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Statistical Analysis on Gender Difference in Neural Activity for Spatial Ability Tasks

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Abstract

Gender differences are investigated from the viewpoint of cognitive neuroscience in the domain of spatial ability. Five task types of geometric problems are used for the collection of task-evoked fMRI data. Although there was no gender-difference in task performance, we found gender differences in neural activity. Some of the important gender differences that we found are 1) that there are far more joint neuro-activations among the brain regions, co-activations or reverse-activations, in males than in females, 2) that the two types of joint activations were nearly half and half in females while it was mostly co-activations in males, 3) that males tend to have more co-activations in the left hemisphere than expected while females tend to have more between-hemisphere co-activations than expected, and 4) that the left-right pairs of BA's are more highly associated than average for males while they are far less associated than average for females.

Keywords

Cross-Correlation, Functional Magnetic Resonance Imaging, Co-Activation and Reverse-Activation, Between and Within Hemisphere

1. Introduction

Spatial ability is the ability that is employed for executing cognitive tasks such as generating, storing, retrieving, and transforming visuo-spatial information. This ability is known to produce robust gender differences favoring males [1]-[7]. It is also reported in the literature that males usually perform better on mental rotation tasks than females [8]-[16]. As correlates of gender differences in spatial ability, biological factors such as sex hormones associated with the phase of the menstrual cycle [13] [17] [18] [19] [20] or the ratio of the 2nd to 4th finger length [14] [21] [22] [23], bodily measures [24], and structural brain morphology [25], and environmental factors such as gender role socialization [26] [27] and the level of education [1] [28] [29] [30] have been inspected. Although some supporting hypotheses for gender differences in spatial ability, such as an evolutionary hypothesis [31] [32] [33] [34] [35], a gender similarity hypothesis [36] [37], and a functional lateralization hypothesis [38]-[45] were proposed, the issue of gender difference in spatial ability is yet wide open.

In this study, we analyzed functional magnetic resonance imaging (fMRI) data of task performances and explored gender differences in spatial ability by using five task types of spatial ability in an effort to refine the neurocognitive understanding of spatial ability. The five task types consist of picture completion (PC), mental rotation (MR), surface development (SD), aperture passing (AP), and hole punching (HP). We found gender differences in neural correlates and activations in response to the five task types. We also saw a gender difference in the functional relationship among brain regions.

2. Method

2.1. Participants

61 young healthy undergraduate students (27 males and 34 females) participated in the study. They were recruited by announcements on the bulletin boards of a local university and all of them majored in natural sciences or engineering. All the participants reported no history of psychiatric or neurological abnormality and submitted the signed informed consent forms.

2.2. Data Acquisition and Task Types

fMRI data were acquired from an ISOL FORTE scanner (ISOL Technology, Gyeonggi, Korea) operating at 3 Tesla. A total of 177 whole-brain images were collected using a T2*-weighted single-shot echo-planar imaging (EPI) sequence (repetition time (TR) = 3000 msec, echo time (TE) = 35 msec, number of slices = 36, slice thickness = 3 mm, matrix size = 64 × 64, the field of view = 220 mm × 220 mm). Subjects performed 5 types of spatial ability tasks during the scanning. In a block designed experiment, 15 problem sets (5 task types × 3 problem sets) were presented in a random order to each subject. A set of problems were presented at regular intervals (21 seconds) after instructions on how to solve problems (6 seconds). Fixations were provided before a subsequent problem set (9 seconds). As shown in **Figure 1**, each problem was displayed in two figure frames, one for a stimulus and the other for a test probe. If the test probe corresponded appropriately to the stimulus figure, that is, 1) in picture completion if the test probe fitted the stimulus, 2) in mental rotation if the test probe was rotated to match the stimulus, 3) in surface development if the test probe was constructed by folding the stimulus, 4) in aperture passing if the test probe was a projection from the stimulus, and 5) in hole punching if the stimulus was acquired by

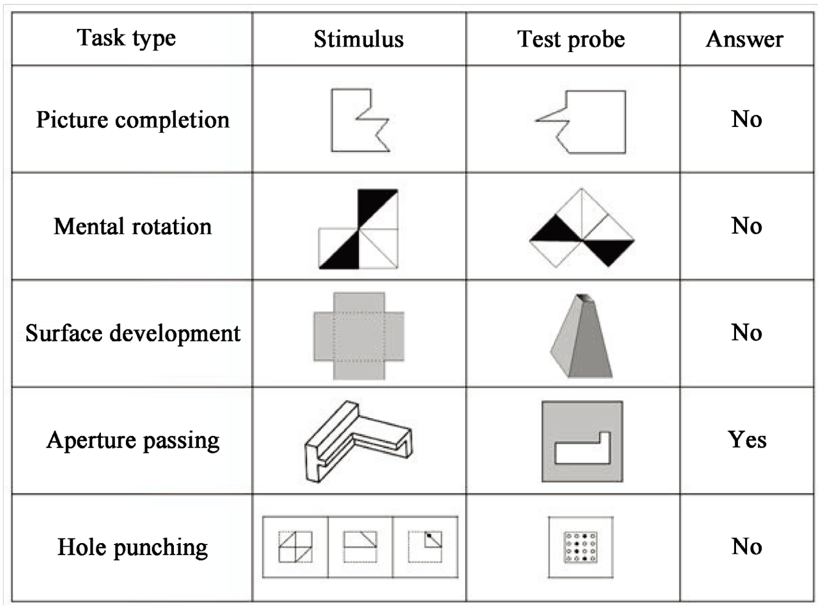


Figure 1. Sample problems of the five task types.

unfolding the test probe, a subject was supposed to answer ‘Yes’ or ‘No’ by pressing the left or right mouse button, respectively. The overall performance of the tasks was measured as discriminability, that is, hit rate minus false alarm rate. The cognitive complexity of the five task types of spatial ability was measured by task scores.

2.3. fMRI Data Analysis

Preprocessing and statistical analysis of the fMRI data were carried out using the SPM8 software (Wellcome Trust Centre for Neuroimaging, University College London, London, UK). The preprocessing steps included spatial realignment to the mean volume of a series of images, normalization into the same coordinate frame as the MNI-template brain, and smoothing using a Gaussian filter of 8 mm FWHM. The fMRI data were then analyzed statistically for each participant and the analysis results were used for random-effects analysis. In random-effects analysis, we used a factorial design for repeated measures ANOVA with gender as a between-group factor and task type as a within-group factor. We checked for an interaction effect between gender and task type and for consistent gender differences in neural activation across the five task types. In all statistical inferences, we determined the statistical significance at the height threshold of an uncorrected p-value less than 0.001 and the cluster extent threshold of more than ten voxels.

3. Results

3.1. Trend in Task Scores

We saw no significant gender difference in the mean of the task scores with the p-value, 0.052. For more detailed description of the difference, the 95% simultaneous confidence intervals of the difference are given in **Table 1** and the boxplots of the task scores in **Figure 2**. For convenience' sake, we will label the five task types, PC, MR, SD, AP, and HP, respectively, by 1, 2, ⋯, 5.

We can apparently see a trend of the mean scores across the task types as displayed in panel (a) of **Figure 3**. The mean scores are decreasing in the order of PC, MR, AP, SD, and HP. The difference among the score means is displayed in panel (b) by grouping. The task scores in the same parentheses suggest no significant difference between them at the significance level 0.05. For both sexes, task type 1 and each of task types 3, 4, and 5 are significantly different in the context of task scores, and so are task types 2 and 5. The score grouping is slightly different between males and females in that task types 4 (AP) and 5 (HP) are significantly different in females while they are not in males. As for males,,

Table 1. The 95% simultaneous confidence intervals of the differences of means, $\mu_M - \mu_F$.

Task type	Lower limit	Upper limit
1 (PC)	−1.83	3.57
2 (MR)	−1.96	6.32
3 (SD)	−2.69	6.61
4 (AP)	−2.88	3.87
5 (HP)	−0.08	7.77

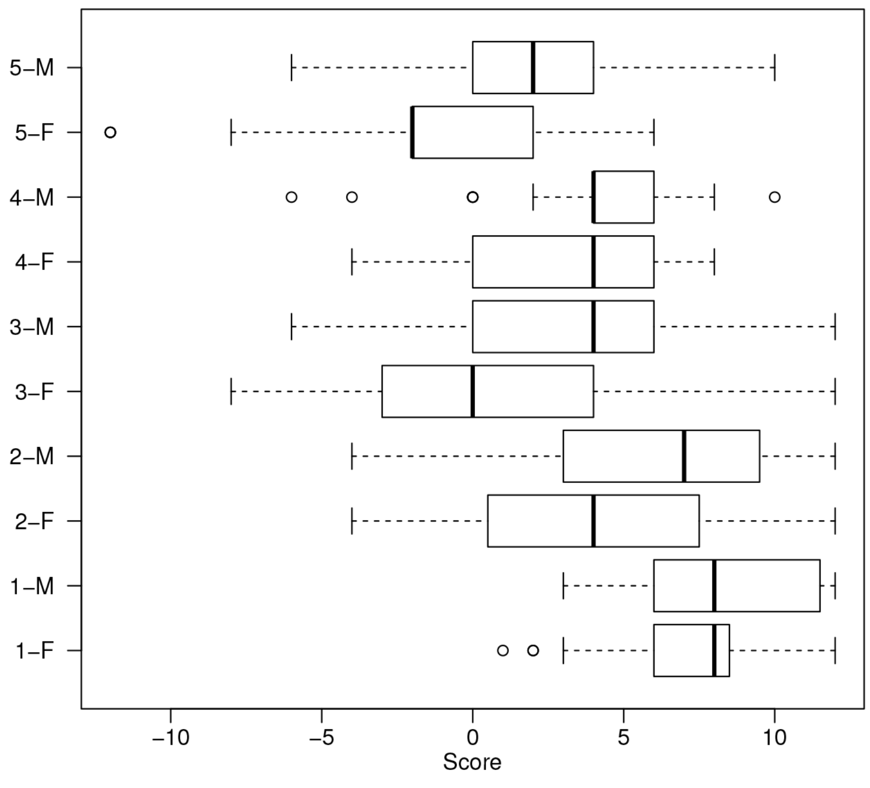
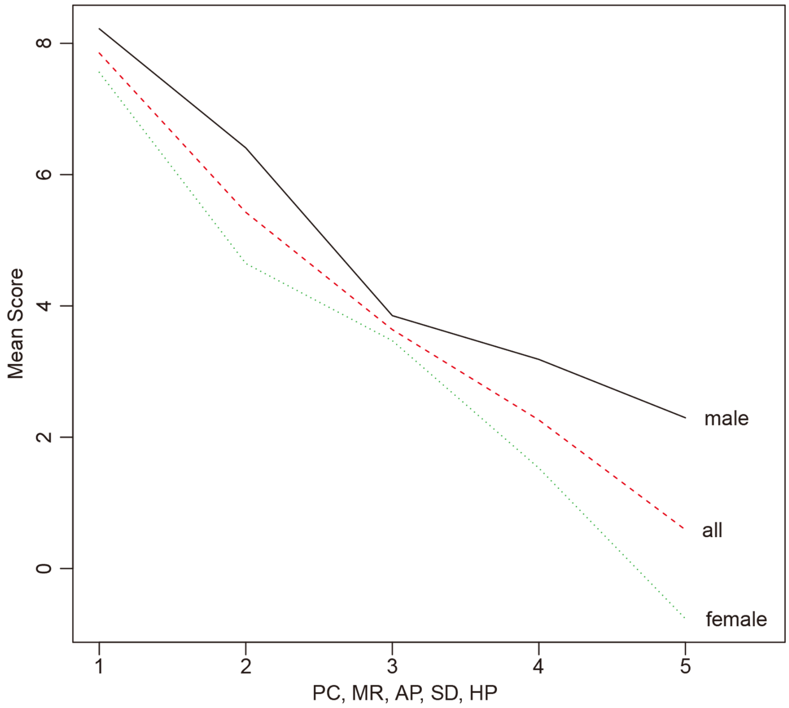


Figure 2. Boxplots of task scores.



(a)

Sex	Grouping
Male	(PC, MR), (MR, AP, SD), (AP, SD, HP)
Female	(PC, MR), (MR, AP, SD), (SD, HP)

(b)

Figure 3. Comparison of the mean task scores between male and female for the 5 task types. In panel (b), the task types in the same group (in parentheses) are regarded as of equal mean task scores at the significance level $\alpha = 0.05$. (a) Mean task scores; (b) Multiple comparison of mean task scores.

task types 3, 4, and 5 belong to the same score group while only task types 3 and 5 (*i.e.*, SD and HP) belong to the same score group for females.

3.2. Gender Difference in Neural Activity for All the Tasks

While there was no significant gender difference in task scores, we could see significant gender differences in neural activities. Across the five task types, males showed higher activations consistently in the occipital cortex (OC) (BA 17, 18, 19), left prefrontal cortex (PFC) (BA 44) and posterior parietal cortex (PPC) (BA 7, 23), whereas females showed higher activations consistently in the left PPC (BA 40). In repeated measures ANOVA, an interaction effect between gender and task type was shown in the OC.

3.3. Cross-Correlations of Neural Activation

Let X_{kt} denote the activity level at brain region k in response to task type t. Then the cross-correlation $corr(X_{kt}, X_{lu}) = 0$ means, under the Gaussian assumption, that the activity level at brain region k in response to task type t is independent of the activity level at brain region l in response to task type u. In other words, a high activity level at brain region k in solving a problem of task type t does not necessarily imply a high (or low) activity level at brain region l in solving a problem of task type u.

Figure 4 summarises the cross-correlations of the activity levels among the 82

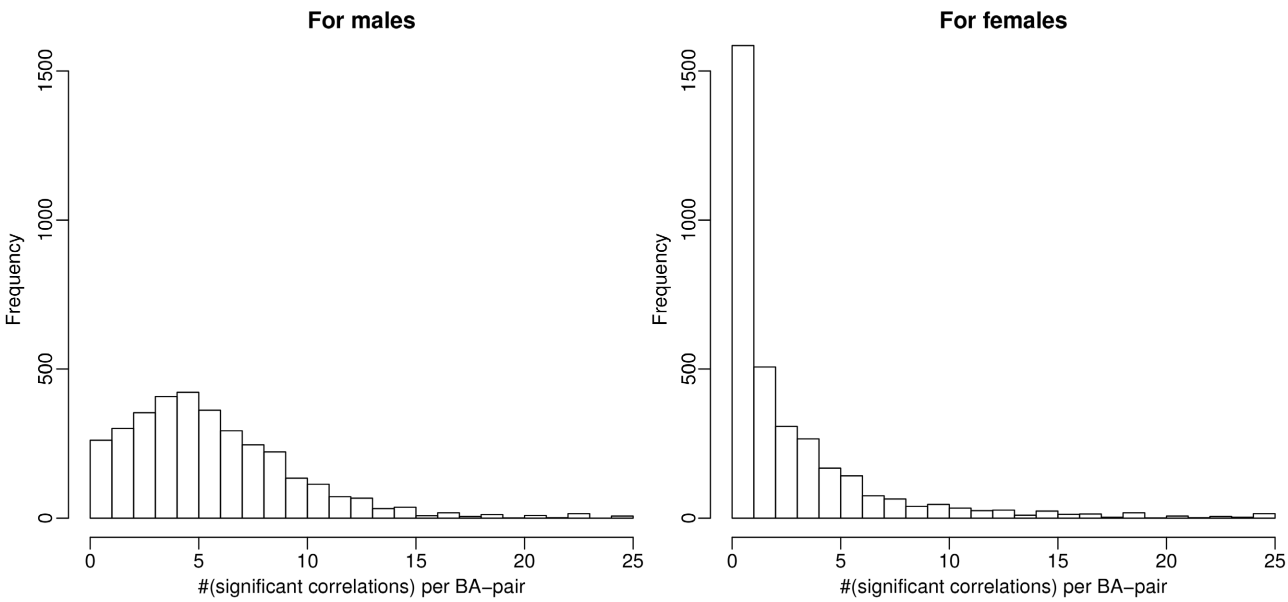


Figure 4. Gender-difference in cross-correlations of the brain activitivation in response to the 5 task types across the 82 BA's. For each BA-pair, the number (n_{kl}) of the task-type pairs are counted whose correlations are significant ($\alpha = 0.05$), and the distribution of $n_{kl}, 1 \le k \le l \le 82$, is given in histogram for each sex.

Table 2. Frequency table of $n_{kl} \le 7$.

Sex	n_{kl}							
	0	1	2	3	4	5	6	7
F	1585	507	308	266	168	142	75	64
M	261	301	354	408	422	362	293	246

Brodmann areas (BA's). For each BA-pair, BA's k and l ($1 \le k, l \le 82$), we counted the number n_{kl} of the task-type pairs for which the brain activity levels are correlated significantly. Note that $0 \le n_{kl} \le 25$ for all k, l. The histograms in the figure show the distribution of n_{kl}. We can see a dramatic gender difference in the distribution. A part of the frequency table is given in **Table 2** as a zoom-in for the histograms. This apparent difference indicates that brain regions are more associated functionally in males than in females. The number of the BA-pairs for which $n_{kl} = 0$ is 1585 which is about a half (48%) of the total number of BA-pairs (=3321). If we consider up to the numbers of $n_{kl} \le 1$, it is 2092 (63%) for females and 562 (17%) for males. This is a strong indication that there is a far less functional association among the brain regions for females than for males. We may interpret this as that: males are more co-operative in brain activity than females as far as the problem solving of geometric problems is concerned.

Another question we were interested in was if there is a stronger association between the left-right counterparts of BA than between every other pair of BA's. We can see a gender difference in **Table 3**. As for the male, the association between the left-right counterparts of BA is a more often occurrence than it is among

Table 3. Quantiles of n_{kl} for two types of BA pairs. (a) For males; (b) For females.

(a)

Brain regions	Proportion (%)								
	10	20	30	40	50	60	70	80	90
Left-right pairs	5	7	9	10	11	13	14	17	19
All the other pairs	2	3	4	4	5	6	7	8	10

(b)

Brain regions	Proportion (%)								
	10	20	30	40	50	60	70	80	90
Left-right pairs	0	0	0	1	1	1	2	2	5
All the other pairs	0	0	1	1	2	2	3	4	7

the other pairs of BA's. The asymptotic *z*-score of the Mann-Whitney-Wilcoxon (MWW) test [46] is 6.79 (with its upper tail probability near 0), which strongly indicates a higher left-right association of BA's than the average of the associations among the BA's. The phenomenon is quite a contrary for females, as can be seen in the table. The left-right association is shown to be weaker than average with the asymptotic *z*-score of the MWW test −4.40 (with its lower tail probability near 0). In a nutshell, there are more pairwise left-right BA associations than average in males while there are fewer of them than average in females. We need a little bit of prudence here in that the MWW test is used under the assumption that n_{kl}'s are independent of each other. As a matter of fact, they may not be independent. We however used this test as an approximate surrogate to measure the difference between the two pair types of BA's, left-right counterpart pairs and the other type of pairs.

So far we have investigated significance of the association without regard to the sign of the correlation. If the correlation is positive, we may interpret the association of a pair of BA's as co-activation; otherwise, as reverse-activation. **Table 4** summarizes the analysis result of the pairwise activation patterns. The patterns are surprisingly contrasting between males and females. Among the associations between BA's, they are mostly due to co-activation for males while they are divided nearly half and half between the two types of activities for females. This result seems to be well in tune with the findings by [47] in the context of neural processing efficiency.

We were also interested in whether there are more co-activations or reverse-activations between hemispheres than within hemispheres or vice versa. To further investigate in this line, we took each of the numbers in **Table 4** into three pieces, one corresponding to the mutual activations of the BA's in the left hemisphere, another in the right hemisphere, and a third between hemispheres. This refinement is summarized in **Table 5**. For instance, the value 1518 for males in **Table 4** is broken into three pieces, 409, 746, and 363. 409 BA-pairs co-activate

Table 4. Co-activation and reverse-activation counts of BA's. The numbers are of the BA-pairs for each task type which are significant at the significance level 0.05. "+" ("-") stands for co-activation (reverse-activation).

Sex	Task type									
	1		2		3		4		5	
	−	+	−	+	−	+	−	+	−	+
M	26	1518	0	2408	2	1637	0	2253	0	2249
F	178	196	180	171	152	156	175	172	180	183

Table 5. Co-activation and reverse-activation counts of BA's between and within hemispheres. The numbers are of the BA-pairs for each task type which are significant at the significance level 0.05. "L" and "R" stand for the left and right hemispheres, respectively, and "Between" for "between hemisphere".

Task type	Male			Female					
	Co-activation			Co-activation			Reverse-activation		
	L	Between	R	L	Between	R	L	Between	R
1	409↑	746	363	35	115↑	46	41	84	53
2	608	1225	575	34	93	44	52	76↓	52
3	455↑	788↓	394	28	95↑	33	37	70	45
4	606↑	1124	523	38	107↑	27	39	92	44
5	589	1114↓	546	34	108↑	41	40	85	55

Note (1) The ↑ in the "L" column means that its value significantly larger than its counterpart in the "R" column at the significance level $\alpha = 0.05$. (2) The ↑ in the "Between" column means that the number of the between-hemisphere BA-pairs which co-activate (or reverse-activate) are significantly larger (↓ for smaller) than the number of the within-hemisphere BA-pairs which co-activate (or reverse-activate) at $\alpha = 0.05$.

in the left (L) hemisphere, 363 BA-pairs in the right (R) hemisphere, and 746 between-hemisphere BA-pairs. We ignored the reverse-activation for males since there were only 28 such cases.

It is obvious in **Table 5** that, in males, there are a larger or equal number of co-activations in the left hemisphere than expected. On the other hand, the between-hemisphere co-activations occur at least as often as expected in females. There are no significant differences in the number of reverse-activations in females except that the between-hemisphere reverse-activation occurs less often than expected for task type 2. In a nutshell, males tend to use the left hemisphere more often than expected and, as for females, between-hemisphere co-activations are more often than expected.

The two types of joint activations in females are displayed in **Figure 5**, which is obtained by applying the modelling method as proposed in [48]. Co-activation BA-pairs are connected by red lines and reverse-activation BA-pairs by blue lines. We can see in the figure that the two types of joint activations occur over almost the same brain regions each other and that some brain regions are functionally connected with other regions more in co-activation than in reverse-activation and vice versa. It is obvious in the figure that a brain region co-activates with another region while it reverse-activates with a third. As a visual aid, we added a figure of the joint activations for the five task types in **Figure 6**.

To sum up the analysis results of correlations, as long as the problem solving of geometric problems are concerned, 1) brain regions are far more associated functionally in males than females (**Table 2**), 2) the left-right pairs of BA's are more highly associated than average for males while they are far less associated than average for females (**Table 3**), 3) the association between brain regions are mostly due to co-activation for males while, for females, only half of the associations are due to co-activation and the other half by reverse-activation (**Table 4**), and 4) males tend to have more co-activations in the left hemisphere than expected while females tend to have more between-hemisphere co-activations than expected (**Table 5**).

4. Concluding Remarks

In the correlation analysis, we tried to investigate functional connectivity among

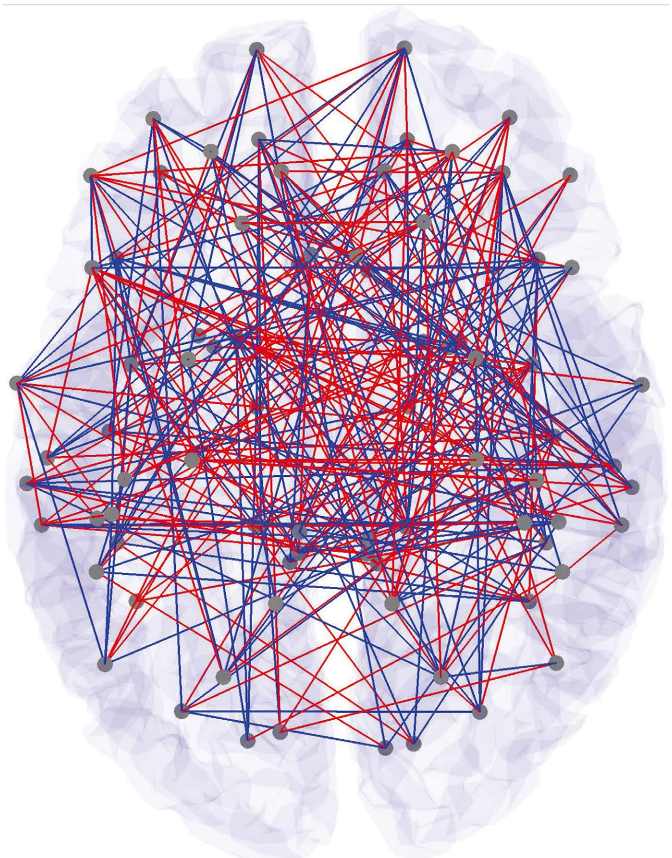


Figure 5. Inferior view of co-activation (in red) and reverse-activation (in blue) between brain areas of a female participant.

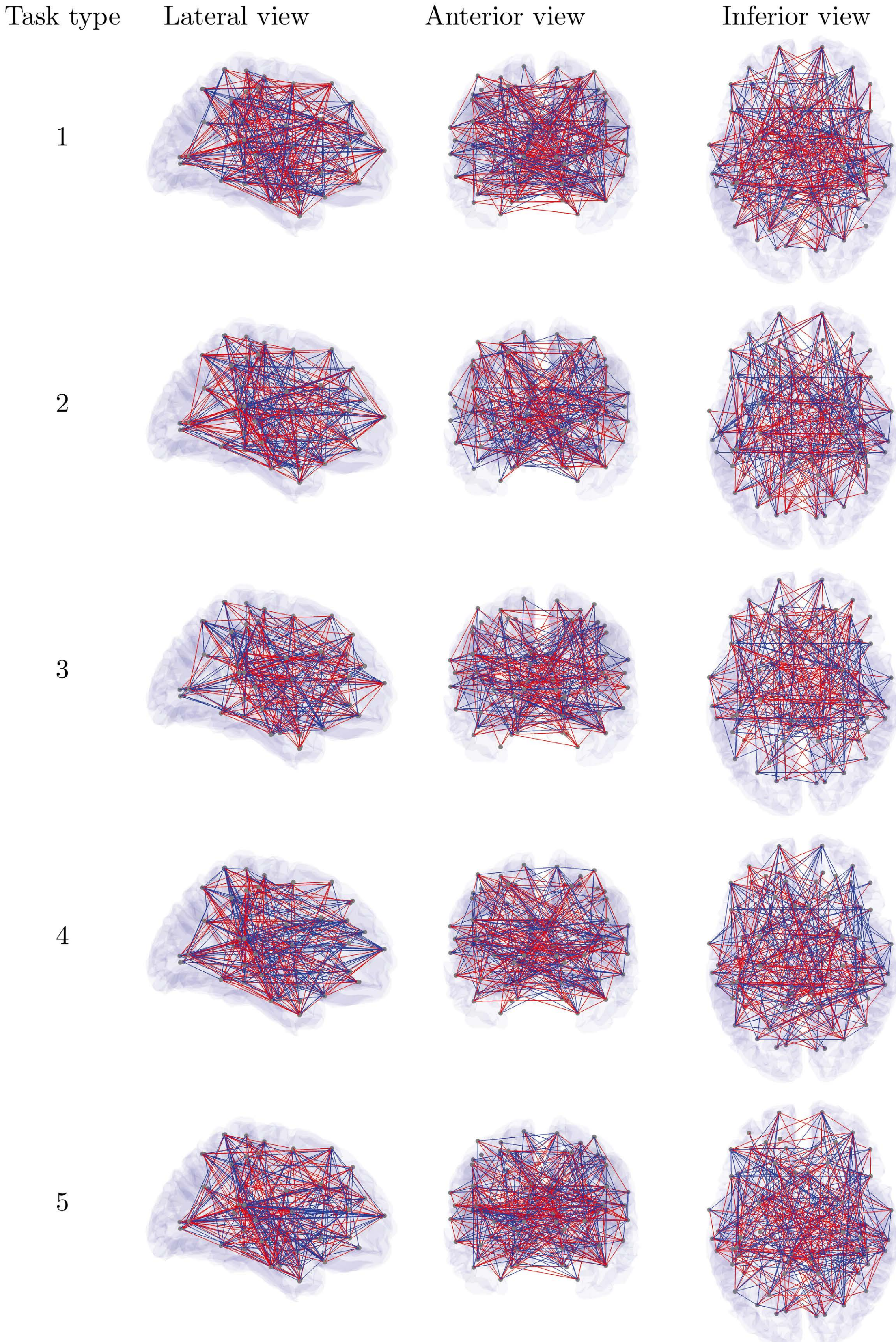


Figure 6. Co-activation (in red) and reverse-activation (in blue) graphs for females from three viewpoints, lateral, anterior, and inferior.

brain regions from two viewpoints. In one of them, we counted the number (n_{kl}) of task type pairs for which a certain pair of BA's, say BA's k and l, are correlated significantly. For each $k \neq l$, $0 \leq n_{kl} \leq 25$. A larger n_{kl} can be interpreted as a stronger correlation between BA's k and l. There was no significant functional connectivity for nearly half (48%) of the BA-pairs for females while it is only 8% for males. This is a global look at functional connectivity without regard to the task type.

A refined description of the functional connectivity for each task type is that males are found to have more or as many co-activations of BA's in the left hemisphere as expected, while females are found to have more or as many co-activations between hemispheres as expected. This result is well in tune with the gender difference in the structural connectome of the brain found in [49]. As for the patterns of functional connectivity, the connectivity is shown to be via co-activation for males while it is divided almost half and half into co-activation and reverse-activation for females.

The result of this work is limited in interpretation in the sense that the data for this work is from college students majoring in natural sciences or engineering. However, it is worthwhile to note that male and female students could get the same performance scores on spatial ability tasks while the neural activity pattern was quite contrasting between males and females, as was found in the paper.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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