

Research on Inter-brain Synchronization in Dyadic Risk Decision-Making

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Abstract: This study aims to explore the relationship between inter-brain synchronization and decision-making behavior during dyadic risky decision-making, so as to provide theoretical support for the systematic research on the neural mechanism of dyadic risky decision-making and enrich the research system of interpersonal interactive decision-making in the field of social cognitive neuroscience. Based on brain-to-brain coupling, this study adopts hyperscanning technique with functional magnetic resonance imaging, electroencephalography, functional near-infrared spectroscopy and other devices to simultaneously record the interaction and brain activities of two subjects in the scenario of dyadic interactive risky decision-making, and collect and analyze the brain signals during the decision-making process. The results clarify the correlation between inter-brain synchronization and decision-making behavior in dyadic risky decision-making, which provides theoretical support for relevant research and enriches the research system of interpersonal interactive decision-making. The innovation of this paper lies in that it investigates dyadic risky decision-making from the perspective of inter-brain synchronization using hyperscanning technique, which provides a new perspective for understanding the cognitive mechanism in such decision-making process and fills part of the gaps in empirical research on the neural mechanism of interpersonal interactive decision-making in the field of social cognitive neuroscience.

1. Introduction

In modern society, research on risk-based decision-making has garnered increasing attention. Risk-based decision-making refers to choices made under incomplete information where the probabilities of outcomes from various alternatives are known, but the process and results remain uncertain [1,2]. Decision quality plays a critical role in the development of individuals and groups. As environments become increasingly complex, traditional single-person decision-making models exhibit the following drawbacks: First, individuals are prone to being constrained by their own thinking during information processing, increasing decision-making risks [3]; Second, complex tasks (such as handling medical emergencies) require integration of knowledge from multiple

domains, where multi-person decision-making demonstrates greater advantages. Studies show that in dynamic uncertainty tasks, the error rate of single-person decision-making is 18%-25% higher than that of two-person decision-making, highlighting the importance of collaborative decision-making [4]. Two-person risk-based decision-making involves interactive choices made by two individuals in the face of uncertainty, presenting a complex and dynamic psychological process [5]. Interbrain synchronization refers to the phenomenon of coordinated brain activity patterns between two individuals during collaboration [6,7]. Researchers have found that when participants engage in eye contact during cooperative tasks, interbrain synchronization in the prefrontal cortex and temporoparietal junction significantly increases, and this synchronization shows a positive correlation with task performance. Research on two-person risk-based decision-making not only holds theoretical significance but also has broad practical applications. In medical decision-making, communication between physicians and patients often involves complex emotional and cognitive interactions. A study found that the doctor-patient shared decision-making model can significantly improve patient satisfaction, and the effectiveness of this model partially depends on the synchronization between the brains of both parties [8]. In the field of education, brain synchronization in teacher-student interactions is also considered an important predictor of learning outcomes [9]. In the field of autonomous driving, in two-way decision-making models (such as collaborative decision-making between drivers and autonomous driving systems) [10], vehicles need to predict the actions of other vehicles and make corresponding adjustments to avoid collisions or optimize driving paths, thereby enhancing system safety and reliability. These studies indicate that brain synchronization not only plays a critical role in two-person risk decision-making but also holds potential application value in multiple fields. Two-person risk decision-making has extensive real-world application scenarios, and research on brain synchronization provides a new perspective for understanding this complex process. In-depth studies on brain synchronization can not only reveal the neural mechanisms of two-person decision-making but also provide scientific evidence for optimizing decision-making processes. Therefore, a systematic review of brain synchronization research in two-person risk decision-making holds significant theoretical and practical implications.

2. Research on Dual-Risk Decision-Making

2.1. Two-person risk decision-making

Two-person risk decision-making refers to the process where two individuals jointly make decisions through interaction when facing uncertain outcomes [5,11]. This decision-making form is widely prevalent in both daily life and professional domains, such as investment decisions in business collaborations and treatment plan selection in medical teams. Compared to single-person decision-making, two-person risk decision-making exhibits significant interactivity and strategic characteristics.

2.2. Theoretical Models and Research Paradigms

The theoretical framework of two-person risk decision-making provides a crucial perspective for understanding individual behavior in uncertain environments. Among these theories, Prospect Theory [12] stands out as one of the most seminal, developed by Kahneman and Tversky. It highlights irrational behaviors in risk-taking, such as loss aversion and framing effects. This theory also applies to two-person decision-making scenarios, particularly in situations where cooperation and competition coexist, where an individual's risk preference may shift in response to the other party's decision.

In practical research, the neural mechanisms underlying two-person risk decision-making can be

explored through various task paradigms. The Balloon Analogue Risk Task (BART) [13], a widely used risk decision-making task, effectively evaluates individuals' decision-making behaviors under different risk scenarios. Studies have found that in cooperative two-person conditions, participants' risk decision-making behaviors in BART tasks show significant differences compared to solo decision-making, particularly when a companion is present and exhibits risk preference, leading to a marked increase in individual risk decision tendencies. Further functional near-infrared spectroscopy (fNIRS) research indicates that this behavioral change is closely associated with enhanced inter-brain synchronization in the prefrontal cortex.

2.3. Early Behavioral Studies

The core of two-person risk decision-making research focuses on examining the decision-making processes and outcomes of two individuals in risk scenarios [1]. Early studies primarily concentrated on behavioral aspects, analyzing factors influencing decisions such as risk preference, information sharing, and communication methods. In zero-sum games, participants demonstrated significantly lower brain synchronization compared to cooperative tasks, indicating that individuals tend to make independent decisions rather than rely on each other's information in competitive situations [14]. Additionally, research shows that decision-making behaviors are often influenced by the presence of peers, particularly when peers exhibit high risk preferences, leading to a significant increase in an individual's risk-taking tendencies [15]. While such behavioral studies provide a foundation for understanding two-person risk decision-making, they fail to reveal the underlying neural mechanisms.

2.4. Research Based on Neuroscience Technology

The introduction of functional near-infrared spectroscopy (fNIRS) technology has enabled researchers to monitor brain activity in real time without interfering with subjects' natural interactions. A fNIRS-based hyper-scan study found that during a two-person collaborative decision-making task, the synchronization between the prefrontal cortex (PFC) and the temporal-parietal junction (TPJ) was significantly enhanced, and this synchronization was positively correlated with the accuracy of decision outcomes [16]. This finding indicates that the brain's role in two-person risk decision-making is not limited to individual independent decision-making but involves information integration and coordination through interbrain synchronization.

2.5. Research Results

Neuroscientific research demonstrates that the neural mechanisms underlying two-person risk decision-making are influenced by both individual characteristics and situational factors. Gender differences exhibit significant effects in this context. Studies reveal that women are more susceptible to peer influence when making risk-related decisions, particularly when their peers demonstrate high risk preferences, leading to a marked increase in women's risk-taking tendencies. This gender disparity may be associated with distinct activation patterns in the brain's reward system and social cognitive networks. Notably, women exhibit significantly higher inter-brain synchronization in the prefrontal cortex and temporoparietal junction during two-person risk decision-making compared to men, with this synchronization positively correlated to decision accuracy [17]. Furthermore, research indicates that in collaborative decision-making tasks involving two individuals, inter-brain synchronization in these brain regions is notably enhanced, and this synchronization also shows a positive correlation with decision accuracy [18].

When investigating the neural mechanisms of two-person risk decision-making, researchers frequently employ fNIRS as a tool for studying interbrain synchronization. This technology enables non-invasive monitoring of neural activity by measuring changes in cerebral hemoglobin oxygenation, allowing for the simultaneous acquisition of brain signals from multiple subjects during interactive processes and precise capture of dynamic changes in interbrain functional connectivity. For instance, in his study, Li Xianchun utilized fNIRS-based super-scan technology to have female participants complete three rounds of cooperative button-pressing tasks in sequence, recording their brain activity to explore cooperative behavior under acute physical pain. The findings revealed that participants in the pain group exhibited enhanced interbrain synchronization between the left frontal lobe and right parietal lobe across different rounds of cooperative tasks, with the changes in right parietal lobe interbrain synchronization showing a positive correlation with the subjective pain scores of the pain treatment group [19].

3. Research on Interbrain Synchronization

3.1. Concept and Measurement Techniques of Interbrain Synchronization

Interbrain synchronization refers to the temporal and phase consistency of neural activity between specific brain regions or networks during certain tasks. This phenomenon is widely recognized as a key indicator for studying interpersonal interactions, reflecting the degree of cognitive and behavioral coordination between individuals. In recent years, research on interbrain synchronization has become a focal point in neuroscience and social psychology, particularly in areas such as social cognition, cooperative behavior, and emotional communication, offering new perspectives for understanding human interactions.

In the study of brain synchrony, functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and electroencephalography (EEG) are three widely used brain imaging techniques, as shown in Table 1 [7,20]. fMRI can provide high-resolution maps of brain activity, but fMRI hyper-scan technology cannot offer the real environment required for social interaction. Due to factors such as the need for subjects to remain still, noise-induced discomfort, and high purchase costs, the use of fMRI hyper-scan technology in research is relatively limited. EEG offers high flexibility and simplicity, with relatively low equipment costs, but the instability of local networks (especially wireless or Bluetooth) can affect experimental data. fNIRS reflects neural activity by measuring changes in the oxygenation state of cerebral cortex hemoglobin, based on the scattering and absorption characteristics of near-infrared light in tissues. This technology has high spatiotemporal resolution, enables long-term monitoring in natural conditions, and is less sensitive to motion artifacts, making it particularly suitable for experimental scenarios requiring real-time interaction, such as two-person cooperative tasks [21]. Therefore, fNIRS hyper-scan technology has gradually become a widely adopted emerging technology in social cognitive neuroscience research involving interpersonal interaction. In 2021, researchers reported that the average annual publication volume in the fNIRS field over the past decade was approximately 192 articles, with China ranking third in terms of annual publications in the fNIRS field, showing a stable growth trend overall [22].

Table 1 Comparison of Super-Scan Techniques

technology	spatial resolution	time resolution	applicable scene	boundedness
fMRI	~1 mm ³	~2 s	Static tasks, deep brain region studies	High cost, noise interference, and low ecological validity
EEG	~5 cm ²	<1 ms	neural oscillations, rapid temporal dynamics	Susceptible to motion/environmental noise interference
fNIRS	~1 cm ³	~0.1 Hz	natural interaction, long-term monitoring	Detection of deep brain regions (such as the amygdala) is limited.

3.2. Interbrain Synchronization and Social Cognition and Cooperative Behavior

In the field of social cognition, interbrain synchronization is considered a key indicator of cognitive coordination between individuals. Research has found that women who have experienced social exclusion together exhibit higher interbrain synchronization during cooperative tasks, particularly in the prefrontal cortex and temporoparietal junction [17]. This finding suggests that social exclusion scenarios can enhance cognitive coordination between individuals, thereby promoting cooperative behavior. Studies have demonstrated that interbrain synchronization is closely related to responsibility and reward distribution in cooperative tasks, supporting its significant role in social cooperation [16]. Research on cooperative behavior has revealed that participants' interbrain synchronization in the prefrontal cortex and parietal cortex significantly increases when completing tasks in cooperative contexts, while it shows lower synchronization in competitive scenarios. These results indicate that interbrain synchronization not only reflects the degree of coordination in cooperative behavior but may also be closely associated with emotional interactions and responsibility allocation in tasks [23]. Additionally, studies have found that factors such as intimate relationships, gender differences, and empathy traits can influence interbrain synchronization, further revealing the complexity of interbrain synchronization across different social interactions. A comparison of interbrain synchronization is presented in Table 2.

Table 2 Comparison of Inter-Regional Synchronization in Different Brain Areas

encephalic region	decision situation	synchronism	correlation analysis	remarks
Prefrontal (PFC)	cortex two person risk decision	Significant enhancement in synchronization	Significantly correlated with decision outcomes, demonstrating stronger predictive power	The synchronization is enhanced under the conditions of cooperation and competition, and it is positively correlated with the consistency of decision-making and the level of cooperation.
Prefrontal (PFC)	cortex cooperative decision	Female synchronicity is significantly higher than that of males.	Significant gender differences	Women exhibit higher prefrontal cortex (PFC) synchronization than men in cooperative decision-making, whereas the opposite pattern is observed in competitive decision-making.
Prefrontal (PFC)	cortex anxiety decision	Significant reduction in synchronization	closely related to emotional states	Increased anxiety levels are associated with reduced prefrontal cortex (PFC) synchronization and enhanced temporal-parietal junction (TPJ) synchronization.
temporoparietal junction (TPJ)	decision making under uncertainty	Significant enhancement in synchronization	closely related to decision accuracy	Synchrony in intimate relationships is significantly higher than that in general social relationships, reflecting social cognitive coordination.
temporoparietal junction (TPJ)	low risk decision	Synchronization is more prominent	related to social cognitive coordination	Low-risk tasks demonstrate prominent synchronicity, involving social cognitive coordination
Anterior cingulate cortex (ACC)	high-risk decision	Significant enhancement in synchronization	associated with high-risk decision control	Enhanced synchronization in high-risk tasks and participation in decision-making control

4. Application of 4 fNIRS Super-Scan in Two-Person Risk Decision Making

4.1. Advantages and Research Progress of fNIRS Super-Scanning in Bivariate Risk Decision

The fNIRS super-scan technology demonstrates significant advantages in the field of two-person risk decision-making research due to its unique technical characteristics, achieving a series of important research outcomes. Technically, the fNIRS super-scan possesses high spatiotemporal resolution, enabling real-time tracking of the concentration changes of oxygenated hemoglobin and deoxygenated hemoglobin in the cerebral cortex, accurately capturing the instantaneous dynamics of neural activity during two-person risk decision-making processes. Its non-invasiveness and portability greatly enhance the ecological validity of experiments, as subjects are not restricted to enclosed or confined spaces and can participate in experiments in a more natural and relaxed state, making the research results more reflective of real-life scenarios. Additionally, the technology's high tolerance for motion artifacts allows subjects to engage in moderate body language and interaction during decision-making, ensuring the integrity and validity of data acquisition [6].

At the research level, fNIRS hyper-scan technology has revealed neural coupling mechanisms in two-person risk decision-making. By synchronously monitoring blood oxygen changes in brain regions such as the prefrontal cortex and temporoparietal junction (TPJ) in both participants, researchers found that in cooperative scenarios, neural activity in the right TPJ exhibited significantly enhanced synchronization, which was positively correlated with the speed and success rate of consensus reaching [24]. In competitive scenarios, differences in activation of the dorsolateral prefrontal cortex became a key predictor of decision conflict intensity [25]. For instance, Li Xianchun et al. employed a "suggestion game" task, manipulating reward-punishment contexts (incentive/non-incentive conditions) to induce a shift in the confidant's confidence expression strategy. The study demonstrated that interpersonal neural synchronization (INS) in the TPJ supports influence management [26]. In the field of education, fNIRS hyper-scan has been used to observe neural synchronization during teacher-student interactions, providing a neuroscientific basis for optimizing teaching strategies [27-29].

4.2. Experimental Paradigm

In the study of neural mechanisms underlying two-person risk decision-making, researchers integrated computational psychiatry paradigms with population neurodynamics approaches, employing fNIRS ultra-scan technology to achieve precise decoding of neural cluster activity during social interactions. This provides critical evidence for elucidating the neural coding principles of decision collaboration. The experimental paradigms are illustrated in Table 3.

In the neural mechanism study of the Balloon Adventure Task (BART), researchers discovered through time-varying Dynamic Causal Modeling (TDCM) that the prefrontal cortex (PFC), as the core hub of the executive control network, exhibits significant phase-locking phenomena between the power spectral density changes of the gamma band (30-100 Hz) and the risk prediction error signal. This finding suggests that the PFC may encode and transmit risk-related information through gamma band neural oscillations during risk decision-making [13]. The researchers found that in the friend group, the θ - γ cross-frequency coupling intensity in the left inferior frontal gyrus (l-IFG) was significantly negatively correlated with uncertainty avoidance behavior, indicating that higher θ - γ coupling intensity correlates with reduced risk avoidance behavior in the face of uncertainty [15]. This phenomenon may achieve trans-regional transmission of risk signals through functional connectivity reconfiguration in the prefrontal-lobal system, reflecting the neural computational mechanism of social relationship regulation in decision bias.

In the prisoner's dilemma task, fNIRS hyper-scan data demonstrated significantly higher

inter-brain synchronization under cooperative conditions compared to competitive conditions [30]. Granger causality analysis revealed that negative feedback induces significant alterations in the phase-amplitude coupling pattern of delta- θ oscillations in the anterior cingulate cortex (ACC) [31]. This neural oscillatory reorganization may facilitate the neural computational processes of decision conflict monitoring and behavioral strategy adjustment through dynamic interactions between the default mode network (DMN) and the salience network.

In the Stroop task, fNIRS hyper-scan data revealed significantly higher prefrontal oxygenated hemoglobin (ΔHbO_2) levels under conflict conditions (inconsistent stimuli) compared to non-conflict conditions (consistent stimuli), indicating enhanced metabolic activity in the prefrontal cortex during conflict task execution [32].

Table 3 Paradigm of fNIRS Super-Scan Technology in Risk Decision Research

experimental paradigm	core neural network	neurodecoding findings	Theoretical contribution
Simulated Balloon Adventure Mission (BART)	frontoparietal executive control network (FPN)	The theta- γ cross-frequency coupling strength in the left inferior frontal gyrus (l-IFG) was negatively correlated with risk prediction error signals; the friend group exhibited significant prefrontal-limbic functional connectivity reorganization under positive feedback conditions.	Revealing the Neural Collaborative Processing Mechanism of Risk Decision
prisoner's dilemma	social cognitive neural network (SCN)	The brain inter-synchronization was significantly higher under the condition of cooperation compared to the competition condition; negative feedback induced changes in the δ - θ phase amplitude coupling pattern of the anterior cingulate cortex (ACC).	Conflict Adaptation Model Based on Game Theory
Stroop assignment	The frontoparietal executive control network (DLPFC, inferior frontal gyrus)	In the Stroop task, changes in the concentration of oxygenated hemoglobin (HbO) in the dorsal lateral prefrontal cortex (DLPFC), inferior frontal gyrus (IFG), and temporal-parietal region (TP) were associated with inhibitory control ability.	reveals the neural basis of different types of inhibitory control

4.3. Data Analysis Methods

In the analysis of data obtained from fNIRS hyperscan technology, researchers employed multiple mainstream algorithms, each based on its unique mathematical principles and analytical logic, demonstrating their respective advantages and limitations under different research questions and data characteristics, as shown in Table 4.

Table 4 fNIRS Super-Scan Data Analysis Method

computational neuroscience approach	neural decoding scenario	algorithmic characteristic	methodology	technical implementation platform
wavelet transform coherence (WTC)	Time-frequency domain joint analysis of blood oxygen signal	Joint time-frequency domain analysis based on Morlet wavelet basis functions; supports multi-scale decomposition of non-stationary signals; enables precise coherence quantization in the 0.01-0.5Hz frequency band	Phase information loss restricts cross-band coupling analysis; the wavelet entropy stability assumption ($H > 0.5$) must be satisfied.	MATLAB Wavelet Toolbox
Granger causality analysis (GCA)	Modeling of trans-cortical directional information flow	A causal inference framework based on vector autoregression (VAR) models; supports partial directed coherence (PDC) computation; enables the construction of dynamic causal network topologies	The time series must satisfy stationarity (ADF test $p < 0.05$); it is susceptible to multicollinearity in high-dimensional data.	NIRS-SPM v5.0
network analysis of graph theory	Topological Modeling of Group Neural Dynamics	Modular analysis based on complex network theory; computable small-world properties ($\sigma > 1$); supports dynamic community detection in multi-layer networks	Threshold selection of network edge weights depends on empirical criteria; high-dimensional matrix factorization is NP-hard	Brain Connectivity Toolbox

The Wavelet Transform Coherence (WTC) method [33] employs Morlet wavelet basis functions

to perform joint analysis in both time and frequency domains, with its mathematical expression as follows: $\psi(t) = \pi^{-\frac{1}{4}} e^{i\omega_0 t} e^{-\frac{t^2}{2}}$

Where ω_0 is the dimensionless central frequency parameter (typically set to 6).

The wavelet transform coherence method leverages the temporal and frequency localization properties of wavelet functions to perform multi-scale analysis on fNIRS signals. This approach captures signal variation characteristics across different time scales and frequency ranges, enabling precise quantification of coupling conditions in specific frequency bands. However, the method focuses solely on signal amplitude synchronization while neglecting the potential role of phase information in brain neural activity, which may result in the omission of critical neural data.

Granger Causality Analysis (GCA) [34] is constructed based on the Vector Autoregression (VAR(p)) model:

$$\mathbf{X}(t) = \sum_{k=1}^p \mathbf{A}_k \mathbf{X}(t-k) + \boldsymbol{\varepsilon}(t)$$

Here, \mathbf{A}_k denotes the coefficient matrix, and $\boldsymbol{\varepsilon}(t)$ represents white noise. The causal direction is determined by comparing the ratio of residual variances between the full model and the restricted model (F-statistic). In fNIRS super-scan applications, preprocessing is required, including:

Signal to Trend (Polynomial Fit)

Stability test (ADF unit root test)

Model order selection (AIC criterion).

Recent research proposes partial directed coherence (PDC) as an enhancement to traditional GCA, defined as:

$$|\pi_{ij}(f)| = \frac{|\mathbf{A}_{ij}(f)|}{\sqrt{\sum_{k=1}^m |\mathbf{A}_{ik}(f)|^2}}$$

It can effectively reduce the false causality caused by volume conduction effect.

Granger causality analysis, grounded in time series prediction principles, determines causal relationships between variables by evaluating how adding historical data of one variable enhances the predictive accuracy of another. In functional neuroimaging (fNIRS) super-scan data analysis, this method effectively reveals information flows between different brain regions, providing a powerful tool for studying directional brain connectivity. However, its practical application is limited by the requirement of time series stationarity and high temporal resolution data.

Graph network analysis employs the theoretical framework of complex networks, with key parameters [35] including:

Path length (L): Reflects the global efficiency of the network

Clustering coefficient (C): A measure of local information integration capability

Modular Index (Q): Quantifying the Structure of Functional Communities

Network construction is typically based on Pearson correlation coefficient matrices, generating binary/weighted networks through either the proportion threshold method (retaining the top 20% edges) or the density threshold method. Recent methodological advancements propose multi-layer network models capable of simultaneously analyzing time-varying functional connectivity and cross-band coupling, with the mathematical expression as follows:

$$G_t = (V, \mathcal{E}_t), \quad t = 1, 2, \dots$$

Each temporal layer network G_t consists of a node set $\mathcal{E}_t V$ and a time-varying edge set. While this approach captures the time-varying characteristics of neural dynamics, it faces challenges of

high computational complexity ($O(n^2)$) and multiple comparison correction.

Graph network analysis treats the brain as a complex network system. By constructing hyper-brain network models, it analyzes the network's topological structure and functional characteristics [36]. This method enables comprehensive understanding of neural activity patterns during group decision-making, revealing key features such as the small-world property and modular structure of brain networks. However, its computational process is complex, requiring substantial computing resources and specialized analytical software. Additionally, the subjective nature of network construction and metric selection may compromise the accuracy and reliability of the analysis results.

5. Discussion

Although research on interbrain synchronization in two-person risk decision-making has made some progress, it still faces numerous limitations. In terms of scope, most current studies primarily focus on the prefrontal and temporal-parietal regions, with limited exploration of the role of other brain regions in two-person risk decision-making, making it difficult to fully reveal the overall collaborative mechanisms of the brain. Technically, existing brain imaging techniques have shortcomings in spatial resolution, temporal resolution, and the ability to detect deep brain regions. fNIRS performs poorly in detecting deep brain activity, EEG is susceptible to environmental interference, and fMRI faces issues such as unrealistic experimental environments. Methodologically, existing interbrain synchronization analysis methods, such as coherence analysis and Granger causality analysis, are constrained by their assumptions and computational complexity, limiting their application in complex decision-making scenarios. Additionally, insufficient sample representativeness remains a significant challenge in current research. Many studies are often limited to specific age groups, genders, or cultural backgrounds, leading to questions about the generalizability of the findings.

Therefore, future research could focus on the following aspects: (1) Expanding the scope of studies on brain region synchronization to explore the role of whole-brain coordination in risk decision-making; (2) Increasing sample diversity by including participants from different age groups, disease states, and socio-cultural backgrounds; (3) Standardizing the operational definition of risk scenarios to enhance the comparability of research findings; (4) Integrating multimodal neuroimaging techniques (e.g., combined use of fNIRS and EEG) or deep learning-based approaches to provide new perspectives for elucidating the dynamic mechanisms of inter-brain synchronization.

Research on brain synchronization in two-person risk decision-making provides a groundbreaking perspective for understanding the neural basis of social interactions. Through technological innovation and interdisciplinary collaboration, future studies may reveal whole-brain coordination mechanisms and promote their practical applications in real-world scenarios. Advances in this field will not only deepen our understanding of the essence of human cooperation but also potentially provide scientific foundations for building efficient collaborative social systems.

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