NeuroImage 158 (2017) 397–405

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

Sex-linked association between cortical scene selectivity and navigational ability

Xiang-Zhen Kong [a], Yi Huang [a], Xin Hao [a], Siyuan Hu [b], Jia Liu [b,*]

[a] State Key Laboratory of Cognitive Neuroscience and Learning & IDG/McGovern Institute for Brain Research, Beijing Normal University, Beijing, 100875, China
[b] Beijing Key Laboratory of Applied Experimental Psychology & National Demonstration Center for Experimental Psychology Education (Beijing Normal University), Faculty of Psychology, Beijing Normal University, Beijing, 100875, China

ARTICLE INFO

Keywords:
Parahippocampal place area
Sex differences
Spatial navigation
Scene processing

ABSTRACT

Spatial navigation is a crucial ability for living. Previous studies have shown that males are better at navigation than females, but little is known about the neural basis underlying the sex differences. In this study, we investigated whether cortical scene processing in three well-established scene-selective regions was sexually different, by examining sex differences in scene selectivity and its behavioral relevance to navigation. To do this, we used functional magnetic resonance imaging (fMRI) to scan the parahippocampal place area (PPA), retrosplenial complex (RSC), and occipital place area (OPA) in a large cohort of healthy young adults viewing navigationally relevant scenes (N = 202), and correlated their neural selectivity to scenes with their self-reported navigational ability. Behaviorally, we replicated the previous finding that males were better at navigation than females. Neurally, we found that the scene selectivity in the bilateral PPA, not in the RSC or OPA, was significantly higher in males than females. Such differences could not be explained by confounding factors including brain size and fMRI data quality. Importantly, males, not females, with stronger scene selectivity in the left PPA possessed better navigational ability. This brain-behavior association could not be accounted for by non-navigational abilities (i.e., intelligence and mental rotation ability). Overall, our study provides novel empirical evidence demonstrating sex differences in the brain activity, inviting further studies on sex differences in the neural network for spatial navigation.

1. Introduction

Spatial navigation is a crucial ability for living, since way-finding and environmental exploration are features of our daily lives. Additionally, many previous studies have shown that males have better navigational ability when compared with females (Astur et al., 1998; Moffata et al., 1998). From a behavioral perspective, the sex differences in spatial navigation are thought to be caused by differences in the environmental cues and strategies (e.g., egocentric versus allocentric) used during navigation and orientation (Chai and Jacobs, 2009; Lawton, 1994; Lovden et al., 2007; Wolbers and Hegarty, 2010). However, given the complex nature of human navigation, little is known about the neural basis underlying the differences.

To date, only a handful of neuroimaging studies involving navigation-related tasks have examined this issue. Perhaps the most relevant example is the functional neuroimaging study conducted by Gron et al. (2000), which involved a virtual maze task. This study reported that activation in the medial temporal areas was greater in males when compared with females performing the same task, whereas prefrontal cortex and inferior and superior parietal region activation was greater in females when compared with males (Gron et al., 2000). Given that this virtual navigation task involved complex cognitive processes such as encoding, memory storage and retrieval, and movement, further detailed studies are required to better understand the neural basis underlying sex differences in human navigation. In this study, we focused on the cortical processing of surrounding scenes, which is a critical early-stage component of spatial navigation.

Previous functional magnetic resonance imaging (fMRI) studies have identified three regions in the human brain as the cortical machinery specialized for processing scenes (i.e., scene-selective regions). These include the parahippocampal place area (PPA) in the posterior parahippocampal cortex (Epstein et al., 1999), the retrosplenial complex

* Corresponding author. Room 405, Yingdong Building, 19 Xinjiekouwai St, Haidian District, Beijing, 100875, China.
E-mail address: liujia@bnu.edu.cn (J. Liu).

http://dx.doi.org/10.1016/j.neuroimage.2017.07.031
Received 18 February 2016; Received in revised form 13 July 2017; Accepted 14 July 2017
Available online 16 July 2017

(RSC) in the parieto-occipital sulcus (Maguire, 2001), and the occipital place area (OPA, previously known as the TOS) in the transverse occipital sulcus (Dilks et al., 2013; Grill-Spector, 2003). While the PPA is primarily involved in presenting the visuospatial structure of the immediate scene, the RSC appears to encode or integrate the spatial information of the scene (Epstein, 2008; Epstein and Higgins, 2007; Park and Chun, 2009). Although little is known about the precise function of the OPA, it has been shown to be causally and selectively involved in scene processing (Dilks et al., 2013; Ganaden et al., 2013). Neuropsychological evidence has shown that lesions in these scene-responsive regions (e.g., the PPA and RSC) impair patients' navigational abilities. For example, patients with damage to the parahippocampal cortex show selective deficits in navigating novel environments (Epstein et al., 2001; Mendez and Cherrier, 2003), and patients with damage in the RSC are unable to describe the relationship between locations (Takahashi et al., 1997). In short, these previous studies suggest that scene-selective regions play a critical role in human navigation. Taking into account the sex differences in human navigation, we hypothesized that scene processing in these regions might contribute to spatial navigation through different mechanisms in healthy females and males.

To test our hypothesis, we used fMRI to scan a large cohort of healthy young adults viewing navigationally relevant environmental scenes (N = 202), and collected self-reported data corresponding to their navigational ability. We then replicated the sex differences in navigational ability, and subsequently identified the possible sex-differences in scene selectivity of scene-selective regions. Finally, we examined whether a sex-linked association between cortical scene processing and variability in individual navigational ability actually exists.

2. Materials and methods

2.1. Participants

Two hundred and two college students (124 females; mean age = 20.3 years, standard deviation (SD) = 0.90 years) from Beijing Normal University (BNU), Beijing, China, participated in this study. The participants were asked to report whether they considered themselves as right-, left- or both-handed. One hundred eighty-four were right-handed (114 females), 7 were left-handed (4 females), and 11 both-handed (6 females), the distribution of which was consistent with a national survey in China showing that Chinese are predominantly right-handed (Li, 1983). The dataset is part of the Brain Activity Atlas Project (BAA, http://www.brainactivityatlas.org/) (Kong et al., 2014, 2017; Zhen et al., 2015). All participants had normal or corrected-to-normal vision, and had no psychiatric and neurological problems. The study was approved by the Institutional Review Board of BNU, and written informed consent was obtained from each participant before the experiment.

All participants (N = 202) underwent the fMRI scanning. Most of these participants completed two paper-pencil assessments, including a standard questionnaire on spatial navigation performance in daily life (i.e., SBSOD), Raven test for general ability (N = 167; 104 females; mean age = 20.2 years, SD = 0.90 years), and a computer test on small-scale spatial ability (N = 199; 122 females; mean age = 20.3, SD = 0.90 years) (see below).

2.2. Behavioral assessment

2.2.1. Santa Barbara Sense of Direction scale (SBSOD)

Navigational ability was operationalized by scores on the SBSOD scale (Hegarty et al., 2002), which is a standard questionnaire used to assess one's sense of direction in a large-scale environment, and is increasingly being used as a reliable proxy for actual navigational ability (Auger et al., 2012; Epstein et al., 2005; Janzen et al., 2008; Wegman et al., 2014; Wegman and Janzen, 2011). The SBSOD consists of 15 items, including statements such as "I very easily get lost in a new city," and "I can usually remember a new route after I have traveled it only once." Participants were instructed to indicate the extent to which they agreed or disagreed with each statement in a 5-point Likert-type scale. The total score was used to index individual navigational ability, with higher scores indicating better performance in daily navigation.

Note that previous studies have shown that people have explicit and accurate knowledge on their own navigational ability (Kozlowski and Bryant, 1977; Sholl, 1988; Wolbers and Hegarty, 2010), and therefore it is not surprising that the scale, which is based on navigation experiences in daily life, has been found highly reliable (test-retest reliability: 0.91). Another reason of choosing the SBSOD is that it can be easily administrated and thus has been widely used as a reliable proxy for real-world navigation performance in a variety of neuroimaging studies (Auger et al., 2012; Epstein et al., 2005; Janzen et al., 2008; Wegman et al., 2014; Wegman and Janzen, 2011). For instance, with structural MRI and DTI data, Wegman et al. (2014) have demonstrated that the gray and white matter of the caudate nucleus and medial temporal regions correlates with navigational ability measured by the SBSOD. With task fMRI, the strength of fMRI adaptation effect in the PPA correlates with SBSOD score (Epstein et al., 2005), and the effect of memory consolidation of landmarks in the hippocampus is observed only in good navigators who are screened by the SBSOD (Janzen et al., 2008), whereas poor navigators who are also screened by the SBSOD are less reliable at identifying landmarks with reduced activation in the RSC and anterodorsal thalamus (Auger et al., 2012). With resting-state fMRI, Wegman and Janzen (2011) have demonstrated that the functional connectivity at rest between the parahippocampal gyrus (PHG) and the hippocampus/caudate is related to participants' navigational ability measured by the SBSOD. Taken together, the SBSOD is valid to be used as a proxy of real-world navigation performance in neuroimaging studies.

2.2.2. Mental Rotation Task (MRT)

To measure individual mental rotation ability, participants were administered the MRT (Shepard and Metzler, 1971), which consists of 40 trials. Each trial began with a blank screen for 0.5 s, followed by an initial cube stimulus presented at the center of the screen. The three-dimensional asymmetrical assemblages of the cube image were presented for 0.7s followed by an interval of 0.5 s, after which the second stimulus appeared for the same duration as the first, with the viewpoint changed. Subjects were instructed to indicate whether the second stimulus was either a rotated version of the first stimulus or another stimulus entirely, as quickly as possible. Participants were given 3 min to finish all 40 trials, which included 20 trials for the 'rotated' condition and 20 for the 'another' condition. The accuracy of the results was used to index individual mental rotation ability.

2.2.3. Raven's Advanced Progressive Matrices (RAPM)

To eliminate the possible influence of general ability on the relationship between navigational ability and cortical scene processing, individual general intelligence was measured using the standard RAPM (Raven, 1995). The number of correct responses to the test items of the RAPM was used to index intelligence for this study.

2.3. fMRI stimuli and procedure

The stimuli used during fMRI scanning consisted of colored movie clips belonging to the following four object categories: scenes, objects, faces, and scrambled objects. Movie clips of scenes mostly consisted of pastoral scenes shot from a car window while driving slowly through leafy suburbs, along with some other films that were included for variety, taken while flying through canyons or walking through tunnels (see Fig. 1 for examples). Movie clips of objects consisted of moving toys (i.e., objects). The fMRI stimuli to simulate real environment have been used in previous fMRI studies (e.g., Huang et al., 2014; Kong et al., 2017; Pitcher et al., 2011; Saygin et al., 2012; Zhen et al., 2015) on category selectivity. Following the tradition in fMRI studies (e.g., Epstein et al., 2003; Epstein and Kanwisher, 1998; Kong et al., 2017; Wolbers et al.,

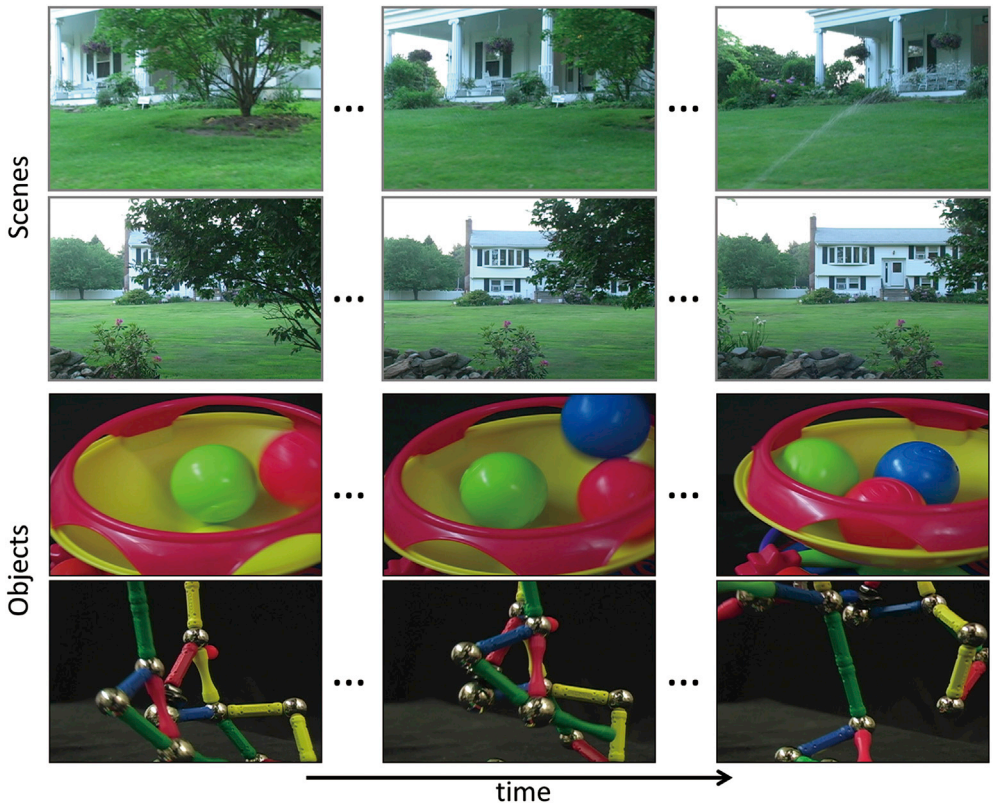

Fig. 1. Example screen shots of the video clips used in this study: the first two lines for scenes, and the next two for objects.

2011), we used the contrast of scenes versus objects to index scene selectivity and identify the scene-responsive regions. Movie clips of faces and scrambled objects were designed for face and object recognition, and were therefore not involved in this work (for further details on the stimuli see Pitcher et al., 2011).

Each participant attended three block-designed fMRI runs in total, each of which lasted 3 min 18 s. Each run consisted of two block sets, intermixed with three 18-s rest blocks at the beginning, middle, and end of the run. Each block set consisted of four blocks with four stimulus categories, with each stimulus category presented in an 18-s block that contained six 3-s clips. The order of stimulus category blocks in each run was palindromic and randomized across runs. Participants were instructed to passively view movie clips during the scanning.

2.4. MRI scanning

Scanning was conducted at the BNU Imaging Center for Brain Research in Beijing, China, on a Siemens 3T scanner (MAGENTOM Trio, a Tim system) with a 12-channel phased-array head coil. Functional images were acquired with a T2*-weighted gradient-echo, echo-planar-imaging (GRE-EPI) sequence (TR/TE = 2000/30 ms; flip angle = 90°, in-plane resolution = 3.1 × 3.1 mm). Whole-brain coverage for the functional data was obtained using 30 contiguous interleaved 4.8 mm axial slices. In addition, a high-resolution T1-weighted magnetization-prepared rapid acquisition gradient echo (MP-RAGE) scan (TR/TE/TI = 2530/3.39/1100 ms, flip angle = 7°) was acquired for spatial normalization and anatomically localizing functional activation. Ear-plugs were used to attenuate scanner noise, and head motion was restrained with a foam pillow and extendable padded head clamps.

2.5. Image processing and data analysis

Functional data were analyzed using imaging tools available in the Functional MRI of the Brain's Software Library (FSL, http://www.fmrib.ox.ac.uk/fsl) and in-house Python code. Preprocessing included the following steps: high-pass temporal filtering (120-s cutoff), motion correction, brain extraction, spatial smoothing (Gaussian kernel, FWHM = 6 mm), and grand-mean intensity normalization. Statistical analyses on time series were performed using FILM (FMRIB's Improved Linear Model) with a local autocorrelation correction. A standard analysis for block design fMRI experiments was performed. Initially, the first-level analysis was conducted separately on each run. The general linear model (GLM) modeled the scene, object, face, and scrambled object blocks as explanatory variables (EVs) convolved with a hemodynamic response function (HRF). The onset and duration of every block was modeled within the time course of each EV, and the temporal derivative of each EV was modeled to improve the sensitivity of the model. Six parameters of head motion were entered into the GLM as confounding variables of no interest. The statistical contrast "scene > object" was evaluated in this process. After the first level analysis, all runs for each participant were combined for second-level analysis. To achieve comparability between individuals, the individual maps were transformed into a standard space. Specifically, the parameter (i.e., beta) images from the first-level analysis were initially aligned to one's own structural images through FLIRT (FMRIB's linear image registration tool) with 6 degrees of freedom, and then warped to the MNI152 template using FNIRT (FMRIB's nonlinear image registration tool) with the default parameters. The spatially normalized parameter images (resampled to 2-mm isotropic voxels) were then summarized across runs for each participant using a fixed-effects model. The statistic maps from the second-level analysis were then used to identify the scene-responsive regions for each participant and extract individual scene selectivity (see below).

In addition, structural MRI images were processed using Voxel Based Morphometry (VBM) implemented in SPM8 (http://www.fil.ion.ucl.ac.uk/spm/), while employing a smoothing kernel of 8-mm FWHM. A detailed description of this procedure has been described by Kong et al. (2015). The obtained gray matter volume (GMV) value was mainly used

to rule out the possible influences of anatomical variability on the associations between cortical scene selectivity and navigational ability.

2.6. Scene-selective regions

Given the inter-subject variability in the locations of category-specific activations (Brett et al., 2002; Fedorenko et al., 2010; Nieto-Castanon and Fedorenko, 2012; Zhen et al., 2015), the scene-selective regions were delineated manually based on individual activation maps, for the contrast of scene versus object (i.e., subject-specific functional localizer). These regions included the bilateral PPA, RSC, and OPA. Each region was defined as the contiguous voxels in the corresponding location (PPA in the posterior parahippocampal cortex, RSC in the parieto-occipital sulcus, and OPA in the transverse occipital sulcus) showing significantly stronger activation ($Z > 2.3$, $p < 0.01$, uncorrected) to scenes than to objects. A specialized tool, called FreeROI (http://freeroi.brainactivityatlas.org), was used to aid in the delineating procedure. In a few cases where there was no clear scene-selective neural activation in one of these regions (even at a level of $p < 0.05$, uncorrected), the subjects were excluded in further corresponding analysis (Table 1). Specifically, seven subjects (2 males/5 females) were excluded for the left PPA; 7 (1/6) for the right PPA; 6 (2/4) for the left RSC; 9 (3/6) for the right RSC; 23 (6/17) for the left OPA and 24 (5/19) for the right OPA. The rates of localizing the scene-sensitive regions in our study (88%–97%) are comparable to rates reported in previous studies with similar approaches (82%–98%) (e.g., Epstein et al., 2003; Fox et al., 2009; Korkmaz Hacialihafiz and Bartels, 2015; Zhen et al., 2015). To ensure uniformity of size and shape, these ROIs were defined as spheres with a radius of 5 mm, centered on the local maxima (i.e., peak) of the activity. For each ROI in each participant, cortical scene selectivity was quantified, averaging z-statistic values from the contrast of scenes versus objects (i.e., scene > object) across all voxels within that ROI. For further control analyses, we also extracted the average z-statistic values in these ROIs for objects (i.e., objects > fixation). Note that scene selectivity of each ROI was calculated from the same set of data used to define subject-specific ROIs. However, it is unlikely that the sex-difference in scene selectivity and brain-behavior correlation suffer the "non-independent" bias because the ROIs were defined for each participant using an fMRI contrast that is "blind" to the subsequent across-participant analyses (Vul et al., 2009). The same approach was also used with different sphere sizes (radius = 1 mm [i.e., peak voxel], 3 mm, and 7 mm) to define individual ROIs, and the follow-up analyses were repeated.

Table 1
Demographics and group differences.

Variables		N(M/F)	M	F	*p* values
Age		202(78/124)	20.38(0.94)	20.18(0.87)	0.135
Handedness		202(78/124)	70:3:5	114:4:6	0.863
SBSOD		167(63/104)	51.22(8.96)	47.20(9.61)	0.008**
RAPM		167(63/104)	25.38(5.07)	25.63(3.59)	0.706
MRT		199(77/122)	0.66(0.11)	0.65(0.09)	0.444
Cortical Scene Selectivity	Left PPA	195(76/119)	5.60(1.78)	4.95(1.62)	**0.009****
	Right PPA	195(77/118)	5.57(2.28)	4.77(1.70)	**0.006****
	Left RSC	196(76/120)	5.10(2.00)	4.71(1.83)	0.165
	Right RSC	193(75/118)	5.15(2.08)	4.54(1.58)	0.022*
	Left OPA	179(72/107)	3.67(1.63)	3.30(1.27)	0.090
	Right OPA	178(73/105)	3.74(1.43)	3.42(1.37)	0.138

N (M/F), sample size for the variable with numbers for males and females in parentheses; SBSOD, Santa Barbara Sense of Direction scale; RAPM, Raven's Advanced Progressive Matrices; MRT, Mental Rotation Task. Mean values are given with the standard deviation in parentheses. Values for handedness are Right:Left:Both.
* indicates significance at $p < 0.05$; ** indicates $p < 0.01$; *p* values that survived multiple comparisons correction across scene-responsive regions are reported **in bold**.

2.7. ROI analysis

First, we examined whether there were any significant sex differences in cortical scene selectivity using an independent-samples *t*-test for each scene-selective ROI separately. The scene selectivity for each ROI was obtained by averaging z-statistic values from the contrast of scenes versus objects (i.e., scene > object) across all voxels within in the ROI. To control the false positive rate, only ROIs that survived the Bonferroni-Holm correction for multiple comparisons (Holm, 1979; Huang et al., 2013) were reported (two-tailed $p < 0.05$, corrected).

Next, we assessed the Pearson correlation between individual navigational ability and the scene selectivity, for each ROI and each sex group separately. Similarly, only correlations that survived the Bonferroni-Holm correction were reported (two-tailed $p < 0.05$, corrected). To eliminate the possible influence of extreme samples (i.e., outliers) on the correlation, outliers were checked for each behavioral test and ROI, and removed in the corresponding correlation analysis. Outliers were defined in the conventional manner for boxplot, with the criterion for data exclusion being 1.5 times the interquartile range (IQR). This approach identified 0 participants for both the SBSOD and Raven tasks, 2 for the left PPA and right RSC, 1 for the right PPA and RSC, 6 for the left OPA, and 7 for the right OPA. In order to ensure the effects were robust to non-normality and the influence of other possible outliers, Spearman's rank-correlation coefficients were calculated to confirm the findings presented.

Finally, in order to investigate the difference between correlations in female and male groups (i.e., the interaction effect of sex and scene processing on individual navigational ability), we employed the standard procedure described by Cohen and Cohen to compare independent correlation coefficients, following Fischer's z test (Cohen and Cohen, 1983). A two-tailed p value of strictly under 0.05 was considered statistically significant.

2.8. Control analyses

To rule out the possibility that sex differences in scene selectivity were actually accounted for by the differences in head size and other factors, we calculated 5 measures on signal quality based on the protocol of task fMRI quality control for Human Connectome Project (Marcus et al., 2013; Barch et al., 2013). These measures included temporal standard deviation (tSD) as a signal loss index, temporal signal-to-noise ratio (tSNR), both absolute and relative movement, and smoothness. Besides, 3 measures, including the number of significant voxels, the mean magnitude of scene selectivity across the whole brain, and head size as signal quality metrics were also calculated. After obtaining these metrics, we examined whether there were significant sex differences in them with independent *t*-test. If so, further analyses were conducted to determine how those differences might have influenced the main findings reported here. Moreover, to further ensure that there was no contamination due to SNR differences between sex groups, we also calculated the SNR estimates, including tSNR and tSD, of each ROI, and repeated the above-mentioned control analyses.

3. Results

3.1. Behavioral differences

We found a significant sex difference in navigational ability measured by SBSOD, with males scoring significantly higher than females on average ($t(165) = 2.69$, $p = 0.008$, Cohen's $d = 0.42$), which is consistent

with the results of previous studies (Wegman et al., 2014). No sex differences were observed in age, handedness, and general ability (i.e., intelligence) measured by the RAPM. Similarly, no sex difference was observed in mental rotation ability measured by the MRT (see also Peters and Battista, 2008) (Table 1). These findings suggest that sex differences in navigational ability cannot be attributed to general ability or small-scale spatial ability. Next, we investigated the neural basis underlying the behavioral differences in terms of scene processing, which is a critical early-stage component of spatial navigation.

3.2. Sex differences in the scene selectivity of scene-selective regions

Scene selectivity was indexed with the fMRI contrast of scenes versus objects. Fig. 2 shows the group level statistical maps for the scene selectivity of males (top) and females (bottom) separately. As the figure illustrates, males and females in general showed similar spatial distributions of scene selectivity, and as expected, all scene-selective regions including the PPA, RSC and OPA showed strong scene selectivity.

To accurately measure individuals' scene selectivity and investigate the sex differences, we created ROIs for six different scene-selective regions, defined individually for each participant (bilateral PPA, RSC, and OPA; see Fig. 3 for the respective locations of these regions). After excluding participants with no clearly-defined scene-selective ROIs, we obtained the samples used for the further analyses: 195 samples for both the left and right PPA, 196 for the left RSC, 193 for the right RSC, 179 for the left OPA, and 178 for the right OPA. To ensure the same size and shape across participants, these ROIs were defined as spheres with a radius of 5 mm, centered on the peak of the activity. In terms of cortical scene selectivity in the scene-selective regions, significant sex differences were found for scene selectivity in the bilateral PPA (left: $t(193) = 2.64$, $p = 0.009$, Cohen's $d = 0.38$; right: $t(193) = 2.80$, $p = 0.006$, Cohen's $d = 0.40$; $p < 0.05$, corrected for six ROIs), not in the other scene-selective regions (i.e., RSC and OPA) (see Table 1). In addition, the results were stable when the PPA was defined with different spherical sizes (for example, radius = 1 mm (i.e., peak voxel), left: $t(193) = 3.32$, $p = 0.003$, Cohen's $d = 0.48$; right: $t(193) = 3.35$, $p = 0.001$, Cohen's $d = 0.48$) (for different sizes, see Table S1).

3.3. Sex differences in the associations between cortical scene processing and navigational ability

Based on the observed sex differences in spatial navigation, both in terms of behavior and neural activation, we further examined whether or not there was a sex-linked association between these two measures. To do this, we analyzed the relationship between the navigational ability and cortical scene selectivity in scene-selective regions separately in females and males. We found a positive correlation between SBSOD score and scene selectivity in the left PPA (lPPA) of the males ($r = 0.36$, $p = 0.005$; Spearman rho = 0.34, $p = 0.009$; corrected $p < 0.05$), but not in females ($r = -0.14$, $p = 0.155$; Spearman rho = −0.13, $p = 0.189$) (Fig. 4A and B). To test for differences in the strength of the corresponding correlations in males and females in the lPPA, we conducted Fisher's z test. Fisher's z-test indicated a significant sex difference ($Z = 3.12$, $p < 0.001$), confirming that the correlation was specific to males (Fig. 4A). Additionally, the association in males was stable when the ROI was defined with different spherical sizes (for example, radius = 1 mm (i.e., peak voxel), males: $r = 0.27$, $p = 0.037$; females: $r = -0.17$, $p = 0.09$; Fisher's z test: $Z = 2.58$, $p = 0.004$) (for different sizes, see Table S2). Besides, because the aforementioned analyses and previous studies (Chai and Jacobs, 2009; Gron et al., 2000; Lawton, 1994; Lovden et al., 2007; Wolbers and Hegarty, 2010) suggest that males and females may have distinct mechanisms for navigation, it is not surprising there was no brain-behavior association in the lPPA when males and females were considered as a unified population ($r = 0.06$, $p = 0.457$; Spearman rho = 0.06, $p = 0.424$).

No significant correlation was observed in the right PPA (rPPA) in

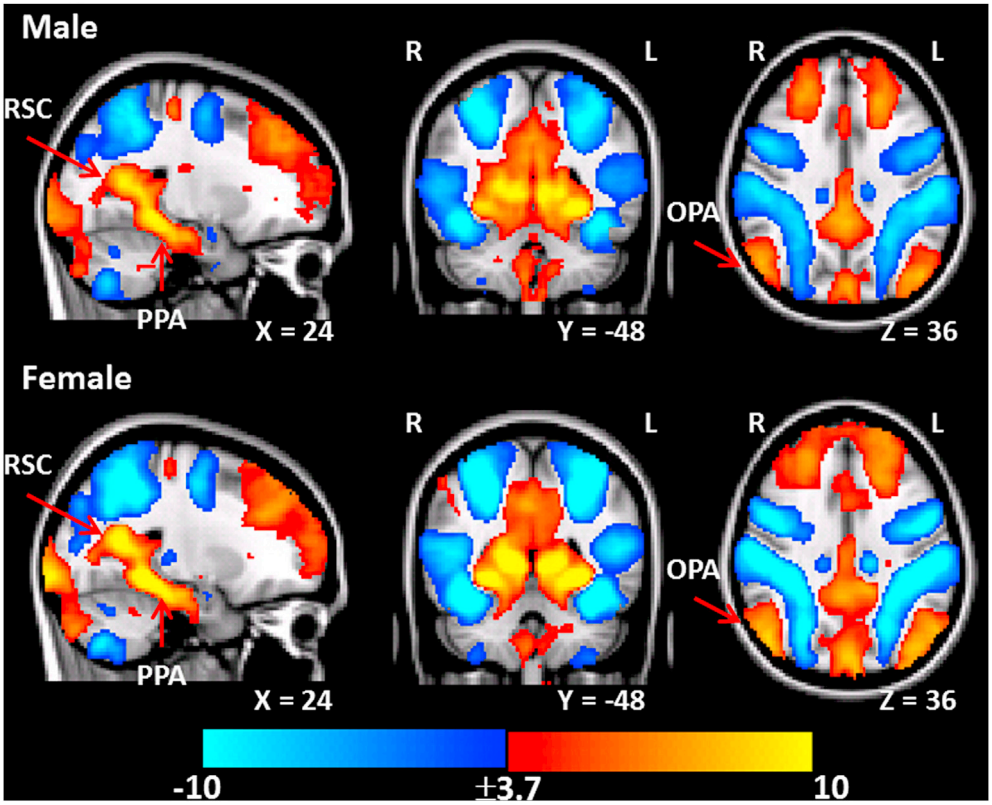

Fig. 2. Group-average maps (random-effect) of scene selectivity for male and female groups.

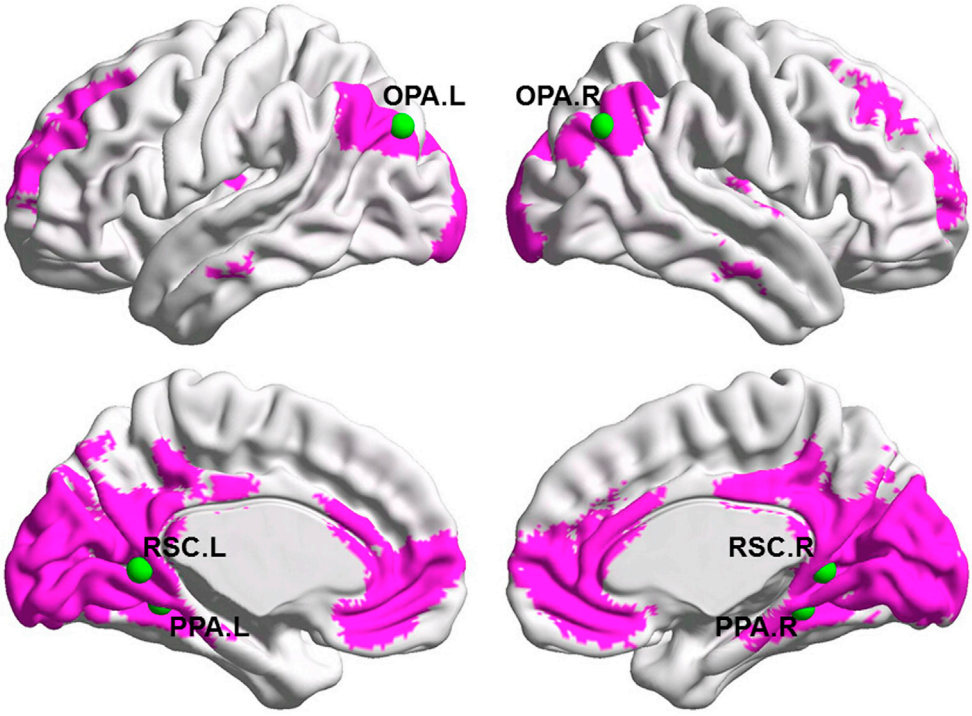

Fig. 3. Locations for scene-selective regions and the probabilistic activation map (PAM) for scene recognition. Peak locations are shown in green for bilateral PPA (left PPA/PPA.L: MNI = −26, −46, −8; right PPA/PPA.R: MNI = 24, −42, −10), RSC (left RSC/RSC.L: MNI = −10, −54, 4; right RSC/RSC.R: MNI = 14, −50, 4), and OPA (left OPA/OPA.L: MNI = −40, −80, 34; right OPA/OPA.R: MNI = 50, −68, 34). The PAM for scene recognition with a threshold of 20% is shown in purple. To avoid any bias to one group relative to the other in ROI definition (e.g., sample size, variability in locations), the ROI analysis in this study was based on the subject-specific ROIs rather than these group-level peaks.

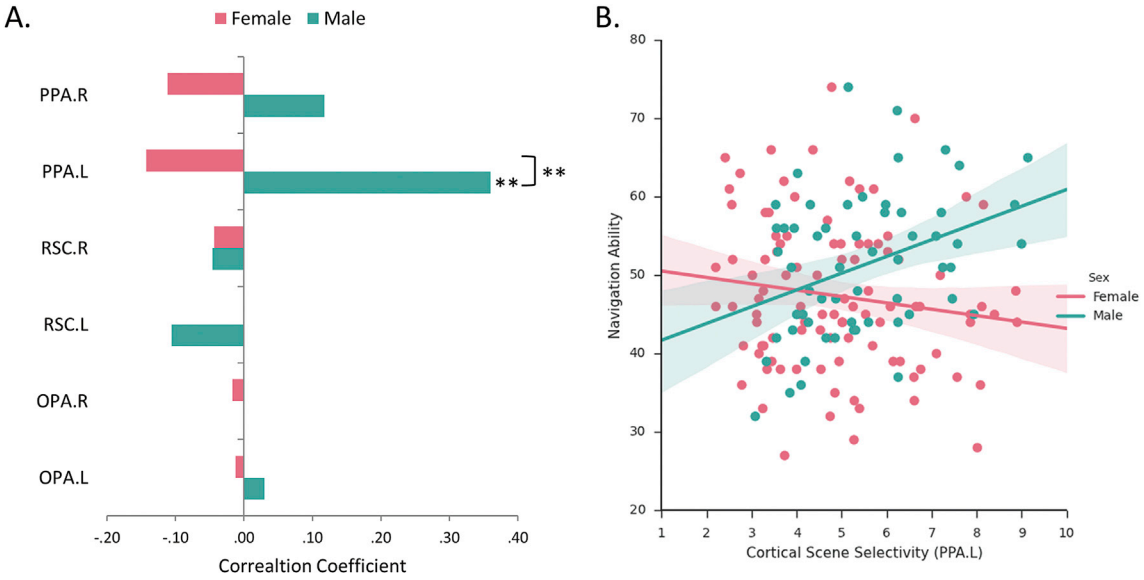

Fig. 4. Navigation-scene selectivity correlations. (A) The scene selectivity in the left PPA positively correlated with individual navigational ability in males ($p < 0.05$, corrected), while no significant correlation was found in females. Note that the correlation between the left PPA and navigational ability in males was significantly higher than that in females. The x-axis denotes the correlation coefficient for the navigation-scene selectivity correlation. (B) Scatterplots showing that scene selectivity in the left PPA (x-axis) is associated with better navigational ability (y-axis) in males but not in females. PPA.R/L, the right/left PPA; RSC.R/L, the right/left RSC; OPA.R/L, the right/left OPA. ** indicates $p < 0.005$.

both females ($r = -0.11$, $p = 0.270$) and males ($r = 0.12$, $p = 0.366$) (Fig. 4A). Similarly, no significant correlation was found in the RSC (left: $r = -0.11$, $p = 0.423$ for males, $r < 0.01$, $p = 0.990$ for females; right: $r = -0.05$, $p = 0.731$ for males, $r = -0.04$, $p = 0.665$ for females) or in the OPA (left: $r = 0.03$, $p = 0.831$ for males, $r = -0.12$, $p = 0.910$ for females; right: $r < 0.01$, $p = 0.997$ for males, $r = -0.02$, $p = 0.880$ for females) (Fig. 4A).

We then conducted further analyses to rule out possible confounding factors. First, since scene selectivity was calculated from the contrast of scenes versus objects, it is possible that the association based on the scene selectivity resulted from a negative correlation between lPPA responses to objects and navigational ability. We found that the correlation between navigational ability and the lPPA responses to objects (versus fixation) was not significant (males: $r = -0.13$, $p = 0.345$; females:

$r = -0.002$, $p = 0.986$). Furthermore, navigational ability was positively correlated with lPPA responses to scenes (versus fixation), after controlling for the response to objects with partial correlation (males: $r = 0.30$, $p = 0.022$; females: $r = -0.09$, $p = 0.358$; Fisher's z-test: $Z = 2.35$, $p = 0.009$). Therefore, it is not the neural response to objects, but the neural response to scenes that led to the association between cortical scene selectivity and navigational ability. Second, to investigate the specificity of the navigation-lPPA association in males, we ruled out non-navigational factors that may account for the association. We found both general intelligence measured by RAPM and mental rotation ability measured by MRT were negatively correlated with scene selectivity in the lPPA of males (RAPM: $r = -0.37$, $p = 0.004$; MRT: $r = -0.25$, $p = 0.019$), not that of females (RAPM: -0.12, $p = 0.246$; MRT: $r = -0.07$, $p = 0.425$). However, after these two non-navigational factors were controlled for using partial correlation, the association between navigational ability and scene selectivity in the lPPA remained in males ($r = 0.40$, $p = 0.002$), which was also significantly larger than that in females ($r = -0.13$, $p = 0.211$) (Fisher's z-test: $Z = 3.26$, $p < 0.001$). Besides the confounding cognitive factors, we also examined whether local anatomical variability was able to account for this association, because the regional GMV (rGMV) of the lPPA of the males was significant larger than that of females ($t(193) = 3.54$, $p < 0.001$, Cohen's $d = 0.51$), and the rGMV was significantly correlated with the scene selectivity in the lPPA either with or without sex being regressed out (with: $r = 0.15$, $p = 0.043$; without: $r = 0.18$, $p = 0.014$). However, when the rGMV of the lPPA was regressed out, the association in males remained significant (males: $r = 0.36$; $p = 0.005$), which was also significantly larger than that in the females ($r = -0.16$, $p = 0.101$) (Fisher's z-test: $Z = 3.16$, $p < 0.001$). Finally, although the scene selectivity of each ROI was calculated from the same set of data used to define subject-specific ROIs, it is unlikely that the sex-difference in scene selectivity and brain-behavior correlation suffered the "non-independent" bias because the ROIs were defined for each participant using an fMRI contrast that is "blind" to the subsequent across-participant analyses (Vul et al., 2009). In short, neural activation in the lPPA was correlated with self-reported navigational ability in males.

3.4. Control analyses

Fig. S1 displays the distribution of values of the quality metrics, including both absolute and relative head movement, head size, smoothness, tSD, tSNR, the number of significant voxels, and the mean magnitude of scene selectivity. First, the quality assessment metrics indicated that data of the majority of our subjects had high quality. Moreover, no significant sex differences were found in most of these metrics, including absolute head movement ($t(198) < 1.0$), relative head movement ($t(198) = 1.23$, $p = 0.22$), number of significant voxels ($t(198) = 1.22$, $p = 0.23$), or magnitude of scene selectivity ($t(198) < 1.0$). As expected, significant sex differences were found in head size ($t(198) = 8.67$, $p < 0.0005$), and quality related metrics such as smoothness ($t(198) = 5.03$, $p < 0.0005$), tSD ($t(198) = 4.76$, $p < 0.0005$), and tSNR ($t(198) = -5.91$, $p < 0.0005$). Importantly, after these four measures were controlled for as covariates in general linear model, the main findings on sex differences in both scene selectivity (left PPA: $t(194) = 3.01$, $p = 0.002$; right PPA: $t(192) = 2.92$, $p = 0.004$) and the relation between scene selectivity in left PPA and navigational ability (male: $r = 0.37$, $p = 0.005$; female: $r = -0.05$, $p = 0.612$; $Z = 2.53$, $p = 0.006$) remained (Table S3). Results after controlling for the quality metrics for the rest of the ROIs are shown in Table S3. To further ensure that there was no contamination due to SNR differences between sexes, we also calculated the SNR estimates, including tSNR and tSD, of each ROI of each participant. For most of these ROIs, including the bilateral PPA, the SNR estimates showed the same pattern of the sex differences (Fig. S2). Furthermore, after these measures (for each ROI separately) were controlled for, the main findings on the sex differences in both scene selectivity (left PPA: $t(191) = 2.53$, $p = 0.012$; right PPA: $t(191) = 2.95$, $p = 0.004$) and the relation between scene selectivity in the left PPA and navigational ability remained (male: $r = 0.36$, $p = 0.005$; female: $r = -0.14$, $p = 0.16$; $Z = 3.03$, $p = 0.001$). Taken together, the quality assessment metrics indicated high quality of the fMRI data, and our findings were unlikely contributed by sex differences in signal quality.

4. Discussion

In this study, we explored the neural basis underlying sex differences in spatial navigation by focusing on the cortical regions involved in extracting and representing surrounding scenes, which is a critical early-stage component of spatial navigation. We found that both self-reported navigational ability and scene selectivity in scene-selective regions showed considerable sex differences. Specifically, the scene selectivity in the bilateral PPA was significantly greater in males as compared with females, and no sex difference was observed in the RSC or OPA. Further, males with stronger scene selectivity in the lPPA possessed better self-reported navigational ability, while females showed no such correlation. This brain-behavior association could not be accounted for by non-navigational abilities (i.e., intelligence and mental rotation ability), consistent with the role of the PPA in human navigation. In short, our study provided novel empirical evidence demonstrating sex differences related to spatial navigation in the scene-selective regions.

The human brain networks supporting spatial navigation primarily involve the hippocampus, parahippocampal gyrus, parietal lobe, and prefrontal cortex (Aguirre and D'Esposito, 1999; Burgess et al., 2002; Kong et al., 2016). With regard to sex differences in the neural basis of spatial navigation, Gron et al. (2000) found that males primarily activate the left hippocampal region, whereas females engage the right parietal and prefrontal regions during virtual spatial navigation (Gron et al., 2000). Our study extended this finding by focusing on the stage of scene perception where surrounding scenes are extracted and represented. We found that the bilateral PPA showed significantly stronger scene selectivity in males as compared with females. Such sex differences could not be explained by the differences in fMRI data quality metrics (e.g., ICV and tSNR) between males and females or by the fluctuations of female hormonal level because of the menstrual cycle (see supplemental materials). Importantly, we found that the scene selectivity in the lPPA was behaviorally relevant, as males with stronger lPPA scene selectivity showed a better ability in the sense of direction. Such association is apparently domain-specific, because the association remained after ruling out the contribution from general abilities (i.e., general intelligence) and the ability of processing navigation-irrelevant spatial information. Note that the sex differences in both the magnitude of neural activation and the strength of the brain-behavioral association were absent in either the RSC or the OPA, suggesting that it is not a general mechanism in scene perception (e.g., more attention is directed to scenes in good navigators) that differentiate males and females in navigation. Instead, the PPA is likely a key region showing sex differences among the scene-selective regions examined.

The PPA is primarily involved in presenting the spatial layout of the immediate scene (Epstein and Higgins, 2007), which can be used to facilitate individual's navigation behaviors. For example, it has been shown that learning-induced changes in resting-state functional connectivity between the parahippocampal gyrus (where the PPA is located) and the hippocampus is positively related to individual navigational ability (Wegman and Janzen, 2011), and the strength of fMRI adaptation effects in the PPA is correlated with individual navigational ability (Epstein et al., 2005). Interestingly, although the sex differences in scene selectivity were found in the bilateral PPA, the sex-linked brain-behavior association was more prominent in the left PPA. Previous studies have revealed the hemispheric asymmetry of scene processing (Stevens et al., 2012), as the right PPA contributes to form-specific scene processing whereas the left PPA contributes to form-abstract scene processing (Prince et al., 2009; Stevens et al., 2012). That is, the right PPA is mainly

involved in perceptual analysis of scenes and the left PPA prefers conceptual information of scenes (Stevens et al., 2012). Therefore, individual differences in navigation may depend more on the processing of abstract conceptual information of the environment at the stage of scene perception. Taken together, our finding provides new evidence for the critical role of the PPA in spatial navigation by showing the specific association between its scene selectivity and navigation ability.

The correlation between navigation ability and the left PPA was found only in the male group, not in the female group, suggesting a sex-dependent link between cortical scene processing and spatial navigation. In some cases, sex differences in brain structure and function (e.g., scene selectivity in the left PPA) may result in sex differences in behavior (e.g., spatial navigation). However, it is also possible that sex-related differences in brain may actually compensate differences in behavior (De Vries, 2004). Another interesting observation is that two non-navigational tasks (i.e., MRT and RAPM) that rely heavily on small-scale ability showed a negative correlation with the scene selectivity in the lPPA in males, which is opposite to the positive correlation between the large-scale navigation ability (i.e., SBSOD) and the scene selectivity. Further studies are needed to illustrate the role of the PPA in differentiating large-scale and small-scale spatial cognition.

The current research has several limitations. First, in this study the participants' spatial navigational ability was assessed with a self-reported questionnaire (i.e., SBSOD); future studies with more objective tests may provide a direct behavioral measure to explore the neural correlates of spatial navigation. For example, with well-designed navigation tasks on cognitive strategies, researchers may examine whether the greater scene selectivity in the PPA and other scene-selective regions facilitates allocentric and/or egocentric navigation. Another limitation is about potential menstrual cycle and hormonal fluctuation effects. It has long been hypothesized that menstrual cycle of females affects navigation-related brain structure (e.g., hippocampus/parahippcampus) (Pletzer et al., 2010; Protopopescu et al., 2008) and its function (e.g., Petersen et al., 2014; Pletzer et al., 2011). Our preliminary data suggested that the effects might unlikely influence our findings (see supplemental materials), but future studies with more appropriate methods and power are needed to clarify the association between hormone fluctuations, including both estrogen (Pletzer and Kerschbaum, 2014; Warren et al., 2014) and testosterone (Burkitt et al., 2007; Roof and Havens, 1992), and spatial navigation ability. Finally, the stimuli were presented in a pairwise fashion in the MRT and this paradigm is known to reduce the effect size of the sex differences in mental rotation (Peters and Battista, 2008). Another possibility is the menstrual cycle, which has been implicated to affect mental rotation performance (Hausmann et al., 2000; Schoning et al., 2007). Therefore, it is not surprising that no sex differences in mental rotation were observed.

This paper invites future research directions of the neural basis underlying the sex differences in human navigation. First, we found sex differences in the magnitude of the neural activation and the strength of the brain-behavior correlation in the PPA; however, it is unclear whether males and females process scene information qualitatively different. Previous studies that examined the neural representation of the PPA did not directly compare it between sex groups, possibly because of the relatively small number of participants tested. Future studies, therefore, are needed to manipulate stimuli and/or tasks to examine whether PPA responses vary qualitatively between sex groups. Second, sex differences in brain activity may be also found in other components of spatial navigation as well. Note that although scene processing is an early stage component of spatial navigation, it affects but not determines sex differences in later stages. One intriguing topic of future directions is to study sex differences at other stages, such as spatial location memory that shows female advantage in behavioral studies (e.g., Tottenham et al., 2003). Third, previous studies have shown that the RSC and OPA are both causally related to navigationally relevant spatial processing (Dilks et al., 2013; Takahashi et al., 1997), but we failed to observe sex differences in these two regions. One possibility is that the sex differences may be found not only at the regional level but also at the network level (Kong et al., 2016). Indeed, the RSC and OPA work collaboratively with other regions such as the PPA and hippocampus (Wolbers et al., 2011) for scene construction. More generally, future studies are needed to illustrate whether sex differences in navigation can also be observed at the network level.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.neuroimage.2017.07.031.

References

Aguirre, G.K., D'Esposito, M., 1999. Topographical disorientation: a synthesis and taxonomy. Brain 122 (Pt 9), 1613–1628.

Astur, R.S., Ortiz, M.L., Sutherland, R.J., 1998. A characterization of performance by men and women in a virtual Morris water task: a large and reliable sex difference. Behav. Brain Res. 93, 185–190.

Auger, S.D., Mullally, S.L., Maguire, E.A., 2012. Retrosplenial cortex codes for permanent landmarks. PLoS One 7, e43620.

Barch, D.M., Burgess, G.C., Harms, M.P., Petersen, S.E., Schlaggar, B.L., Corbetta, M., Glasser, M.F., Curtiss, S., Dixit, S., Feldt, C., Nolan, D., 2013. Function in the human connectome: task-fMRI and individual differences in behavior. Neuroimage 80, 169–189.

Brett, M., Johnsrude, I.S., Owen, A.M., 2002. The problem of functional localization in the human brain. Nat. Rev. Neurosci. 3, 243–249.

Burgess, N., Maguire, E.A., O'Keefe, J., 2002. The human hippocampus and spatial and episodic memory. Neuron 35, 625–641.

Burkitt, J., Widman, D., Saucier, D.M., 2007. Evidence for the influence of testosterone in the performance of spatial navigation in a virtual water maze in women but not in men. Horm. Behav. 51, 649–654.

Chai, X.J., Jacobs, L.F., 2009. Sex differences in directional cue use in a virtual landscape. Behav. Neurosci. 123, 276–283.

Cohen, J., Cohen, P. (Eds.), 1983. Applied Multiple Regression/correlation Analysis for the Behavioral Sciences. Erlbaum, Hillsdale, NJ.

De Vries, G.J., 2004. Minireview: sex differences in adult and developing brains: compensation, compensation, compensation. Endocrinology 145, 1063–1068.

Dilks, D.D., Julian, J.B., Paunov, A.M., Kanwisher, N., 2013. The occipital place area is causally and selectively involved in scene perception. J. Neurosci. 33, 1331–1336a.

Epstein, R., Deyoe, E.A., Press, D.Z., Rosen, A.C., Kanwisher, N., 2001. Neuropsychological evidence for a topographical learning mechanism in parahippocampal cortex. Cogn. Neuropsychol. 18, 481–508.

Epstein, R., Graham, K.S., Downing, P.E., 2003. Viewpoint-specific scene representations in human parahippocampal cortex. Neuron 37, 865–876.

Epstein, R., Harris, A., Stanley, D., Kanwisher, N., 1999. The parahippocampal place area: recognition, navigation, or encoding? Neuron 23, 115–125.

Epstein, R., Kanwisher, N., 1998. A cortical representation of the local visual environment. Nature 392, 598–601.

Epstein, R.A., 2008. Parahippocampal and retrosplenial contributions to human spatial navigation. Trends Cogn. Sci. 12, 388–396.

Epstein, R.A., Higgins, J.S., 2007. Differential parahippocampal and retrosplenial involvement in three types of visual scene recognition. Cereb. Cortex 17, 1680–1693.

Epstein, R.A., Higgins, J.S., Thompson-Schill, S.L., 2005. Learning places from views: variation in scene processing as a function of experience and navigational ability. J. Cogn. Neurosci. 17, 73–83.

Fedorenko, E., Hsieh, P.J., Nieto-Castanon, A., Whitfield-Gabrieli, S., Kanwisher, N., 2010. New method for fMRI investigations of language: defining ROIs functionally in individual subjects. J. Neurophysiol. 104, 1177–1194.

Fox, C.J., Iaria, G., Barton, J.J., 2009. Defining the face processing network: optimization of the functional localizer in fMRI. Hum. Brain Mapp. 30, 1637–1651.

Ganaden, R.E., Mullin, C.R., Steeves, J.K., 2013. Transcranial magnetic stimulation to the transverse occipital sulcus affects scene but not object processing. J. Cogn. Neurosci. 25, 961–968.

Grill-Spector, K., 2003. The neural basis of object perception. Curr. Opin. Neurobiol. 13, 159–166.

Gron, G., Wunderlich, A.P., Spitzer, M., Tomczak, R., Riepe, M.W., 2000. Brain activation during human navigation: gender-different neural networks as substrate of performance. Nat. Neurosci. 3, 404–408.

Hausmann, M., Slabbekoorn, D., Van Goozen, S.H., Cohen-Kettenis, P.T., Güntürkün, O., 2000. Sex hormones affect spatial abilities during the menstrual cycle. Behav. Neurosci 114 (6), 1245.

Hegarty, M., Richardson, A.E., Montello, D.R., Lovelace, K., Subbiah, I., 2002. Development of a self-report measure of environmental spatial ability. Intelligence 30, 425–447.

Holm, S., 1979. A simple sequentially rejective multiple test procedure. Scand. J. Stat. 6, 65–70.

Huang, L., Song, Y., Li, J., Zhen, Z., Yang, Z., Liu, J., 2014. Individual differences in cortical face selectivity predict behavioral performance in face recognition. Front. Hum. Neurosci. 8, 483.

Huang, Y., Kong, X., Zhen, Z., Liu, J., 2013. The comparison of multiple testing corrections methods in genome-wide association studies. Adv. Psychol. Sci. 21, 1874–1882.

Janzen, G., Jansen, C., van Turennout, M., 2008. Memory consolidation of landmarks in good navigators. Hippocampus 18, 40–47.
Kong, X.Z., Liu, Z.G., Huang, L.J., Wang, X., Yang, Z.T., Zhou, G.F., Zhen, Z.L., Liu, J., 2015. Mapping individual brain networks using statistical similarity in regional morphology from MRI. PLoS One 10.
Kong, X.Z., Song, Y., Zhen, Z., Liu, J., 2017. Genetic variation in S100B modulates neural processing of visual scenes in Han Chinese. Cereb. Cortex 27, 1326–1336.
Kong, X.Z., Wang, X., Pu, Y., Huang, L., Hao, X., Zhen, Z., Liu, J., 2016. Human navigation network: the intrinsic functional organization and behavioral relevance. Brain Struct. Funct 222, 749–764.
Kong, X.Z., Zhen, Z., Li, X., Lu, H.H., Wang, R., Liu, L., He, Y., Zang, Y., Liu, J., 2014. Individual differences in impulsivity predict head motion during magnetic resonance imaging. PLoS One 9, e104989.
Korkmaz Hacialihafiz, D., Bartels, A., 2015. Motion responses in scene-selective regions. Neuroimage 118, 438–444.
Kozlowski, L.T., Bryant, K.J., 1977. Sense-of-direction, spatial orientation, and cognitive maps. J. Exp. Psychol. Hum. Percept. Perform. 3, 590–598.
Lawton, C.A., 1994. Gender differences in wayfinding strategies: relationship to spatial ability and spatial anxiety. Sex. Role 30, 765–779.
Li, X.-t., 1983. The distribution of left and right handedness in Chinese people. Acta Psychol. Sin. 268–276.
Lovden, M., Herlitz, A., Schellenbach, M., Grossman-Hutter, B., Kruger, A., Lindenberger, U., 2007. Quantitative and qualitative sex differences in spatial navigation. Scand. J. Psychol. 48, 353–358.
Maguire, E.A., 2001. The retrosplenial contribution to human navigation: a review of lesion and neuroimaging findings. Scand. J. Psychol. 42, 225–238.
Marcus, D.S., Harms, M.P., Snyder, A.Z., Jenkinson, M., Wilson, J.A., Glasser, M.F., Barch, D.M., Archie, K.A., Burgess, G.C., Ramaratnam, M., Hodge, M., 2013. Human Connectome Project informatics: quality control, database services, and data visualization. Neuroimage 80, 202–219.
Mendez, M.F., Cherrier, M.M., 2003. Agnosia for scenes in topographagnosia. Neuropsychologia 41, 1387–1395.
Moffata, S.D., Hampsona, E., Hatzipantelisa, M., 1998. Navigation in a “virtual” maze:sex differences and correlation with psychometric measures of spatial ability in humans. Evol. Hum. Behav. 19, 73–87.
Nieto-Castanon, A., Fedorenko, E., 2012. Subject-specific functional localizers increase sensitivity and functional resolution of multi-subject analyses. Neuroimage 63, 1646–1669.
Park, S., Chun, M.M., 2009. Different roles of the parahippocampal place area (PPA) and retrosplenial cortex (RSC) in panoramic scene perception. Neuroimage 47, 1747–1756.
Peters, M., Battista, C., 2008. Applications of mental rotation figures of the Shepard and Metzler type and description of a mental rotation stimulus library. Brain Cogn. 66, 260–264.
Petersen, N., Kilpatrick, L.A., Goharzad, A., Cahill, L., 2014. Oral contraceptive pill use and menstrual cycle phase are associated with altered resting state functional connectivity. Neuroimage 90, 24–32.
Pitcher, D., Dilks, D.D., Saxe, R.R., Triantafyllou, C., Kanwisher, N., 2011. Differential selectivity for dynamic versus static information in face-selective cortical regions. Neuroimage 56, 2356–2363.
Pletzer, B., Kronbichler, M., Aichhorn, M., Bergmann, J., Ladurner, G., Kerschbaum, H.H., 2010. Menstrual cycle and hormonal contraceptive use modulate human brain structure. Brain Res. 1348, 55–62.
Pletzer, B., Kronbichler, M., Ladurner, G., Nuerk, H.C., Kerschbaum, H., 2011. Menstrual cycle variations in the BOLD-response to a number bisection task: implications for research on sex differences. Brain Res. 1420, 37–47.
Pletzer, B.A., Kerschbaum, H.H., 2014. 50 years of hormonal contraception-time to find out, what it does to our brain. Front. Neurosci. 8, 256.
Prince, S.E., Dennis, N.A., Cabeza, R., 2009. Encoding and retrieving faces and places: distinguishing process- and stimulus-specific differences in brain activity. Neuropsychologia 47, 2282–2289.
Protopopescu, X., Butler, T., Pan, H., Root, J., Altemus, M., Polanecsky, M., McEwen, B., Silbersweig, D., Stern, E., 2008. Hippocampal structural changes across the menstrual cycle. Hippocampus 18, 985–988.
Raven, J. (Ed.), 1995. Advanced Progressive Matrices Sets I and II. Oxford Psychologist Press Ltd, Oxford.
Roof, R.L., Havens, M.D., 1992. Testosterone improves maze performance and induces development of a male hippocampus in females. Brain Res. 572, 310–313.
Saygin, Z.M., Osher, D.E., Koldewyn, K., Reynolds, G., Gabrieli, J.D., Saxe, R.R., 2012. Anatomical connectivity patterns predict face selectivity in the fusiform gyrus. Nat. Neurosci. 15, 321–327.
Schöning, S., Engelien, A., Kugel, H., Schäfer, S., Schiffbauer, H., Zwitserlood, P., Pletziger, E., Beizai, P., Kersting, A., Ohrmann, P., Greb, R.R., 2007. Functional anatomy of visuo-spatial working memory during mental rotation is influenced by sex, menstrual cycle, and sex steroid hormones. Neuropsychologia 45, 3203–3214.
Shepard, R.N., Metzler, J., 1971. Mental rotation of three-dimensional objects. Science 171, 701–703.
Sholl, M.J., 1988. The relationship between sense of direction and mental geographic updating. Intelligence 12, 299–314.
Stevens, W.D., Kahn, I., Wig, G.S., Schacter, D.L., 2012. Hemispheric asymmetry of visual scene processing in the human brain: evidence from repetition priming and intrinsic activity. Cereb. Cortex 22, 1935–1949.
Takahashi, N., Kawamura, M., Shiota, J., Kasahata, N., Hirayama, K., 1997. Pure topographic disorientation due to right retrosplenial lesion. Neurology 49, 464–469.
Tottenham, L.S., Saucier, D., Elias, L., Gutwin, C., 2003. Female advantage for spatial location memory in both static and dynamic environments. Brain Cogn. 53, 381–383.
Vul, E., Harris, C., Winkielman, P., Pashler, H., 2009. Puzzlingly high correlations in fMRI studies of emotion, personality, and social cognition. Perspect. Psychol. Sci. 4, 274–290.
Warren, A.M., Gurvich, C., Worsley, R., Kulkarni, J., 2014. A systematic review of the impact of oral contraceptives on cognition. Contraception 90, 111–116.
Wegman, J., Fonteijn, H.M., van Ekert, J., Tyborowska, A., Jansen, C., Janzen, G., 2014. Gray and white matter correlates of navigational ability in humans. Hum. Brain Mapp. 35, 2561–2572.
Wegman, J., Janzen, G., 2011. Neural encoding of objects relevant for navigation and resting state correlations with navigational ability. J. Cogn. Neurosci. 23, 3841–3854.
Wolbers, T., Hegarty, M., 2010. What determines our navigational abilities? Trends Cogn. Sci. 14, 138–146.
Wolbers, T., Klatzky, R.L., Loomis, J.M., Wutte, M.G., Giudice, N.A., 2011. Modality-independent coding of spatial layout in the human brain. Curr. Biol. 21, 984–989.
Zhen, Z., Yang, Z., Huang, L., Kong, X.Z., Wang, X., Dang, X., Huang, Y., Song, Y., Liu, J., 2015. Quantifying interindividual variability and asymmetry of face-selective regions: a probabilistic functional atlas. Neuroimage 113, 13–25.