Coherence, and the results showed significant inter-brain synchrony in the prefrontal regions of both players in the Cooperative condition compared to the Betrayal condition. Astolfi et al. (2010) employed the PD by recording the neuroelectrical activity of two subjects simultaneously using an EEG-based hyperscanning and found stronger inter-brain synchronization in the cooperative condition[9-13].

3.1.3. Ultimatum Game

Li et al. (2022) recorded the brain activity of interacting subjects who engaged in both the modified ultimatum game and modified the dictator game to explore how the introduction of external punishment affected inter-brain synchronization. The results showed that inter-brain synchronization was significantly greater in the Dictator game than in the Ultimatum game, i.e., the introduction of external punishment significantly reduced inter-brain synchronization. They proposed a hypothesis to explain this phenomenon: the introduction of external punishment crowds out the intrinsic moral motivation of proposer and thus undermines the inter-brain synchronization. Yun et al. (2008, 2010) explored inter-brain synchronization between the proposer and the responder in the Ultimatum game and found that in high frequency bands, brain activity in the fronto-central region increased significantly, as did inter-brain synchronization between the proposer and the responder. Tang et al. (2016) combined a modified Ultimatum game with fNIRS hyperscanning to explore how face-to-face interactions affect inter-brain synchronization. Their results showed that inter-brain synchronization was stronger in the right temporoparietal joint area (rTPJ) in the face-to-face condition[14-19].

3.2. Experimental studies on inter-brain synchronization of Cooperation and Competition

Sinha et al. (2016) investigated the effects of cooperative and competitive interactions on inter-brain synchronization in a table tennis game. The aim of the game is to hit the ball back and forth to beat the opponent by using a vertical stick (competitive condition) or as a team to beat a computer program (cooperative condition). Results showed that the cooperative condition was marked by significantly greater synchronization compared to the competitive. Hsu et al. (2021) explored inter-brain synchronization in single, cooperative and competitive modes during a card game, and they found that inter-brain synchronization was significantly stronger in the cooperative and competitive modes than in the single mode. The inter-brain synchronization increased significantly when subjects switched from the competitive mode to the cooperative mode. Cui et al. (2012) found that the coherence of cortical signals from two brains increased in a cooperative condition compared to a competitive. Yang et al. (2020) investigated the relationship between within-group synchronization and inter-group conflict in a three-person versus three-person inter-group competition by controlling for in-group bounding. They found that in-group bounding significantly increased within-group synchronization between the right dorsolateral prefrontal cortex (rDLPFC) and the right temporoparietal joint area (rTPJ).

4. Conclusion

This paper begins with an introduction to the interdisciplinary disciplines of Cognitive Neuroscience, Neuroeconomics, and Neuromanagement, describing methods used to measure two or more brain activities simultaneously to measure inter-brain synchronization. In addition, this paper discusses experimental studies of inter-brain synchronization in economic behavior. The most popular game models used in recent experimental studies of inter-brain synchronization involve the Trust Game, the Dictator Game, and the Ultimatum Game. Inter-brain synchronization in cooperative and competitive behavior is also discussed [20-23].

All these experimental results are in accordance with the call for a more ecologically valid approach to study the social brain (Hari and Kujala, 2009; Hari et al., 2013). This appeal has emerged in the last decade, and it suggests that we require more interaction paradigms and neuroimaging data from more than one brain to understand the human brain and its social nature comprehensively. These results all suggest that human decision-making behavior generates inter-brain synchronization and that different types of interactions can affect inter-brain synchronization in different ways. However, as hyperscanning is an emerging technology, more research is necessary to understand the neural interactive mechanisms of human economic behavior.

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