Cerebral Cortex, 2024, **34**, 1–12
https://doi.org/10.1093/cercor/bhad541
Advance access publication date 17 January 2024
Original Article

Differential effects of specific emotions on spatial decision-making: evidence from cross-frequency functionally independent brain networks

Yanyan Zhao[1,2], Danli Wang[1,2,*], Xinyuan Wang[1,2], Qiao Jin[3], Xuange Gao[1,2]

[1]The State Key Laboratory of Multimodal Artificial Intelligence Systems, Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China,
[2]The School of Artificial Intelligence, University of Chinese Academy of Sciences, Beijing, 100049, China,
[3]Department of Computer Science and Engineering, University of Minnesota, Minneapolis, MN 55455, United States

[*]Corresponding author: Email: danli.wang@ia.ac.cn

Emotions significantly shape the way humans make decisions. However, the underlying neural mechanisms of this influence remain elusive. In this study, we designed an experiment to investigate how emotions (specifically happiness, fear, and sadness) impact spatial decision-making, utilizing EEG data. To address the inherent limitations of sensor-level investigations previously conducted, we employed standard low-resolution brain electromagnetic tomography and functional independent component analysis to analyze the EEG data at the cortical source level. Our findings showed that across various spectral-spatial networks, positive emotion activated the decision-making network in the left middle temporal gyrus and inferior temporal gyrus, in contrast to negative emotions. We also identified the common spectral-spatial networks and observed significant differences in network strength across emotions. These insights further revealed the important role of the gamma-band prefrontal network. Our research provides a basis for deciphering the roles of brain networks in the impact of emotions on decision-making.

Key words: emotion; EEG; decision-making; spectral-spatial network.

Introduction

Decision-making is a crucial aspect of our lives, constantly shaping our actions. In daily life, our choices are frequently swayed by our emotions. For example, when we feel fear, we tend to make lower-risk decisions. Decision-making is defined as an important cognitive process where individuals decide actions or form opinions from various options, based on their personal beliefs or reasoning of various factors (Lerner et al. 2015). Initially, studies on decision-making were mostly based on the assumption of rational behavior (Browning et al. 1999), which was questioned with the deepening of decision-making research. The somatic marker hypothesis pointed out that people's emotional reactions (i.e. somatic markers) in decision-making could regulate the decision-making behavior of people in complex and uncertain situations (Damasio, 1994). Lerner et al. (2015) also pointed out that emotions could exert a widespread, potent influence on decision-making, which could be both beneficial and detrimental, yet often predictable. Therefore, given the intricate interplay between emotions and decision-making processes, it is particularly important to explore the effect of emotions on decision-making.

Early studies on the influence of emotions on decision-making primarily relied on subjects' subjective emotional data and decision-making behavior data collected in the psychological experiment paradigm. Bagneux et al. (2012) used movie clips to induce emotions in the subjects and then asked the subjects to complete decision-making tasks. The subjective emotional data and decision-making behavior data indicated that participants under angry and happy were more possible to make decisions with less risk than participants under fear. Weller et al. (2010) used the Iowa Gambling Task (IGT) and the Cups task to conduct experiments and found that women are more inclined to take risks than men under circumstances of loss. Charpentier et al. (2017) compared the behavioral data of pathological anxiety participants with the behavioral data of healthy participants in a gambling task and found that pathological anxiety participants were more inclined to avoid risk, but the two groups had similar loss aversion. Although these studies explored the relationship between human emotion and decision-making behavior, most of the reports on emotions are based on subjective scoring, lacking objectivity, and are limited to only analyzing the impact of emotions on the final decision-making behavior.

As the most advanced part of the mammalian nervous system, brain uncovers the mechanisms behind human emotion, cognition, and behavior (Naqvi et al. 2006). Therefore, methods of brain science to explore the impact of emotions on decision-making have attracted the attention of researchers. Among various physiological signals, EEG has been applied to research in this field due to its high time resolution and low price (Alarcao and Fonseca, 2017). This approach not only addresses the limitations of previous studies mentioned above but also delves deeper into the impact of emotions on decision-making through the lens of brain functionality.

In EEG-based studies, Angus et al. (2015) evoked anger in subjects through recall and asked them to complete a simple gambling task. The results showed that approach motivation related to anger increased the positive correlation relationship between

Received: November 22, 2023. **Revised:** December 26, 2023. **Accepted:** December 27, 2023

reward positivity (RewP) and the desire for reward. Giustiniani et al. (2019) used balloon analog risk task and IGT to explore the relationship among emotion, risk-taking, and decision-making performance. Yang et al. (2020) studied the impact of three emotions (anger, fear, happiness) on risk decision-making. The event-related potential analysis showed that the amplitude of feedback-related negativity (FRN) under the fear stimulus was larger than that under the neutral, happy, and anger stimulus when the reward was large. Wang et al. (2017) considered the impact of state and dispositional emotions on uncertainty decision-making. This study divided participants into a high-trait anxiety group (HG) and a low-trait anxiety group (LG). Results showed larger FRN amplitudes in LG compared with HG under control, fear, and neutral conditions. In the fear and happy conditions, larger P3 amplitudes were appeared in HG compared with LG. Other researchers have explored the difference in risk decision-making under the impact of emotion between healthy people and those with autism spectrum disorder (ASD). The results showed that the EEG approximate entropy (ApEn) revealed the presence of emotion. The ApEn of ASD patients was lower than that of healthy participants, suggesting a diminished influence of emotions on subsequent responses and risk awareness in ASD patients (Kakkar, 2019). While current EEG research on the influence of emotion on decision-making has yielded insightful conclusions, its decision task and methods still exhibit notable limitations.

In decision tasks, they are still confined to risk decision-making and uncertainty decision-making. Iribe-Burgos et al. (2022) emphasized that, while the above-mentioned two types of decisions held significant value, further exploration was needed for decisions capable of predicting choice outcomes. Spatial decision-making, as a type of decision where outcomes can be anticipated, has attracted considerable attention from researchers, underscoring its significant value in addressing the cognitive science question of cognitive navigation (Bellmund et al. 2018). The importance of spatial decisions is apparent in their pivotal role in accurate navigation and path planning (Kaplan et al. 2017). In the context of practical applications, Stokes et al. (1997) further underscored the vital importance of spatial decision-making, particularly in the realm of emergency aviation decisions. In the realm of existing spatial decision-making research, Patai and Spiers (2021) underscored the often overlooked but significant role of the prefrontal cortex (PFC) in spatial navigation. Moreover, the PFC has been identified in association with route planning during spatial navigation (Kaplan et al. 2017). Activation in the lateral PFC and the superior frontal gyrus was observed when participants encountered detours and needed to explore alternative routes (Epstein et al. 2017). Despite the recognition of crucial activations in specific regions in previous spatial decision-making studies, the impact of emotions on spatial decision-making has been neglected. Moreover, a substantial body of research has demonstrated the intimate connection between emotion and the PFC (Dixon et al. 2017; Fitzgerald et al. 2019; Page and Coutellier, 2019; Kebets et al. 2021). Therefore, further exploration is needed to investigate the spatial decision-making brain network under the influence of distinct emotions, specifically examining the involvement of PFC regions in this process and whether other brain regions contribute to this process.

In terms of methods, existing approaches to studying the impact of emotion on decision-making are confined to the sensor level. While these studies have yielded significant findings, they lack precision in identifying the true origin of the neural signal. Analyzing at the cortical source level offers a solution to this issue, providing more anatomical information. Among these methods, standardized low-resolution brain electromagnetic tomography (sLORETA) has gained favor among researchers due to its ability to generate current density images with zero localization error (Pascual-Marqui, 2002). In addition, sLORETA can effectively make up for the lack of spatial resolution of EEG data (Bersagliere et al. 2018; Awan et al. 2019). After tracing the data through sLORETA, we can obtain the voxel domain data at the cortical source level. Based on it, researchers have observed that the functional state of the brain involves temporally coordinated activity of spatially distributed neural networks. Independent component analysis (ICA), compared with other methods, effectively captured this brain's functional state in the voxel domain, as demonstrated by Liu et al.'s research (Liu et al. 2018). Moreover, Caravaglios et al. (2023) validated the efficacy of the sLORETA combined with the functional independent component analysis (fICA) method in identifying functional networks and discerning intergroup connectivity differences. Therefore, we used the sLORETA-fICA (Pascual-Marqui et al. 2011) to analyze the spatial decision-making EEG data of the subjects under different emotional stimuli and extract independent spectral-spatial components (i.e. functional spectral-spatial networks).

This paper designed an EEG experiment and explored the impact of emotions (happy, fear, and sad) on spatial decision-making using sLORETA-fICA. Our main findings of this paper are as follows: (i) we identified the two most prominently activated decision-making functional spectral-spatial networks under each emotion. Notably, the cross-frequency decision-making network in the left middle temporal gyrus and inferior temporal gyrus of the beta and gamma bands under positive emotions is an important feature that distinguishes it from decision-making under negative emotions. (ii) The prefrontal networks except for the alpha band, theta-band parietal networks, theta-band frontoparietal network, and the beta-band temporal network were found to play important roles in the decision-making process under all three emotions. (iii) The activation strength of Component 2, a gamma-band prefrontal common decision network, was found to be able to effectively distinguish the three emotions.

In consequence, the main contributions of this paper are as follows: (i) we addressed the existing issue of overlooking emotional influences in current spatial decision-making. Through experimental results, we demonstrated the imperative need to consider the impact of emotions in the study of spatial decision-making. (ii) To our best knowledge, we introduced sLORETA-fICA for the first time into the study of emotional influences on decision-making, addressing the limitations of existing research methods confined to the sensor level. (iii) We uncovered key brain regions (as mentioned in the findings) influenced by various emotions in spatial decision-making, demonstrating the existence of both common and different decision-making networks under different emotions. Furthermore, we have provided evidence of intensity variations within the common decision-making network across different emotions.

Methods

Participants

We analyzed data that we previously collected from 16 college students who had normal or corrected-to-normal vision (mean: 23.25 years old; range: 22–28 years old; 11 females) (Zhao et al. 2022). All participants provided their written informed consent and were paid. Our study was performed in accordance with the ethical standards in the Declaration of Helsinki, and approval was

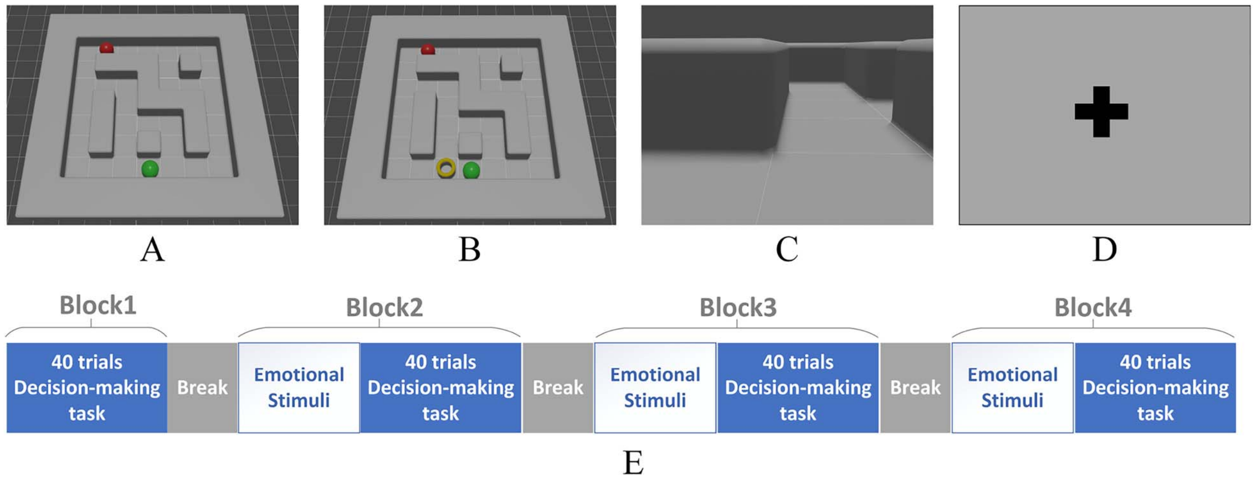

Fig. 1. Spatial decision task and Procedure. (A) Picture 1. Participants need to find the shortest path between the bottom ball (start point) and the top ball (end point). (B) Picture 2. A circle (choice point) appears randomly on the shortest path, participants need to decide which direction to choose is the shortest. (C) Picture 3 is the first-person viewpoint of the choice point. Participants need to operate in this part (W: go forward, A: go left, D: go right, S: all directions have the same path length). (D) Interstimulus interval (ISI). (E) Procedure. Four blocks are included in our experiment. Block 1 contains 40 trials of decision task, while block 2–4 contains emotional stimuli and 40 trials of decision task.

granted by the Biomedical Research Ethics Review Committee, Institute of Automation, Chinese Academy of Sciences.

Emotion stimuli

Three video clips (Bean clip, Curve clip, and Aftershock clip) were used to stimulate happy, fear, and sad, respectively (Zhao et al. 2022). The duration of Bean, Curve, and Aftershock clips are 197s, 189s, and 209s, respectively.

Decision task

The decision task referred to the spatial decision task raised by Kaplan et al. (2017). Mazes were generated by Blender (http://www.blender.org). In this task, participants need to find the shortest path between the bottom ball and the top ball. As shown in Fig. 1, there are four parts in a trial. In Fig. 1A, a maze with two balls is present. The bottom and top balls correspond to the starting and ending points, respectively. In Fig. 1B, a circle (choice point) appears randomly on the shortest path, participants should decide which direction to choose is the shortest. Figure 1C is the first-person viewpoint of the circle. Participants need to operate at this time. Pressing W, A, and D means going forward, left, and right, respectively. Pressing S means that all directions in this point have the same path length. Figure 1D is the interstimulus interval (ISI). The four pictures display 3,000 ms, 500 ms, 1,500 ms, and 1,500 ms, respectively.

Procedure

Four blocks are contained in our experiment, as shown in Fig. 1E. Among them, block 1 contains 40 trials of decision tasks without additional emotional stimuli, block 2–4 contains emotional stimuli and 40 trials of decision tasks. The presentation order of emotional stimuli is randomized. Before and after the emotional stimuli, participants need to fill out a V-A scale (Russell, 1980). During the whole experiment, EEG signals were recorded by the Neuroscan 64-channel EEG device.

Data analysis

To explore the impact of different emotions on decision-making, we preprocessed the EEG data and then used sLORETA-fICA analysis (Pascual-Marqui and Biscay-Lirio, 2011; Pascual-Marqui et al. 2011) to obtain spectral-spatial functional networks of decision-making under three emotions. We assumed that different emotions activated different decision networks. We also assumed that decision-making tasks under different emotions activated common decision-making networks because of the consistency of the decision-making tasks. In common decision-making networks, activation strengths may vary across emotions. Based on these assumptions, we analyzed our data as follows.

Preprocessing

In order to remove the noise in the EEG, we refer to the method of Yue et al. (2018) and preprocess the EEG. Specific steps are as follows: (i) Downsampling EEG data to 250Hz. (ii) The data after downsampling are put into a 1–40Hz bandpass filter for noise reduction. (iii) Remove noise and artifacts automatically by artifact subspace reconstruction algorithm. (iv) Interpolated reconstruction channel data. (v) Set the reference to average reference (vi) using ICA to remove electroophthalmic artifacts.

sLORETA functional ICA

The above preprocessed EEG signals were then used to estimate the cortical source distribution of electrical neuronal activity by the LORETA software (https://www.uzh.ch/keyinst/loreta). Firstly, 56-channel cross-spectral density matrices were computed for each of the 3.7-s EEG epochs. The collected EEG channels were consistent with the 56 channels of the LORETA scalp file, so the 64-channel data was reduced to 56-channels (Removed the A1, A2, F11, F12, FT11, FT12, CB1, and CB2). Matrices were computed in five EEG frequency bands (delta: 1–4 Hz, theta: 4–8 Hz, alpha: 8–13 Hz, beta: 13–30 Hz, gamma: 30–40 Hz). Secondly, sLORETA was used to calculate the spectral power of electrical neuronal activity on 6,239 cortical voxels in five EEG bands for each EEG cross-spectrum. Finally, these data can be used in fICA analysis to obtain 15 functional independent components by maximizing the spatial-spectral independence of second and fourth moments for all samples.

Different decision-making spectral-spatial networks evoked by varying emotions

To find different decision-making spectral-spatial networks under varying emotions and ensure that it is caused by emotional stimuli, we performed sLORETA analysis on the emotional data and decision-making data separately and then performed fICA analysis on the emotional data and decision-making data under the same emotion to find their common independent components. According to the activation strength, the two spectral-spatial networks with the highest activation strength were selected for each emotion. Take the EEG data under happy stimulus as an example, the emotional data were the EEG data collected when the subjects watched the happy video clip, and the decision-making data were the EEG data collected when the subjects performed the decision-making task after watching the happy video clip. We combined the emotional data and decision-making data under the happy stimulus for fICA analysis. By comparing the activation strengths of 15 functional spectral-spatial networks, two functional spectral-spatial networks with the highest activation strengths, namely the corresponding functionally independent components, were finally presented.

Common decision-making spectral-spatial networks under varying emotions

In order to find the common decision-making spectral-spatial network, we performed sLORETA analysis on the decision-making data under three emotions and performed fICA analysis on the decision data under the three emotions together. The 15 decision-making spectral-spatial networks under varying emotions were obtained through fICA.

Common decision-making spectral-spatial network with the significant difference in intensity among varying emotions

After obtaining 15 common decision-making spectral-spatial networks, one-way analysis of variance (ANOVA) was conducted on the corresponding activation intensity of each spectral-spatial network under three emotions and obtained the common decision-making spectral-spatial networks with the significant difference in intensity among different emotions ($p \leq 0.01$).

Results

Different activation patterns for decision-making evoked by varying emotions

In order to find different decision-making spectral-spatial networks under different emotions and ensure that it is caused by emotional stimuli, we performed sLORETA-fICA analysis on the emotional data and decision-making data under the same emotion to find their common independent components. The two functional spectral-spatial networks with the most prominent activation under the influence of happy, fear, and sad were shown in Figs. 2–4, respectively. The six networks were named happy component 1 (HC1), happy component 2 (HC2), fear component 1 (FC1), fear component 2 (FC2), sad component 1 (SC1), and sad component 2 (SC2). Under happy stimulus, HC1 was the negatively activated gamma-band network of the right superior frontal gyrus and middle frontal gyrus (Fig. 2A). HC2 was the positively activated cross-frequency network of beta and gamma bands of the left middle temporal gyrus and inferior temporal gyrus (Fig. 2B), and the activation intensity of the gamma band was higher. Under fear and sad stimuli, the two main spectral-spatial networks in decision-making were similar. FC1 and SC1 had positively activated networks in the gamma band of the right prefrontal lobe (Figs. 3A and 4A). FC2 and SC2 were positively activated cross-frequency networks of beta and gamma bands of the partial prefrontal lobe and partial prefrontal lobe negative activation (Figs. 3B and 4B), and the activation intensity of the gamma band were higher. Specifically, the activation area of SC1 was larger than that of FC1, the former included the right superior frontal gyrus, medial frontal gyrus, and middle frontal gyrus, and the latter only included the right superior frontal gyrus. In FC2 and SC2, the activation areas of the two were close, but the activation was opposite. The positive activation of FC2 mainly appeared in the bilateral medial frontal gyrus and some appeared in the superior frontal gyrus, and the negative activation mainly appeared in the right middle frontal gyrus and partly appeared in the superior frontal gyrus, inferior frontal gyrus. On the contrary, the positive activation of SC2 mainly appeared in the right middle frontal gyrus; the negative activation mainly appeared in the bilateral medial frontal gyrus and partly appeared in the activation of the superior frontal gyrus and inferior frontal gyrus.

By comparing the spectral-spatial network under the three emotions, the band consistency of the decision-making spectral-spatial network under the emotion was found. The bands were mainly the gamma band and beta band, and the activation intensity of the gamma band was stronger. On the cross-frequency network, the areas activated by the two bands were consistent, that was the network was cross-frequency interaction in the same area. For example, although HC2 involved the cross-frequency interaction of gamma and beta bands, they were all positive activations of the left middle temporal gyrus and inferior temporal gyrus, that was the activation areas and activation directions of the two bands were consistent.

Although the decision-making network under the three emotions had the above consistency, it can also be found that there were differences among the three emotions. Compared with the difference between negative emotions, the spectral-spatial network differences between positive and negative emotions were larger. Firstly, HC1 was negatively activated in the right PFC, whereas FC1 and SC1 were positively activated in the right PFC. Secondly, HC2 was the activation of the left temporal lobe area, while FC2 and SC2 activation areas were similar, still the prefrontal area, especially the right prefrontal area. The activation areas of negative emotions were relatively small, mainly reflected in the opposite positive and negative activation areas of FC2 and SC2.

Common decision-making spectral-spatial networks under different emotions

In order to find the common decision-making spectral-spatial network, we performed sLORETA-fICA analysis on the decision data under the three emotions together. We obtained 15 common spectral-spatial networks under the three emotions through fICA analysis, as shown in Fig. 5. For a better description, we abbreviated component 1 to C1. The rest of the components were similar. According to the results of all 15 spectral-spatial networks, the common decision-making networks under different emotions mainly involved the prefrontal and parietal regions, and a few involved the temporal lobe. Its bands involved delta, theta, beta, and gamma. Specifically, there were 11 networks activated in the frontal lobe (C1–C7, C9–C11, C13), involving the activation of all bands except alpha. The activation of the spectral-spatial networks in the parietal lobe (C8, C14) was all in the theta band. The network activated in the temporal lobe contained only C12, which was beta band activation. Similarly, the frontoparietal network contained only C15, which was the activation of the theta band. In terms of activation direction and intensity, the components of the parietal lobe in the theta band were all positively activated, and it can be found that they all had lateralization. Activation

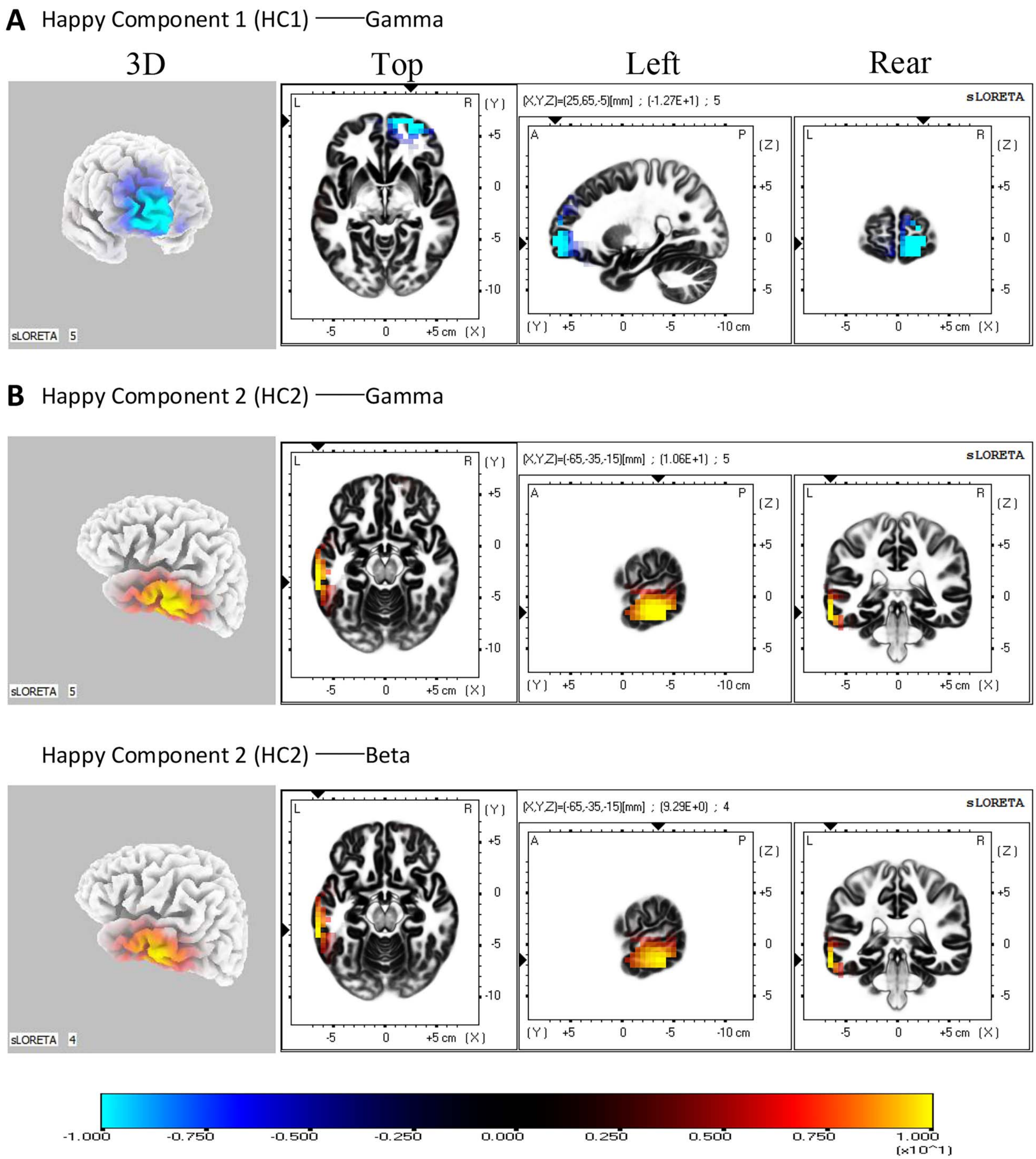

Fig. 2. The two most prominently activated spectral-spatial networks activated under the happy stimulus. The presentation of each spectral-spatial network contains four pictures, the first picture corresponded to its 3D picture, and the second, third, and fourth pictures corresponded to three cross-sectional views of this network. HC1 was the negatively activated gamma-band network of the right superior frontal gyrus and middle frontal gyrus (A). HC2 was the positively activated cross-frequency network of beta and gamma bands of the left middle temporal gyrus and inferior temporal gyrus (B), and the activation intensity of the gamma band was higher.

in the left parietal area was stronger than in the right parietal area. Similarly, activation in the temporal lobe was also positive and lateralized, involving only the activation of the left temporal lobe. There were many components in the frontal lobe area, and different components involved different activation directions and intensities, but there was also obvious lateralization. In terms of positive activation, the activation intensity of the right frontal cortex was greater than that of the left (C1, C2, C3, C4, C5, C6, C9, C10, C13). In terms of negative activation, both C2 and C3 showed lateralization of the left frontal lobe, while C10 showed lateralization of the right frontal lobe.

In summary, we obtained 15 common decision-making spectral-spatial networks under three emotions. The results showed that the frontal network, the theta-band parietal network, the beta-band temporal network, and the theta-band frontoparietal network played an important role in the decision-making process of three emotions. The above-mentioned networks have lateralization in both positive and negative network activations.

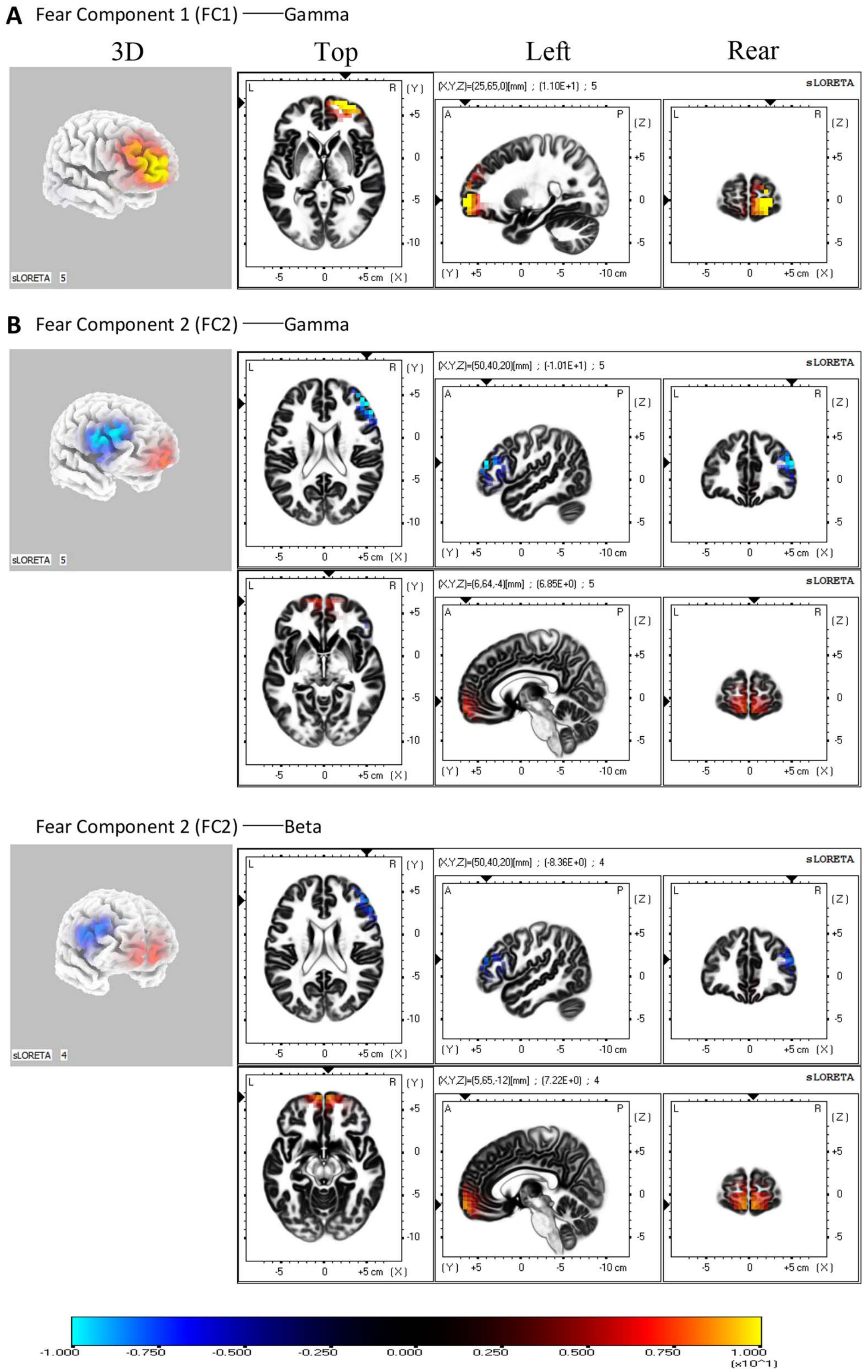

Fig. 3. The two most prominently activated spectral-spatial networks activated under the fear stimulus. Some networks had more than one activation area in the same band. For a clearer presentation, we have drawn the cross-sectional views of networks of multiple locations of this network, such as FC2. FC1 was the positively activated gamma-band network of the right superior frontal gyrus, medial frontal gyrus, and middle frontal gyrus. FC2 was a cross-frequency network of beta and gamma bands. The positive activation of FC2 mainly appeared in the bilateral medial frontal gyrus and some appeared in the superior frontal gyrus, and the negative activation mainly appeared in the right middle frontal gyrus and partly appeared in the superior frontal gyrus, inferior frontal gyrus.

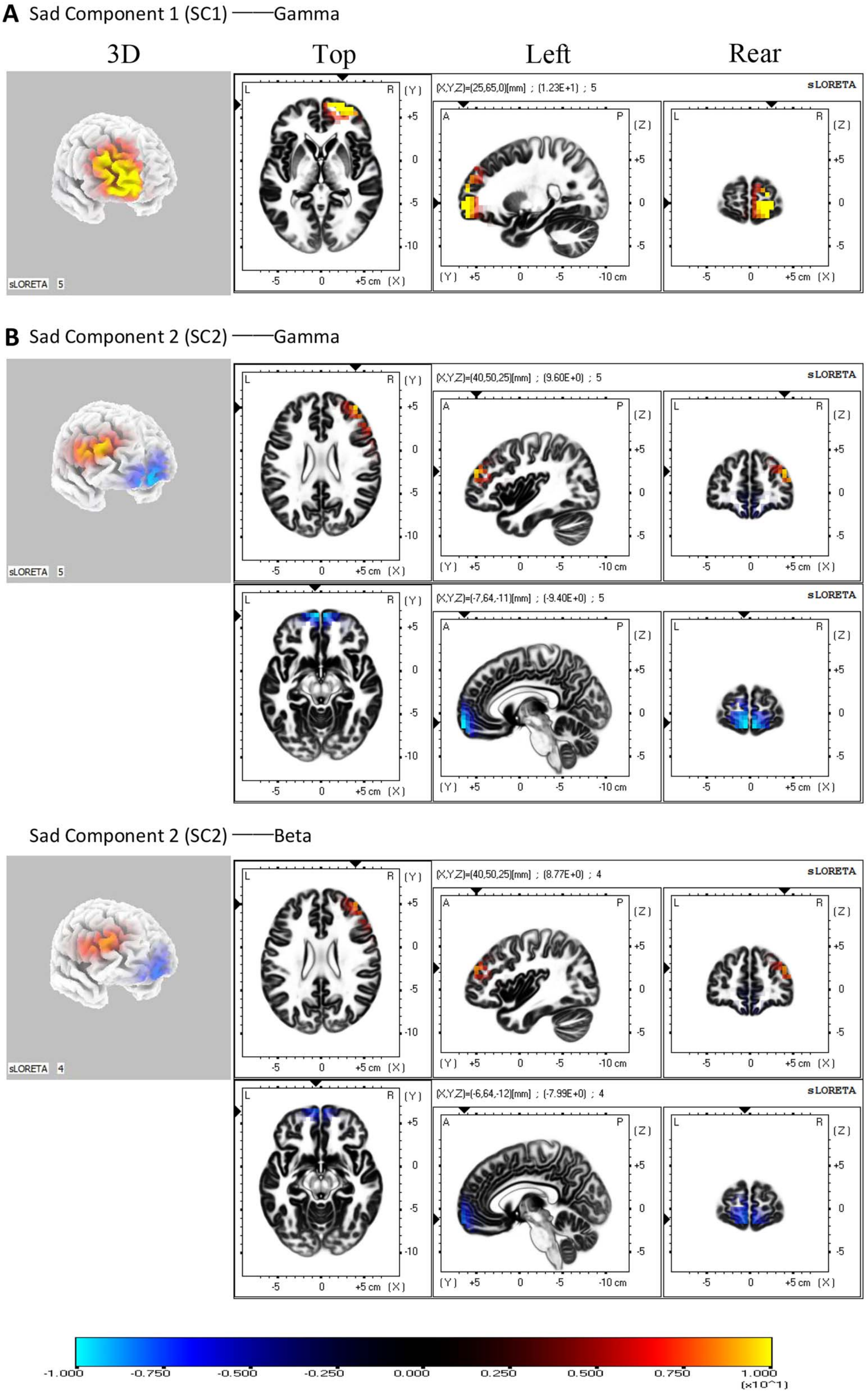

Fig. 4. The two most prominently activated spectral-spatial networks activated under the sad stimulus. SC1 was the positively activated gamma-band network of the right superior frontal gyrus. SC2 was a cross-frequency network of beta and gamma bands. The positive activation of SC2 mainly appeared in the right middle frontal gyrus, and the negative activation mainly appeared in the bilateral medial frontal gyrus and partly appeared in the activation of the superior frontal gyrus and inferior frontal gyrus.

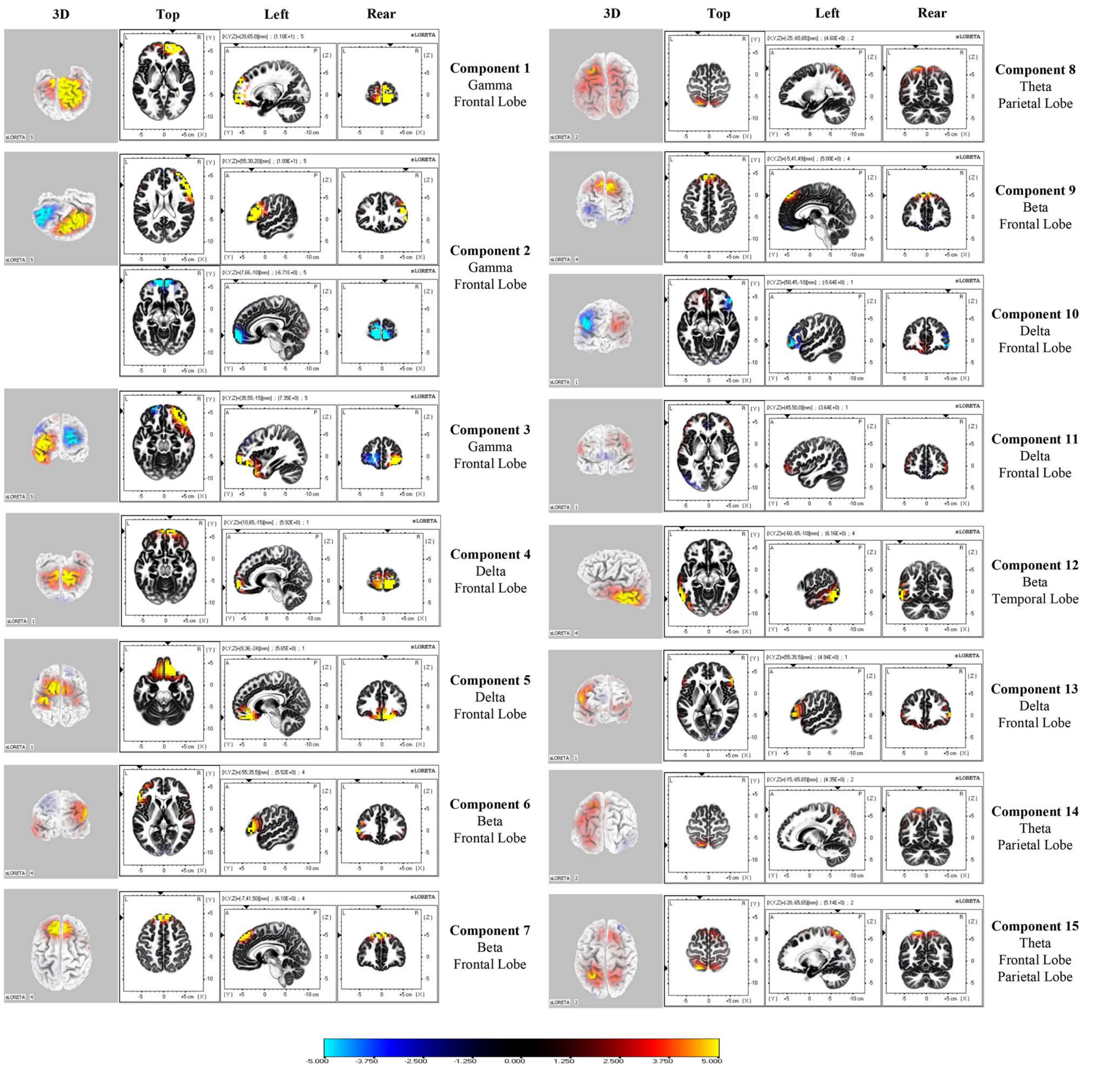

Fig. 5. Common frontal spectral-spatial network of decision-making under three emotions. The name of each component and its activation region of brain and activation bands are presented on the right side of each component map.

There are significant differences in the activation intensity of the common decision-making spectral-spatial network under three emotions

We performed ANOVA analysis on the above 15 common spectral-spatial networks under the three emotions to obtain networks with significant differences ($p \leq 0.01$) in intensity. The results of ANOVA analysis were presented in Table 1. Due to space limitation, we only showed the results of components with significant differences in this paper (C2,C4,C7,C8). We conducted a comparison of the activation intensity between any two emotions using the Tukey post-hoc test, and the results are presented in Table 2. We used >, <for the part with significant differences in activation intensity to express the comparison of activation intensity under two kinds of emotions. Among the above independent components with significant differences, happy and fear, sad and fear all had significant differences in the activation intensity of C2, C4, and C7, and happy and sad had significant differences in the activation intensity of C2 and C8. C2, C4, C7, and C8 have been shown in Fig. 5.

Table 1. Results of ANOVA analysis.

	C2	C4	C7	C8
***F*-value**	18.86	19.07	18.00	9.75
***p*-value**	1.12e−6	1.00e−06	1.80e−06	3.04e−4

The spectral-spatial network of C2 was mainly the positive activation of the inferior frontal gyrus, middle frontal gyrus, and superior frontal gyrus and the negative activation of the superior frontal gyrus, medial frontal gyrus, and rectal gyrus in the gamma band. Among them, the positive activation was in the right PFC, and the negative activation was in both the left and right PFC,

Table 2. Comparison of activation strengths of common networks with significant differences.

	C2	C4	C7	C8
Happy vs. Fear	<	<	>	
Happy vs. Sad	>			<
Sad vs. Fear	<	<	>	

but the left side was lateralized. This component had significant differences among the three emotions, and its activation intensity was fear>happy>sad.

The spectral-spatial network of C4 was mainly the positive activation of the medial frontal gyrus and superior frontal gyrus in the delta band. This component had a significant difference between fear and happy, fear and sad, and the activation intensity of fear was greater than that of the other two emotions. No significant difference was found between happy and sad.

The spectral-spatial network of C7 was mainly the positive activation of the superior frontal gyrus in the beta band. This component had a significant difference between fear and happy, fear and sad, and the activation intensity of fear was smaller than that of the other two emotions. No significant difference was found between happy and sad.

The spectral-spatial network of C8 was the positive activation of the superior parietal lobule in the theta band. This component only had a significant difference between happy and sad, and the activation intensity of sad was greater than that of happy.

This result provided further evidence of the important role of the PFC in the influence of emotion on decision-making. In particular, C2, which was activated in the PFC of the Gamma band, was not only the most prominently activated spectral-spatial network among the above four components but also the only spectral-spatial network whose intensity all had significant differences between the three emotions. Not only does the prefrontal lobe played an important role in the impact of emotion on decision-making, but the parietal lobe also played an important role in the impact of emotion on spatial decision-making. The activation intensity of the superior parietal lobule network (C8) in the theta band can effectively distinguish between sad and happy.

Discussion

At present, a large number of studies have proved the close relationship between emotion and the PFC (Dixon et al. 2017; Fitzgerald et al. 2019; Page and Coutellier, 2019; Kebets et al. 2021). Additionally, an extensive body of research has indicated a close connection between decision-making and PFC (Domenech and Koechlin, 2015; Vassena et al. 2017; Dezfouli et al. 2021; Hunt, 2021). For example, Ouerchefani et al. (2017) studied decision-making in the PFC with different damaged regions and found that decision-making depends on a large brain network, including the dorsolateral and ventromedial regions of the PFC. However, few studies have investigated the decision-making brain network under the influence of different emotions, and how specific regions of the PFC play a role in this process. Furthermore, it is yet to be explored whether other brain regions are also implicated in this process. Some research studied the mechanism of emotions from the perspective that different emotions affect different areas of the brain (Silberman and Weingartner, 1986), while others have examined that the processing of various emotions may pass through the same circuit, such as the related theory of the limbic system (Molenberghs et al. 2007). Inspired by this, this paper used sLORETA-fICA to compare the differences in decision-making brain networks under different emotions. The EEG data of decision-making under happy, fear, and sad were analyzed from the perspectives of varying decision-making networks (e.g. HC1, HC2, FC1, FC2, SC1, SC2), common decision-making networks (e.g. C1-C15), and common decision-making networks with significant differences in strength of activation (e.g. C2, C4, C7, and C8). Based on the above results, we have drawn some inferences regarding spatial decision-making under the influence of emotions.

In various emotional states, there are common and different decision networks involving common or different decision regions. This underscores that the investigation of spatial decision-making should not solely concentrate on the rational aspect but should also acknowledge its susceptibility to emotional influences. Viewing the different decision-making networks associated with various emotions, notable regional and directional differences existed in HC, SC, and FC. Regarding the common decision-making network under different emotions, C1–C15 demonstrated a degree of consistency in decision networks. Within these common decision networks, there were networks with significantly different strengths. This reinforces the idea that studying spatial decision-making requires the consideration of emotional influences, whether in terms of differences in the strength of the common network or variations in regional and directional activations across different networks.

The PFC plays a crucial role in spatial decision-making under different emotional influences. However, the prefrontal networks associated with decisions under different emotions exhibited regional and directional differences, as well as variations in activation intensity. Furthermore, the activation of the left temporal region suggested that positive emotions, compared with negative emotions, may evoke decision networks associated with nonspatial responses. Whether examining the different decision networks or the common decision networks we obtained, the majority of networks still belonged to the internal networks of the PFC (HC1, FC1, FC2, SC1, SC2, C1–C7, C9–C11, C13). This further substantiated the crucial role of the PFC in spatial decision-making. From different network perspectives, positive emotions elicited the activation of the left middle temporal gyrus and inferior temporal gyrus (HC2), which was not observed in negative emotions. Existing research confirmed that spatial response selection involved the right PFC, while nonspatial response selection involved the left middle temporal gyrus (Schumacher et al. 2003; Talati and Hirsch, 2005). Therefore, we inferred that positive emotions may more significantly activate decision networks associated with nonspatial responses compared with negative emotions.

Based on the significant strength differences in common spectral networks under different emotional states, we inferred that C2, an internal frontal lobe network, was a decision network with a higher degree of emotional relevance. This may imply that emotions influence decision-making by impacting the strength differences in this network. According to the results of the ANOVA analysis, C2 was the only one that could effectively distinguish between the three emotions. The spectral-spatial network of C2 was mainly the positive activation of the right inferior frontal gyrus, middle frontal gyrus, and superior frontal gyrus and the negative activation of the superior frontal gyrus, medial frontal gyrus, and rectal gyrus in the gamma band. Previous fMRI research has shown that the right inferior frontal gyrus is sensitive to the mismatch between real decision and individual's expectation. Lower decision confidence will activate the higher activity of right inferior frontal gyrus (Sherman et al. 2016).

Deppe et al. (2005) found that activity was increased in the right superior frontal gyrus when the participant's favorite target brand appeared. They believed that this area participated in the self-reflections and processing of emotions in the process of decision-making. These studies validated the correlation between the regions involved in C2, emotions, and decision expectancy processing, further confirming the association between C2 and emotion. As a result, we believed that the decision spectral-spatial network of C2 was an important circuit for differentiating decision processing under different emotions and deserved further study.

Based on C8, we inferred that, compared with the happy emotion, sad emotion may exhibit a more robust activation of spatial analysis and attention in the context of spatial decision-making. Our results showed that the superior parietal lobule's positive activation in the theta band (C8) of sad was significantly greater than that of happy. In the existing research on superior parietal lobule, Readers with dyslexia have been found to have abnormally low superior parietal lobule activation (Vialatte et al. 2023). Molenberghs et al. (2007) found that changes in spatial coordinates related to attention priority were associated with the superior parietal lobule. Peyrin et al. (2011) also found that the superior parietal lobule was involved in attention and visuospatial analysis. And it was related to the attention assigned to a specific task. Based on these studies, we believe that compared with happy emotion, sad emotion may have a stronger activation of spatial analysis and attention for spatial decision-making.

The spatial decision network under the influence of emotion also had the characteristics of lateralization, which was consistent with some existing research on decision and emotion. The common decision-making network under different emotions showed obvious lateralization, and the positive activation of the left parietal area in the theta band was significantly stronger than that of the right parietal area (C8, C14). Similarly, activation in the temporal lobe was also positive and lateralized, involving only activation in the left temporal lobe (C12). There were many components in the frontal lobe area, and different components involved different activation directions and intensities but also had obvious lateralization. In terms of positive activation, the activation intensity of the right frontal cortex was greater than that of the left (C1, C2, C3, C4, C5, C6, C9, C10, C13). These decision-making networks further proved that in the decision-making process, there was a lateralization of network activation in the frontal, parietal, and temporal lobes. Several studies have identified lateralization in emotion or decision-making. Gläscher et al. (2012) found that left vmPFC lesions had a strong impact on Iowa decision task performance. Reber and Tranel (2017) explored the impact of vmPFC lesions on social, emotional, and decision-making functions, specifically focusing on gender differences. They observed that men with right-sided vmPFC lesions and women with left-sided vmPFC lesions experienced more severe disturbances in these domains. Our study further found that in spatial decision-making, the decision network also involved lateralization of positive activation in the left temporal, right parietal, and right frontal regions.

The gamma band is a frequency range that demands additional attention in decision-making research. By comparing different networks of HC, FC, and SC under different emotions, we found that the prefrontal and temporal lobe networks of the gamma band played an important role. On the common decision-making network with significant differences under different emotions, C2, as the only network with significant differences among all three emotions, was also the PFC of the gamma band. Current studies on emotion and decision-making have also found that gamma band has important research value. For example, Ma et al. (2012) conducted a study to examine the organization of functional brain networks during various emotional processing tasks. In the low gamma band (30–50 Hz), they observed that the characteristic path length was significantly lower during negative emotion processing compared with positive emotion processing. Zhao et al. (2022) also found a significant negative correlation between characteristic path lengths in the gamma band and decision accuracy. Therefore, the gamma band played an important role in the influence of emotions on decision-making. We speculate that emotions can further affect people's decision-making judgments by affecting the activation of brain networks in the gamma band.

Although the paper discovered some important findings, it still has some limitations. The number of EEG channels can be further increased, and EEG devices with 128 channels or more should be further considered in the future. At present, there are few brain network studies on the impact of fear and sadness on decision-making, and the difference in influence between the two should also be further explored to explain the reasons for the differences in brain networks. The regions involved in C2 and their connectivity require further study to gain a deeper understanding of the coordination role between regions. Furthermore, decision-making models that consider emotions still need to be built based on the above findings. We suggest that future research should work on the above limitations to further explore the mechanism of the influence of emotions on decision-making.

Conclusion

This paper designed an experiment to collect the EEG data of the participants completing the decision-making task under the three emotions of happy, fear, and sad. In various emotional states, there were common and different spatial decision networks involving common or different decision regions. This underscored that the investigation of spatial decision-making should not solely concentrate on the rational aspect but should also acknowledge its susceptibility to emotional influences. The left middle temporal gyrus and inferior temporal gyrus were activated in positive emotions, but this rule was not found in negative emotions. Almost all bands of the prefrontal lobe network (except the alpha band), the theta band parietal lobe network and the frontoparietal lobe network, and the beta band temporal lobe network all played an important role in the decision-making process under different emotions. The activation strength of Component 2, a gamma-band prefrontal network, was found to be able to effectively distinguish the three emotions; a clear lateralization phenomenon in the above network was also found.

Author contributions

Yanyan Zhao, Danli Wang, Xinyuan Wang, QiaoJin, and Xuange Gao contributed to the conception of the study. Yanyan Zhao organized the database, performed the analysis, and wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved thesubmitted version.

Funding

This research is supported by the National Natural Science Foundation of China under Grant Nos. 61872363 and 61672507, the Natural Science Foundation of Beijing and Key project of Science and Technology Plan of Beijing Municipal Education Commission under Grant No. 21JD0044, and the Beijing Natural Science Foundation under Grant No. L232098.

References

Alarcao SM, Fonseca MJ. Emotions recognition using EEG signals: a survey. *IEEE Trans Affect Comput*. 2017:10(3):374–393.

Angus DJ, Kemkes K, Schutter DJLG, Harmon-Jones E. Anger is associated with reward-related electrocortical activity: evidence from the reward positivity. *Psychophysiology*. 2015:52(10):1271–1280.

Awan FG, Saleem O, Kiran A. Recent trends and advances in solving the inverse problem for EEG source localization. *Inverse Probl Sci Eng*. 2019:27(11):1521–1536.

Bagneux V, Bollon T, Dantzer C. Do (un) certainty appraisal tendencies reverse the influence of emotions on risk taking in sequential tasks? *Cognit Emot*. 2012:26(3):568–576.

Bellmund JLS, Gärdenfors P, Moser EI, Doeller CF. Navigating cognition: spatial codes for human thinking. *Science*. 2018: 362(6415):eaat6766.

Bersagliere A, Pascual-Marqui RD, Tarokh L, Achermann P. Mapping slow waves by EEG topography and source localization: effects of sleep deprivation. *Brain Topogr*. 2018:31(2):257–269.

Browning G, Webster F, Halcli A. *Understanding contemporary society*. UK: SAGE; 1999. pp. 1–520.

Caravaglios G, Muscoso EG, Blandino V, Di Maria G, Gangitano M, Graziano F, Guajana F, Piccoli T. EEG resting-state functional networks in amnestic mild cognitive impairment. *Clin EEG Neurosci*. UK: SAG; 2023:54(1):36–50.

Charpentier CJ, Aylward J, Roiser JP, Robinson OJ. Enhanced risk aversion, but not loss aversion, in unmedicated pathological anxiety. *Biol Psychiatry*. 2017:81(12):1014–1022.

Damasio AR. Descartes' error and the future of human life. *Sci Am*. 1994:271(4):144–144.

Deppe M, Schwindt W, Kugel H, Plassmann H, Kenning P. Nonlinear responses within the medial prefrontal cortex reveal when specific implicit information influences economic decision making. *J Neuroimaging*. 2005:15(2):171–182.

Dezfouli MP, Zarei M, Constantinidis C, Daliri MR. Task-specific modulation of PFC activity for matching-rule governed decision-making. *Brain Struct Funct*. 2021:226(2):443–455.

Dixon ML, Thiruchselvam R, Todd R, Christoff K. Emotion and the prefrontal cortex: an integrative review. *Psychol Bull*. 2017:143(10): 1033–1081.

Domenech P, Koechlin E. Executive control and decision-making in the prefrontal cortex. *Curr Opin Behav Sci*. 2015:1:101–106.

Epstein RA, Patai EZ, Julian JB, Spiers HJ. The cognitive map in humans: spatial navigation and beyond. *Nat Neurosci*. 2017:20(11): 1504–1513.

Fitzgerald JM, Klumpp H, Langenecker S, Phan KL. Transdiagnostic neural correlates of volitional emotion regulation in anxiety and depression. *Depress Anxiety*. 2019:36(5):453–464.

Giustiniani J, Joucla C, Bennabi D, Nicolier M, Chabin T, Masse C, Trojak B, Vandel P, Haffen E, Gabriel D. Behavioral and electrophysiological arguments in favor of a relationship between impulsivity, risk-taking, and success on the Iowa gambling task. *Brain Sci*. 2019:9(10):248.

Gläscher J, Adolphs R, Damasio H, Bechara A, Rudrauf D, Calamia M, Paul LK, Tranel D. Lesion mapping of cognitive control and value-based decision making in the prefrontal cortex. *Proc Natl Acad Sci*. 2012:109(36):14681–14686.

Hunt LT. Frontal circuit specialisations for decision making. *Eur J Neurosci*. 2021:53(11):3654–3671.

Iribe-Burgos FA, Cortes PM, García-Hernández JP, Sotelo-Tapia C, Hernández-González M, Guevara MA. Effect of reward and punishment on no-risk decision-making in young men: an EEG study. *Brain Res*. 2022:1779:147788.

Kakkar D. Influence of emotional imagery on risk perception and decision making in autism spectrum disorder. *Neurophysiology*. 2019:51(4):281–292.

Kaplan R, King J, Koster R, Penny WD, Burgess N, Friston KJ. The neural representation of prospective choice during spatial planning and decisions. *PLoS Biol*. 2017:15(1):e1002588.

Kebets V, Favre P, Houenou J, Polosan M, Perroud N, Aubry J-M, Van De Ville D, Piguet C. Fronto-limbic neural variability as a transdiagnostic correlate of emotion dysregulation. *Transl Psychiatry*. 2021:11(1):545.

Lerner JS, Li Y, Valdesolo P, Kassam KS. Emotion and decision making. *Annu Rev Psychol*. 2015:66(1):799–823.

Liu Q, Ganzetti M, Wenderoth N, Mantini D. Detecting large-scale brain networks using EEG: impact of electrode density, head modeling and source localization. *Front Neuroinform*. 2018:12:4.

Ma M, Li Y, Xu Z, Tang Y, Wang J. Small-world network organization of functional connectivity of EEG gamma oscillation during emotion-related processing. In: *5th International Conference on BioMedical Engineering and Informatics*, Chongqing, China. IEEE; 2012. pp. 597–600.

Molenberghs P, Mesulam MM, Peeters R, Vandenberghe RRC. Remapping attentional priorities: differential contribution of superior parietal lobule and intraparietal sulcus. *Cereb Cortex*. 2007:17(11): 2703–2712.

Naqvi N, Shiv B, Bechara A. The role of emotion in decision making: a cognitive neuroscience perspective. *Curr Dir Psychol Sci*. 2006:15(5): 260–264.

Ouerchefani R, Ouerchefani N, Allain P, Rejeb MRB, Le Gall D. Contribution of different regions of the prefrontal cortex and lesion laterality to deficit of decision-making on the Iowa gambling task. *Brain Cogn*. 2017:111:73–85.

Page CE, Coutellier L. Prefrontal excitatory/inhibitory balance in stress and emotional disorders: evidence for over-inhibition. *Neurosci Biobehav Rev*. 2019:105:39–51.

Pascual-Marqui RD, Biscay-Lirio RJ. Interaction patterns of brain activity across space, time and frequency. Part I: methods. *arXiv preprint arXiv:11032852*. 2011.

Pascual-Marqui RD. Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details. *Methods Find Exp Clin Pharmacol*. 2002:24(Suppl D):5–12.

Pascual-Marqui RD, Kochi K, Lehmann D, Koukkou M, Kinoshita T. Functional independent components: revealing cortico-cortical, cross-frequency interactions. *Jap J Pharmaco-EEG*. 2011:12:53–58.

Patai EZ, Spiers HJ. The versatile wayfinder: prefrontal contributions to spatial navigation. *Trends Cogn Sci*. 2021:25(6):520–533.

Peyrin C, Démonet JF, N'Guyen-Morel MA, Le Bas JF, Valdois S. Superior parietal lobule dysfunction in a homogeneous group of dyslexic children with a visual attention span disorder. *Brain Lang*. 2011:118(3):128–138.

Reber J, Tranel D. Sex differences in the functional lateralization of emotion and decision making in the human brain. *J Neurosci Res*. 2017:95(1–2):270–278.

Russell JA. A circumplex model of affect. *J Pers Soc Psychol*. 1980:39(6): 1161–1178.

Schumacher EH, Elston PA, D'esposito M. Neural evidence for representation-specific response selection. *J Cogn Neurosci*. 2003: 15(8):1111–1121.

Sherman MT, Seth AK, Kanai R. Predictions shape confidence in right inferior frontal gyrus. *J Neurosci*. 2016:36(40):10323–10336.

Silberman EK, Weingartner H. Hemispheric lateralization of functions related to emotion. *Brain Cogn*. 1986:5(3):322–353.

Stokes AF, Kemper K, Kite K. Aeronautical decision making, cue recognition, and expertise under time pressure. *Naturalistic Decisi Mak*. 1997:183–196.

Talati A, Hirsch J. Functional specialization within the medial frontal gyrus for perceptual go/no-go decisions based on what, when, and where related information: an fMRI study. *J Cogn Neurosci*. 2005:17(7):981–993.

Vassena E, Deraeve J, Alexander WH. Predicting motivation: computational models of PFC can explain neural coding of motivation and effort-based decision-making in health and disease. *J Cogn Neurosci*. 2017:29(10):1633–1645.

Vialatte A, Aguera P-E, Bedoin N, Witko A, Chabanat E, Pisella L. Enhancing reading accuracy through visual search training using symbols. *Sci Rep*. 2023:13(1):4291.

Wang Y, Gu R, Luo Y-J, Zhou C. The interaction between state and dispositional emotions in decision making: an ERP study. *Biol Psychol*. 2017:123:126–135.

Weller JA, Levin IP, Bechara A. Do individual differences in Iowa gambling task performance predict adaptive decision making for risky gains and losses? *J Clin Exp Neuropsychol*. 2010:32(2): 141–150.

Yang Q, Zhou S, Gu R, Wu Y. How do different kinds of incidental emotions influence risk decision making? *Biol Psychol*. 2020:154:107920.

Yue K, Wang D, Hu H, Fang S. The correlation between visual fatigue and duration of viewing as assessed by brain monitoring. *J Soc Inf Disp*. 2018:26(7):427–437.

Zhao Y, Wang D, Wang X, Chiu SC. Brain mechanisms underlying the influence of emotions on spatial decision-making: an EEG study. *Front Neurosci*. 2022:16:989988.