Role of the Prefrontal Cortex (PFC) on Processing the Social Statistical Information: An fMRI Study

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Abstract. The prefrontal cortex is crucial for memory encoding and processing, in which the lateral prefrontal cortex (LPFC) is more involved in semantic and episodic memory, whereas the medial prefrontal cortex (MPFC) is more related to the associative information processing and social cognition. Social statistical information is a kind of typical associative information with sociality. However, the role of the prefrontal cortex in comprehending the social statistical information remains unknown yet.This study focused on the brain activities of 36 normal subjects in the prefrontal cortex using fMRI while they viewed the social statistical information presented in either visual form as a graph or textual form as a verbal description of the information in the graph. The results showed that the graph and textual tasks consistently activated the anterior and posterior portions of ventrolateral prefrontal cortex (VLPFC), the dorsal and ventral MPFC. The results suggest that the VLPFC and the MPFC commonly contribute to the social statistical information processing.

1 Introduction

The prefrontal cortex (PFC) is the anterior part of the frontal lobes in human brain, lying in the front of the motor and supplementary motor areas. Its contributing to memory encoding and processing has been demonstrated in numerous studies. From the view of functional and anatomical structure, this area can be divided into two parts: the lateral and medial.

The dorsolateral prefrontal cortex (DLPFC) is considered to play an important role in executive control [1], and working memory [2,3], which also activated in many complex cognitive tasks that require maintenance information in working memory, such as planning [4,5], reasoning [6], and decision-making [7].

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The ventrolateral prefrontal cortex (VLPFC) has been implicated in the word-level processing [8,9,10], in which the dorsal aspect (BA44/45) is involved in the phonological processing, and the ventral aspect (BA47/45) is related to the semantic processing of a word [11]. Additionally, the VLPFC is also activated during sentence comprehension [12,13,14], in which the dorsal portion is engaged in the syntactic processing, and the ventral portion is selectively involved in the semantic processing of a sentence [15,16].

Recently, the MPFC has also been associated with the social cognition [17]. The dorsal and ventral parts of the MPFC are considered to play different roles in the social cognition, with the dorsal MPFC being involved in the theory of mind, while the ventral MPFC is involved in self-reference and emotional cognition. For example, the dorsal MPFC was activated when individual performed tasks necessitating the mental states about others, termed the theory of mind [18,19,20]; the ventral MPFC was specifically activated during self-referential processing as compared to other referential reflective tasks [21,22]. A study found that the ventral MPFC was also activated when participants inferred the mental states of others that were sufficiently similar to themselves [23]. The study about emotional cognition suggested that patients with the ventral MPFC damage could normally identify faces, but they showed poorer performance than the control group in emotion recognition, such as happiness, sadness, disgust, and anger [24]. Bar-On et al. revealed that the patients with the ventral MPFC damage not only significantly low emotional intelligence, but also poor judgment in decision-making as well as disturbances in social function [25]. However, the patients got normal levels of cognitive intelligence, executive functioning, perception and memory.

The social statistical information can be used to quantitatively describe an event surrounding us in our daily life, such as the statistics on the product, income and sale. It is a kind of typical associative information, consisting of several objects involving the object-name and its corresponding object-value. The associative encoding and memory between an object-name and object-value is the basis of comprehending and integrating the statistical information. In addition, because the social statistical information is derived from many aspects of our society and is close to people's daily life, people would spontaneously generate self-reference according to their experiences and world knowledge [21]. Accompanying the self-reference, the social statistical information may be consistent or inconsistent with people's background knowledge, which may cause emotion. In other words, according to the characteristics of the social statistical information, the comprehension of it would cover semantic processing, integrating of associations, self-reference and emotional cognition. To date, however, the role of the prefrontal cortex in comprehending the social statistical information remains unknown yet. Collectively, numerous studies have confirmed that the prefrontal cortex plays a critical role in information encoding and memory. This fMRI study mainly examined the activity of the prefrontal cortex during subjects comprehending the social statistical information.

2 Methods

2.1 Participants

Thirty-six volunteers (eighteen female and eighteen male; mean age ± standard deviation (S.D.) = 22.5 ± 1.7) participated in this study. All of the subjects were right-handed and native-Chinese speaker. The subjects had no history of neurological or psychiatric illness, and no developmental disorders, including reading disablities. All of the participants gave their written informed consent, and the protocol was approved by the Ethical Committee of Xuanwu Hospital of Capital Medical University and the institutional Review Board of the Beijing University of Technology.

2.2 Stimuli and Procedure

In the experiment, 20 text and graph stimuli, as well as 8 text-baseline and figure-baseline stimuli were used. Each text stimulus was presented for a period of 16 seconds, the graph was presented for 14 s, and both text-baseline and graph-baseline were presented for 8 s. The presentation time was set according to the behavioral experiment, in which participants can fully understand the information of text or graph presented to them. The text and graph tasks describing the same event were counterbalanced across subjects; no individual read the same event twice [26].

The experiment consists of 4 sessions. The order of the text and graph stimuli was pseudo-randomized in each session. All stimuli were presented on a blank background screen. The participants were instructed to read text and graph information attentively. Four sessions were collected per each participant. The images for the initial 10 s were discarded because of unsteady magnetization; the remaining images in the session were used in the analysis.

2.3 Image Acquisition

Blood oxygenation level-dependent fMRI signal data were collected from each participant using a Siemens 3-T Trio scanner (Trio system; Siemens Magnetom scanner, Erlangen, Germany). Functional data were acquired using a gradient-echo echo-planar pulse sequence (TR = 2000 ms, TE = 31 ms, FA = 90°,the matrix size = 64× 64 mm, Voxel = 4 × 4 × 4 mm, 30 slices, slice thickness = 4 mm, inter-slice interval = 0.8 mm, FOV = 240 × 240 mm). High-resolution T1-weighted anatomical images were collected in the same plane as the functional image using a spin echo sequence with the following parameters (TR = 130 ms, TE = 2.89 ms, FA = 70°, the matrix size = 320 × 320 mm, Voxel = 0.8 × 0.8 × 4 mm, 30 slices, slice thickness = 4 mm, inter-slice interval = 0.8 mm, FOV = 240 × 240 mm). Stimulus presentation and data synchronization were conducted using E-Prime 2.0 (Psychology Software Tools, Pittsburgh, USA). Prior to each run, the first two (10 s) discarded volumes were acquired to enable the stabilization of magnetization. The scanner was synchronized with the presentation of every trial in each run.

2.4 Data Analysis

Data analysis was performed with SPM2 from the Welcome Department of Cognitive Neurology, London, UK. MNI coordinates were transferred into Talairach coordinates (Talairach and Tournoux, 1988). The functional images of each participant were corrected for slice timing, and all volumes were spatially realigned to the first volume (head movement was < 2 mm in all cases). A mean image created from the realigned volumes was coregistered with the structural T1 volume and the structural volumes spatially normalized to the Montreal Neurological Institute (MNI) EPI temple using nonlinear basis functions. Images were resampled into 2-mm cubic voxels and then spatially smoothed with a Gaussian kernel of 8 mm full-width at half-maximum (FWHM). The stimulus onsets of the trials for each condition were convolved with the canonical form of the hemodynamic response function (hrf) as defined in SPM 2. Statistical inferences were drawn on the basis of the general linear modal as it is implemented in SPM 2. Linear contrasts were calculated for the comparisons between conditions. The contrast images were then entered into a second level analysis (random effects model) to extend statistical inference about activity differences to the population from which the participants were drawn. Activations are reported for clusters of 10 contiguous voxels (80 mm^3) that surpassed a corrected threshold of $p < .05$ on the cluster level.

3 Results

The goal of this study was to examine the activity of the prefrontal cortex during comprehending the social statistical information presented either in graph or textual forms. The activation of the prefrontal cortex was obtained through contrasting the graph and textual tasks of the social statistical information with their corresponding baselines.

Figure 1 shows the activation of the prefrontal cortex when participants comprehended the social statistical information. From the Fig. 1 (a) and (b), we can see that the regions activated when comprehending the graph and textual forms of the social statistical information are almost completely overlapped. The social statistical information described in the statistical graph, activated the VLPFC (BA47) involving the anterior portion (y = 30, left; y = 34, right) and posterior portions (y = 11, left; y = 13, right), the MPFC involving the dorsal (BA9/10) and ventral parts (BA10), along with the activation of the dorsal and ventral parts of the ACC (BA32/24), as shown in Table 1; the social statistical information described in the textual form, consistently activated the anterior portion (y = 30, left; y = 30, right) and posterior portion (y = 11, left; y = 13, right) of the VLPFC (BA47), the dorsal (BA9/10) and ventral (BA10) parts of the MPFC, and the dorsal and ventral parts of the ACC (BA32/24), as shown in Table 2.

4 Discussion

In this study, the comprehension of the social statistical information in the both graph and textual forms has consistently activated the anterior and posterior

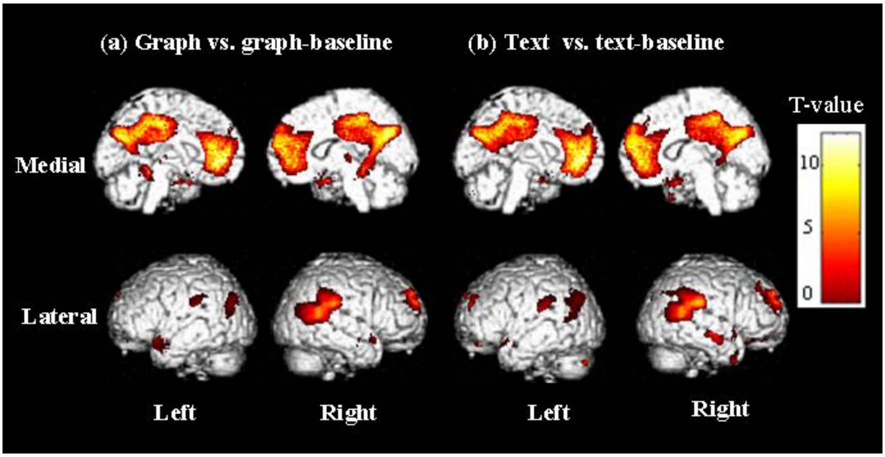

Fig. 1. The regions activated through the graph and textual tasks directly compared with their corresponding baselines. (a) Graph vs. graph-baseline significantly activated the MPFC and VLPFC. (b) Text vs. text-baseline also significantly activated the MPFC and VLPFC. From (a) and (b), we can see that the activation maps of graph and textual forms of the social statistical information are almost completely overlapped. The threshold $p < 0.05$, corrected, Cluster size ≥ 80 mm^3.

portions of the VLPFC. Previous studies have demonstrated that the anterior portion of the VLPFC is activated in semantic processing [11,15,16] and integrating semantics with world knowledge [27], whereas the posterior portion of the VLPFC shows decreasing activation during repeating semantic processing [28], suggesting that the posterior potion of the VLPFC is related to semantic working memory. During comprehending the social statistical information, the semantic processing of the current information and the integration of the semantics with their world knowledge would activate the anterior of the VLPFC. Further more, the on-line semantic retrieval contributing to the integration of semantics in context needs the semantic repetition priming of the prior information that would deactivate the posterior of the VLPFC. Form the change of the blood oxygenation level-dependent (BOLD) signal in both of these areas, the anterior portion of the VLPFC showed increasing activation, but the posterior portion of the VLPFC showed decreasing activation, as detailed in our previous study [29]. These results further suggest that the anterior portion of the VLPFC is more related to semantic processing, whereas the posterior portion of the VLPFC is more related to semantic working memory during the social statistical information processing.

Consistent with our hypothesis, the dorsal and ventral MPFC were activated during comprehending the social statistical information. Previous studies have demonstrated that the dorsal MPFC is engaged in the processing of associating information [30,31], and the ventral MPFC is response to the processing of self-reference [21,22] and emotional cognition [24]. The social statistical information is a kind of typical associating information, and the comprehension of which involves not only associating the object-name with its object-value, but also integrating the information among objects.

Table 1. Brain activations within the prefrontal cortex during graph tasks comparing with baseline ($p < 0.05, corrected$)

Anatomical regions	Coordinates[a] x	y	z	t	Cluster size (mm^3)
Ventral MPFC					
Rt.MPFC/ACC(BA10/32)	6	46	-6	9.76	984
Lt.ACC (BA24)	-4	33	2	10.48	456
Lt.ACC (BA32)	-10	39	2	9.93	648
ACC (BA24/32)	0	35	-2	10.68	648
Dorsal MPFC					
Rt.MPFC (BA10)	4	53	7	11.19	6008
Rt.SFG (BA9)	12	56	30	7.54	1864
Rt.SFG (BA9)	16	44	31	6.23	632
Rt.SFG (BA10)	22	54	23	7.25	648
Rt.ACC (BA32/24)	4	32	19	10.24	2056
Rt.ACC (BA24)	6	35	4	11.04	2000
VLPFC					
Lt.IFG (BA47)	-30	11	-14	9.08	2176
Lt.IFG (BA47)	-30	30	-12	6.88	488
Rt.IFG (BA47)	28	13	-16	7.34	1000
Rt.IFG (BA47)	30	34	-13	6.26	768

[a] The Talairach coordinates of the centroid and associated maximum t within contiguous regions are reported. BA, Brodmann area; MPFC: medial prefrontal cortex; SFG: superior frontal gyrus; ACC: anterior cingulate cortex; VLPFC: ventrolateral prefrontal cortex; IFG: inferior frontal gyrus; Lt: left hemisphere; Rt: right hemisphere.

Our results suggest that the dorsal MPFC is related to the processing of the associations of the social statistical information. Additionally, the social statistical information is very close to our daily life, and we can not help referencing it to our experience and world knowledge, then generating self-reference. Thus, we suggest that the activation of the ventral MPFC response to self-reference. Accompanying the self-reference, the social statistical information may be consistent or inconsistent with people's background knowledge, which may cause emotion. Thus, the activity of the ventral MPFC may be also related to the emotional cognition.

Table 2. Brain activations within the prefrontal cortex during textual tasks comparing with text-baseline ($p < 0.05, corrected$)

Anatomical regions	Coordinates[a] x	y	z	t	Cluster size (mm^3)
Ventral MPFC					
Lt.MPFC(BA10)	-6	49	1	10.89	264
Rt.MPFC/ACC (BA10/32)	8	46	-4	10.57	264
Lt.ACC (BA24)	-6	33	0	10.33	648
Lt.ACC (BA32)	-8	43	-4	10.51	456
Lt.ACC (BA32)	-10	39	0	10.42	456
Dorsal MPFC					
Rt.MPFC (BA10)	4	51	7	11.82	4120
Lt.SFG (BA10)	-20	52	23	6.68	1328
Rt.SFG (BA9)	12	54	30	8.09	1432
Rt.SFG (BA10)	22	52	23	8.83	2056
Rt.MidFG (BA8)	26	39	40	6.35	1704
Rt.ACC (BA24/32)	4	32	17	10.46	1624
Rt.ACC (BA24)	6	35	4	10.73	456
Rt.ACC (BA32)	8	39	9	10.88	1176
VLPFC					
Lt.IFG (BA47)	-30	11	-14	7.70	1584
Lt.IFG (BA47)	-30	30	-12	6.94	768
Rt.IFG (BA47)	26	13	-17	7.51	2256
Rt.IFG (BA47)	30	30	-17	6.05	616

[a] The Talairach coordinates of the centroid and associated maximum t within contiguous regions are reported. BA, Brodmann area; MPFC: medial prefrontal cortex; SFG: superior frontal gyrus; MidFG: middle frontal gyrus; ACC: anterior cingulate cortex; VLPFC: ventrolateral prefrontal cortex; IFG: inferior frontal gyrus; Lt: left hemisphere; Rt: right hemisphere.

Some studies have demonstrated that the ventral ACC was involved in emotion monitoring [32]. In this study, we further investigated of the activity of the ventral ACC, and the activation of this region suggests that emotion is indeed generated during the social statistical information processing. Because the experimental material of this study did not contain any emotional information, it suggests that the emotion is caused by the internal environment of self-reference rather than the external environment of the social statistical information itself. In addition, the dorsal ACC was also activated during the social statistical information processing. Previous studies have consistently suggested that this area is a part of the anterior attentional system engaged in selection of action in complex tasks [33,34], and also takes a part in conflict control [1,35,36]. The comprehension of the social statistical information includes multiple cognitive elements, such as semantic processing, integration of associations, self-reference and emotional cognition. These processes need the dorsal ACC to regulate the attentional resource. This area may be also responsible to the conflict control, because the social statistical information may conflict with people's world knowledge.

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