Brain Neural Activity and Connectivity Revealed by fMRI Study

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***Abstract*—Social interactions play a pivotal role in human life, and unraveling the neural underpinnings of these interactions presents a challenging yet crucial task. The fMRI method serves as a valuable tool for estimating brain networks and synchronization in this context. This project leverages two datasets, focusing on social relationships derived from "Collaborations and deceptions in strategic interactions revealed by hyperscanning fMRI" and "Consensus-seeking and conflict-resolving—an fMRI study on college couples' shopping interaction," both of which involve event-related experiments. Through the analysis of open-source datasets, the project unveils a clear modulation of a significant other's preferences onto one's decision-making process. The contrast between various parameters underscores the influence of a significant other's preferences on individual decisions. Both datasets reveal bilateral activation in the temporal parietal junction (TPJ), among other reward-related regions, likely indicating mentalizing during preference harmony. Furthermore, these decisions uncover the involvement of the left lateral intraparietal sulcus (l-IPL), along with the left TPJ, forming a localized social decision network. This network is further constrained by mediation analysis among the left TPJ, l-IPL, and anterior intraparietal sulcus (aIPL). A notable fMRI finding involves negative correlations between the connectivity of the right temporo-parietal junction (rTPJ), associated with theory of mind function, and regions such as the amygdala, parahippocampal gyrus, and rostral anterior cingulate (rACC). These correlations are linked to the lying rates exhibited by senders in behavioral contexts, shedding light on the intricate dynamics of social decision-making.**

***Index Terms*—fMRI, hyper scanning, theory of mind, congruent and incongruent, Psycho-Physiological Interaction, Region-Of-Interests, brain networks**

I. Introduction

A. Background

The significance of social interaction in shaping the development and maintenance of the human self has been emphasized since Greek philosophy and remains a topic of ongoing discussion. However, cognitive neuroscience has only recently begun to explore brain activity during social interaction in the past few decades. Traditionally, studies recorded the brain activity of only one participant at a time, limiting insights into dyadic or group interactions. When engaging in group economic decisions, individuals often employ theory-of-mind (TOM) to understand others' perspectives and simulate other-oriented decisions. Behavioral research highlights the substantial influence of social, cognitive, and emotional factors, as well as peer feedback, on consumer purchase decisions. Neuroscientists have identified the neural substrates of TOM, including the bilateral temporal parietal junction (TPJ), posterior superior temporal sulcus (pSTS), and medial prefrontal cortex (mPFC), as core components. However, the specific roles and functional interactions of these brain regions in everyday cognition, especially in the context of romantic relationships, have been less explored. To address this gap, our event-related fMRI study delves into the neural substrates and functional interactions of romantic college couples in an interactive shopping task. Participants provided preference ratings for presented products, and their preferences were revealed to each other, allowing for the modulation of significant others' evaluations before making individual shopping decisions. The experimental design included scenarios such as 'shopping together' versus 'shopping alone' and 'preference (in)congruence' reflecting differences in couples' item ratings. In preference incongruent scenarios, participants had the option to change their decisions based on their significant other's evaluation or insist on their own preference. Brain areas such as the mPFC, TPJ, dorsal anterior cingulate cortex (dACC), nucleus accumbens (NAcc), and insular cortex were expected to be activated under various parametric settings, building on existing neuroimaging literature on empathic choices, conformity, and moral concerns. While our study is the first to implement real-life interactions between college couples' shopping behaviors using fMRI, we anticipate that the findings, analyzed through general linear models, parametric modulation, functional connectivity, and confirmatory effective connectivity, will align with earlier results related to self/other evaluations, conflict resolution, and consensus reaching. To examine social interactions comprehensively, we introduce the concept of hyperscanning, which involves measuring the activity of multiple brains simultaneously. This technique allows for the investigation of real-time dynamics between interacting brains, offering a new approach to address the complexity of joint action, including its spontaneity, reciprocity, and multimodality—a challenge for neuroscientific examination using traditional methods.

B. Dataset of Consensus-seeking and conflict-resolving —an fMRI study on college couples' shopping interaction

1) Participants: Thirty healthy adults (16 males; mean age=22.7±2.57 yrs, out of the 22 participating couples), who were recruited via online ads and snowball sampling methods, joined the fMRI experiment taking place at the Mind Research and Imaging (MRI) Center, National Cheng Kung University (NCKU). Eligible couples were to be in a romantic relationship for at least a year, with normal or corrected-to-normal vision, and no known neurological disorders. All participants provided written informed consent prior to the study. All methods and procedures were approved by NCKU

Governance Framework for Human Research Ethics (number 104-206).

2) Task: In this event-related fMRI study, two types of shopping contexts were designed to examine how significant others' preferences affect one's own shopping decisions. As shown in Fig. 1.a, shopping 'alone' trials were indicated by the two inward-pointing, whereas shopping 'together' trials outward-pointing, arrows alongside the fixation cross at the beginning of each trial, and both conditions were with 100arrows (1s), one stimulus was presented with the price underneath on the screen of the two connected-PCs, with evaluation time up to 6s or until one's own response, whichever came first. Participants were required to give preference ratings from 1 (dislike most) to 4 (like most) during these 6s period. Then the two screens would show either one own's rating (always on the left, alone trials), or own-plus-other rankings (on both sides, together trials), together with the stimulus, for a jittered interval (3-6s, or the so-called 'modulation period'), during which the two evaluations will be transmitted, and presented (for together trials) or kept identical (for alone trials, no modulation here). Subsequently, both a 'checked' and a 'X' mark would appear in the lowest part of the screen, cueing the beginning for response period (up to 6s). Each participant's responses would be recorded and displayed independently by a 'purchased' or 'not-purchased' sign, and would last until the 6s period was up (and followed by fixation cross for variable inter-trial intervals, or ITIs). The trial condition orders and ITIs were determined by optseq2 (https://surfer.nmr.mgh.harvard.edu/optseq/).

3) fMRI acquisition: The imaging data were obtained using a 3T General Electric 750 MRI scanner (GE Medical Systems, Waukesha, WI) at the NCKU MRI center, utilizing a standard 8-channel head coil. Whole-brain functional scans were conducted with a T2*-weighted EPI sequence (TR=2 s, TE=35 ms, flip angle = 76 degrees, 40 axial slices, voxel size = 3 x 3 x 3 mm³). High-resolution structural scans were acquired using a T1-weighted spoiled grass (SPGR) sequence (TR=7.5s, TE=7.7ms, 166 sagittal slices, voxel size = 1 x 1 x 1 mm³). For data preprocessing and analysis, BrainVoyagerQX v. 2.6 (Brain Innovation, Maastricht, The Netherlands) and NeuroElf v1.1 (http://neuroelf.net) were employed.

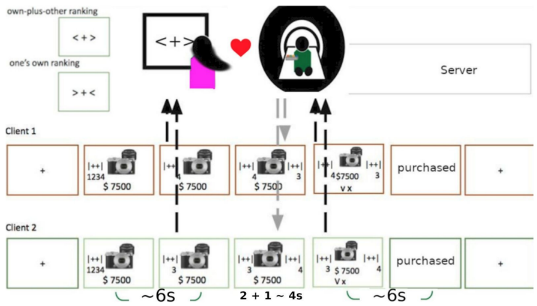
4) fMRI data analysis: General linear model (GLM) and the specific contrasts of interest were applied to identify associated brain regions under various conditions. Together trials were defined by combining the modulation (upon the presentation of both preferences) and subsequent decision time, and the same summation was applied also to the alone trials ('no modulation' + 'decision' times). The "together vs. alone" condition was intending to show the main effect of social 'interaction', therefore the typical theory-of-mind/TOM regions, such as bilateral TPJ, was expected

C. Dataset of Collaborations and deceptions in strategic interactions revealed by hyperscanning fMRI

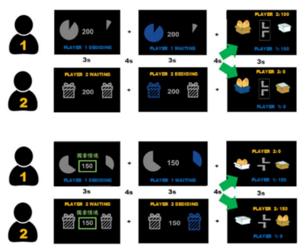
1) Participants: Sixty-six (33 pairs) participants, between 20 and 30 years of age (M=23.4, SD=2.9), participated in the study. They were recruited from National Taiwan University (NTU), Taipei, and National Cheng Kung University (NCKU), Tainan. All participants were native Taiwanese speakers, who had normal or corrected-to-normal vision, and reported no history of psychiatric or neurological disorders. All methods and procedures were performed following the relevant guidelines and regulations approved by the NCKU Governance Framework for Human Research Ethics https://rec.chass.ncku.edu.tw/en, with the case number 106-254. After the fMRI experiment, each participant received 600 $NTD, plus the bonus calculated by the sum of won money divided by 112 (total trial number), around 300 $NTD.

2) Experimental task: In this study, the opening-treasure-chest (OTC) game was conducted within the context of hyperscanning fMRI(Fig. 1.b) . Participants were informed that they would engage with a real partner from another school to jointly play the OTC game, featuring both cooperative and competitive conditions. In each trial, two treasure chests were presented on the screen, with only one containing money while the other remained empty. Participants were tasked with guessing the correct treasure chest to win the reward. When taking on the sender's role, individuals were privy to the probabilities of money being in the left and right chests. Their responsibility was to suggest which chest the receiver should choose. Upon receiving the sender's suggestion, the receiver made the final decision on which chest to open. In the cooperation condition, the chosen treasure chest determined the final choice for both the sender and the receiver, and the dyad split a $200 reward if the correct treasure chest was guessed. In the competition condition, after the receiver's decision, the sender automatically opened the other chest, and the person selecting the correct chest took the entire $150 reward. In the collaboration condition, the program was set to a 75% success rate, ensuring a player's expected utility for each trial was 75 NTD. In the competition condition, the success rate was set to 50%-50% for the final treasure chest, resulting in an expected utility of 75 NTD for either participant. After initial setup, practice sessions, and hyperscanning testing, participants completed four functional runs, each consisting of 28 trials. The 4-trial segments—$200-sender, $200-receiver, $150-sender, and $150-receiver—were repeated seven times. The initial sender role for each pair was determined randomly. Participants were allowed short breaks between runs, and the game resumed when both were ready to continue. Each trial took approximately 17 seconds to complete, with three seconds for the sender's decision, four seconds of fixation, three seconds for the receiver's decision, four seconds of fixation, and three seconds of feedback. The inter-trial interval ranged from approximately 3 to 9 seconds. Each pair of participants took around 70 minutes to finish, allowing for the scheduling of three pairs within a 4-hour time slot (Monday 9 am-1 pm).

3) fMRI data acquisition: fMRI data were acquired with a 3 T General Electric 750 MRI scanner (GE Medical Systems, Waukesha, WI) located in the B3F ofthe NCKU MRI center (http://fmri.ncku.edu.tw), equipped with a standard 8-channel head coil. Whole-brain functional scans were acquired with a T2* EPI (TR = 2s, TE = 33ms, flip angle = 90 deg, 40 axial slices, voxel size = 3.5 x 3.5 x 3 mm3).High-



(a) Shopping interaction



(b) OTC game

Fig. 1. Two fMRI experiments:Shopping interaction and OTC game.

resolution T1-weighted structural scans were acquired using a 3D fast spoiled grass (FSPGR) sequence (TR = 7.65 ms, TE =2.93 ms, inversion time = 450 ms, FA = 12 degree, 166 sagittal slices, voxel size = 0.875 x 0.875 x 1 mm3). Another scanner isthe 3-Tesla PRISMA MRI (Siemens, Erlangen, Germany) located at the National Taiwan University(http://mrimeg.psy.ntu.edu.tw/doku.php), equipped with a 20-channel phase array coil. Whole brain functional scans were acquired with a T2* EPI (TR = 2s, TE = 24 ms, flip angle = 87 degree, 36 axial slices, voxelsize = 3 x 3 x 3 mm3). High-resolution structural scans were acquired using a T1-weighted (MP-RAGE) sequence (TR = 2s, TE = 2.3ms, inversion time = 900ms, FA = 8 deg, 192 sagittal slices, voxel size = 0.938 x 0.938 x 0.94 mm3).

4) fMRI data analysis: Like the majority of task-based fMRI papers, the first step of the analysis is usually the general linear model (GLM), estimating each participant' brain activations and comparing the contrasts of interests under different stages of decision-making. Six regressors of interest were included in the GLM: (a) senders' decision phases in the cooperation condition; (b) senders' decision phases in the competition condition; (c) receivers' decision phases in cooperation; (d)receivers' decision phases incompetition; (e) feedback stages in cooperation; and finally, (f) feedback stages in the competition condition. For the second level (random-effect) analysis, three different contrasts were explored (and offered in results): competition versus cooperation in the sender decisions, the comparison of truth-telling strategy (e.g., the sender suggests the receiver the chest with higher probability) under the corporation vs. under the competition conditions, and the truth-telling vs. lying strategies (e.g., the sender suggests the receiver the chest with lower probability) under the competition condition. Because the goal of the present study is on social deception, senders' decision under both conditions will be the primary focus.

D. fMRI data preprocessing

SPM (Statistical Parametric Mapping) is an fMRI analysis software package that is run in Matlab. In addition to fMRI analysis, SPM contains toolboxes for performing volume-based morphometry and effective connectivity. Similarly, when preprocessing fMRI data cleaning up the three-dimensional images that are acquired every TR. An fMRI volume contains not only the signal that we are interested in changes in oxygenated blood - but also fluctuations that we are not interested in, such as head motion, random drifts, breathing, and heartbeats. These are called other fluctuations noise, since separate them from the signal that we are interested in. Some of these can be regressed out of the data by modeling them (which is discussed in the chapter on modeling fitting), and others can be reduced or removed by preprocessing. To begin preprocessing fMRI data, read through the following chapters. Begin with Realignment and Slice-Timing Correction, which correct misalignments and timing errors in the functional images, before moving on to Coregistration and Normalization, which align the functional and structural images and move them both to a standardized space. Finally, the images are Smoothed in order to increase signal and cancel out noise.

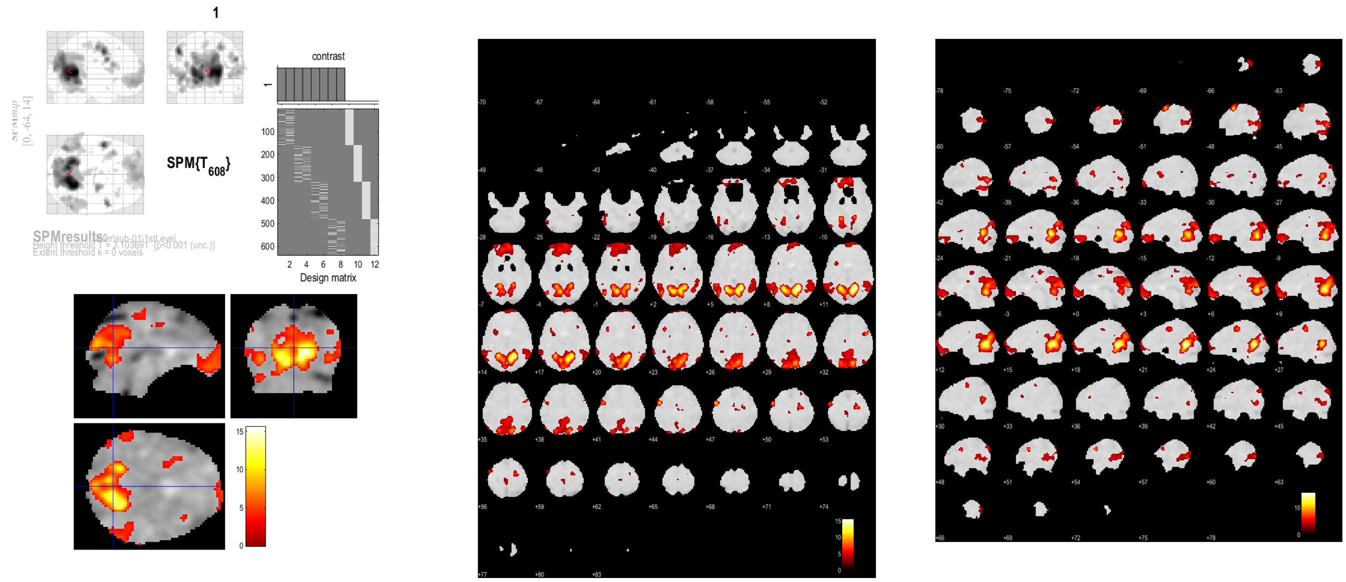
II. Results

A. General linear model of interactive shopping task

In the GLM analysis, brain regions revealed in the "together vs. alone trials" contrast included the bilateral temporal parietal junction (TPJ), superior temporal gyrus (STG), ventral striatum, posterior cingulate cortex (PCC), and dorso-medial prefrontal cortex (dmPFC), all exhibiting higher activation in the "together" condition. On the other hand, the "incongruent vs. congruent" contrast was defined by comparing "both high or both low" to "either A-high-B-low or A-low-B-high" (with low representing 1/2 and high representing 3/4). This contrast revealed that bilateral TPJ, posterior insula, putamen, and PCC/precuneus were more engaged in congruent trials, whereas the anterior insula (AI) and superior frontal gyrus showed higher activation in incongruent trials. It's worth noting that since the majority (68%) of the "together" trials were of the congruent type, finding bilateral TPJ in both contrasts is not surprising. A comprehensive whole-brain cluster table has been provided as supplementary information(Fig.2.a.b.c).

B. General linear model of OTC game

When comparing the sender's brain activities during the decision phase under both the competition and the cooperation conditions, multiple areas showed higher brain activities in the former (e.g., competition): including the bilateral dlPFC, mPFC, IPL, IFG, insula, precuneus, caudate, rTPJ, etc.The neural activity between the truth-telling scenarios for cooperation and competition was compared, and the results showed



(a) GLM of interactive shopping task (b) GLM of interactive shopping task (c) GLM of interactive shopping task

Fig. 2. In the GLM analysis, brain regions revealed in the ”together vs. alone trials” contrast included the bilateral temporal parietal junction (TPJ), superior temporal gyrus (STG), ventral striatum, posterior cingulate cortex (PCC), and dorso-medial prefrontal cortex (dmPFC), all exhibiting higher activation in the ”together” condition.

that multiple brain areas had higher activities in the truth-telling trails of the competition condition than those of the cooperation condition. The brain areas included the bilateral caudate, insula, dlPFC, IPL, precuneus, mPFC, and the rTPJ. Fig3 is the results from calculation.

C. Group analysis

Conducting group analysis is crucial for neuroimaging and other experimental studies for several reasons. Firstly, it enhances statistical power by pooling data from multiple individuals, allowing the detection of shared patterns and effects across the entire group rather than relying solely on individual observations. Secondly, it mitigates the impact of individual differences, which can introduce noise into results due to physiological and cognitive variability. Thirdly, group analysis supports scientific generalization, aiding in the extrapolation of research findings to broader populations or contexts. Additionally, it contributes to the scientific standards of replicability and reliability, ensuring that research results are consistent and can be confidently applied across diverse samples. Furthermore, it provides a more comprehensive understanding by observing average outcomes across the entire group, revealing prevalent effects that exist in the population. Overall, group analysis is essential for yielding more robust and universally applicable conclusions in scientific research, but researchers should carefully employ appropriate statistical methods and consider individual variability within the group. Fig. 4.a and Fig. 5.b show the results of the group analysis.

D. PPI results

In the functional connectivity, or Psycho-Physiological Interaction (PPI), analysis, the 4 different seeds: bilateral TPJ, and left anterior, and left lateral IPL, were chosen to reveal their corresponding brain regions differentiating between incongruent and congruent item-evaluation contexts. The PPI results showed that the left TPJ and left lateral IPL seeds are both functionally connected more (in incongruent than congruent condition) to bilateral mPFC, dACC, caudate, insular, and inferior frontal gyrus (IFG); whereas dmPFC and middle frontal gyrus are specifically more connected to l-TPJ seed, and left mPFC and superior frontal gyrus more to l-lIPL seed. In addition, the left anterior-IPL (or l-aIPL) was connected only to the cuneus more in the incongruent condition. Lastly, the right TPJ is connected more in incongruent condition to bilateral STS, temporal pole, and right caudate. See Fig. 5 for details.

III. Discussion

This study delves into the neural correlates of preference and decision-making in college couples during shopping, exploring how their decisions are influenced by each other’s item preferences. Previous research aimed at understanding the impact of others on decision-making has utilized various design manipulations, such as the number of (virtual) responders in consensus decision-making, adopting real-life-like task designs to ensure participants believe they are interacting with partners during the experiment.The brain areas commonly activated in the ”together vs. alone” and ”congruent vs. incongruent” contrasts include the bilateral TPJ and precuneus. The bilateral TPJ, along with neighboring brain areas like the STG/STS, is frequently associated with various forms of social processing, ranging from passively viewing or ”mirroring” others’ actions to actively inferring their goals, beliefs, or moral dilemmas. On the other hand, the precuneus is typically linked more with self-related and spatial frame-of-

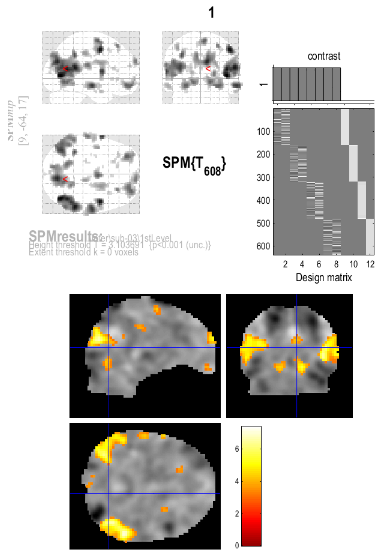
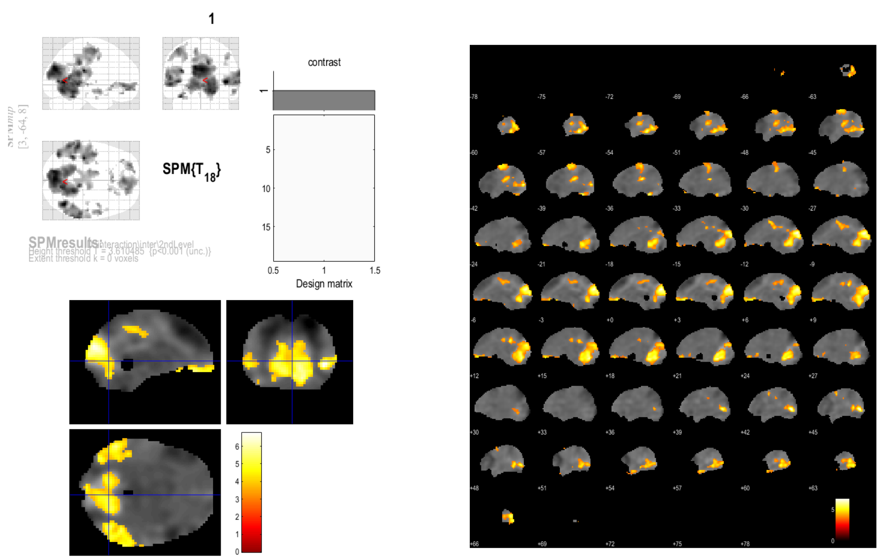


Fig. 3. GLM results of the contrast in the competition versus cooperation interactions during senders' decision phase [Voxel-level threshold p ¡ .005 uncorrected, (cluster threshold ¿ 41 voxels, FWE p=.05 corrected thresholded), via Neuroelf's Alphasim];



(a) Group analysis of the shopping interacion (b) Group analysis of the shopping interacio

Fig. 4. Conducting group analysis is crucial for neuroimaging and other experimental studies for several reasons. Firstly, it enhances statistical power by pooling data from multiple individuals, allowing the detection of shared patterns and effects across the entire group rather than relying solely on individual observations.

reference. However, disentangling the ambiguity between ”me thinking about others” and ”me simulating how I would be in his/her shoes” becomes challenging when faced with the co-activation of TPJ-precuneus in mentalizing others. The dmPFC is associated with conflict monitoring and detection, while the NAcc is related to predicting behavioral changes in response to a wide variety of rewarding stimuli. Lastly, the anterior and posterior insula are separately more activated in incongruent and congruent trials, respectively, representing the functional dissociation in the insular cortex based on varying degrees of empathy, pain, or discomfort arising from misalignment with group or social values.This comprehensive exploration provides valuable insights into the neural mechanisms underlying preference and decision-making processes in the context of social interactions.

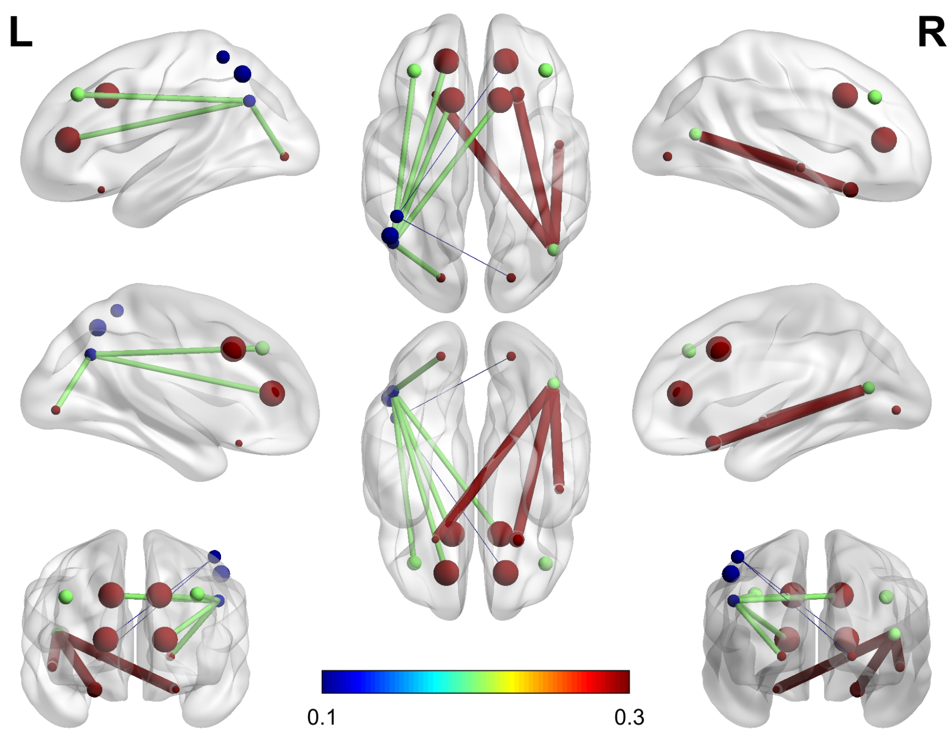


Fig. 5. The left TPJ are connected to bilateral vmPFC, dmPFC, middle frontal gyrus, the right TPJ are connected to bilateral STG/STS and right caudate (violet dotted line), the left lateral IPL are connected to bilateral mPFC, dmPFC, left superior frontal gyrus, insular. The anterior IPL was connected to bilateral cuneus. All the surface brain map was shown in p ¡ 0.05, FWE corrected, the PPI was conducted separately for each seed region and concatenated later for visualization, the individual results are provided in supplementary information .