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CLINICAL REVIEW

Functional brain alterations in acute sleep deprivation: An activation likelihood estimation meta-analysis

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SUMMARY

Sleep deprivation (SD) is a common problem in modern societies, which leads to cognitive dysfunctions including attention lapses, impaired working memory, hindering decision making, impaired emotional processing, and motor vehicle accidents. Numerous neuroimaging studies have investigated the neural correlates of SD, but these studies have reported inconsistent results. Thus, we aimed to identify convergent patterns of abnormal brain functions due to acute SD. Based on the preferred reporting for systematic reviews and meta-analyses statement, we searched the PubMed database and performed reference tracking and finally retrieved 31 eligible functional neuroimaging studies. Then, we applied activation estimation likelihood meta-analysis and found reduced activity mainly in the right intraparietal sulcus and superior parietal lobule. The functional decoding analysis using the BrainMap database indicated that this region is mostly related to visuospatial perception, memory and reasoning. The significant co-activation of this region using the BrainMap database were found in the left superior parietal lobule, intraparietal sulcus, bilateral occipital cortex, left fusiform gyrus and thalamus. This region also connected with the superior parietal lobule, intraparietal sulcus, insula, inferior frontal gyrus, precentral, occipital and cerebellum through resting-state functional connectivity in healthy subjects. Taken together, our findings highlight the role of superior parietal cortex in SD.

Introduction

Despite the recommended seven to nine hours of sleep per night, people in modern societies are suffering from inadequate sleep [1]. It has been well-documented that insufficient sleep is accompanied with cognitive and emotional impairments [2–4]. Prominently, medical errors, motor vehicle accidents and lower performance are highly prevalent in people with prolonged wakefulness [5,6]. The disintegrations of brain functions due to sleep deprivation (SD), might subsequently precipitate neuropsychiatric and neurodegenerative disorders [7].

Thus far, several studies have probed the imbalance activity of brain regions in various cognitive paradigms and imaging modalities due to SD. For example, increasing activity of the default mode network (DMN) and reduced connectivity of different regions in resting-state functional magnetic resonance imaging (fMRI) studies has been reported in SD [8]. Moreover, some studies have found

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Abbreviations

ALE	activation likelihood estimation
cFWE	family-wise error in cluster level
CMBA	coordinate-based meta-analysis
dlPFC	dorsolateral prefrontal cortex
FC	functional connectivity
FDR	false discovery rate
fMRI	functional magnetic resonance imaging
FWHM	full-width half-maximum
IPL	inferior parietal lobule
IPS	intraparietal sulcus
MA	modeled activation
MNI	Montreal neurological institute
mPFC	medial prefrontal cortex
NS	normal sleep
PCC	posterior cingulate cortex
PET	positron emission tomography
PRISMA	preferred reporting items for systematic reviews and meta-analyses
ROI	region of interest
SD	sleep deprivation
SPC	superior parietal cortex
SPL	superior parietal lobule
SVC	small volume correction

aberrant activity of various regions including the intraparietal sulcus (IPS) and dorsolateral prefrontal cortex (dlPFC) while subjects are performing various tasks [9–12]. In addition, the neural activity alterations in the nucleus accumbens and ventromedial prefrontal cortex have been reported [3,13]. Meanwhile, extended wakefulness was associated with higher activity of the amygdala, anterior insular and anterior cingulate cortex during emotional paradigm tasks [14]. The findings of positron emission tomography (PET) experiments have illustrated increased activity in the thalamus and insula in SD condition [15,16]. There is also some evidence of structural changes due to SD, such as reduced thickness of the precuneus and posterior cingulate cortex (PCC) [17].

Although the current neuroimaging findings have helped to unravel the brain alterations due to SD, diversity of applied imaging modalities, statistical methods, cognitive tasks, combined with small and heterogeneous sample of individual studies have provided an ambiguous picture of underlying brain abnormality in SD. Hence, a consolidation of the literature is needed to overcome the heterogeneity of previous publications. The aim of this study was to delineate the potential regions of convergent neurobiological abnormalities in SD by quantitatively summarizing the results of available neuroimaging studies. To do so, we have applied Activation likelihood estimation (ALE) meta-analysis, as a standard algorithm in coordinate-based meta-analyses (CBMA), providing a synoptic view of distributed findings across previous neuroimaging studies on acute SD studies. In particular, ALE algorithm applies a statistical inference by integrating available neuroimaging findings to find “where” in the brain the amount of convergence between reported foci is more than expected by chance [18]. Then, we functionally characterized the obtained consistent regions that have revealed neurobiological aberrations due to SD using the BrainMap database. Moreover, we assessed the task-based and resting-state co-activation patterns to identify the networks that are connected to the identified regions in ALE analysis.

Methods

Search strategy and study selection

Following the Preferred reporting items for systematic reviews and meta-analyses guidelines [19], we performed our search in the PubMed database without any restrictions on the date of publications using the search strings: (“sleep deprivation” OR “sleep loss” OR “sleep restriction”) AND (fMRI OR “functional magnetic resonance imaging” OR “voxel-based morphometry” OR “VBM” OR “positron emission tomography” OR “PET”) in January 2018. In the next step, the identified publications have been screened based on the following inclusion criteria: 1) original studies investigating neural correlates of SD on the healthy subjects without any psychiatric or medical conditions; 2) studies using before-after SD protocol or between two groups of subjects with and without SD; 3) studies focusing on acute SD (between 22 and 48 h at once). Our exclusion criteria were the followings: 1) editorial letters, case-reports, systematic reviews, meta-analyses, and methodological studies; 2) intervention studies; 3) studies in children/adolescent (<18 y); 4) studies with less than seven subjects; 5) studies that did not perform the whole brain analysis. In particular, we excluded studies using region of interest (ROI) or small volume correction (SVC), as recommended previously [20]; 6) studies that did not report coordinates in the standard brain atlases such as Talairach or Montreal neurological institute (MNI) [21,22]. Then, three independent investigators (N.J., N.S. and K.N.) have extracted and checked all required data including number of subjects, reported peak coordinates (x, y, z) in the standard atlas (Talairach or MNI), contrast of each experiment between SD and normal sleep (NS) (i.e., SD < NS or SD > NS), type of imaging modalities (task fMRI, resting-state fMRI, PET), and task paradigms. Of note, SD has two different types, including acute (e.g., 24–48 h) and partial SD (e.g., 3–4 h of sleep per night for few nights) [23]. We identified three partial SD studies [24–26] and due to different mechanisms in acute versus partial SD and the limited number of such studies for a valid meta-analysis [27], we excluded those with partial SD experiments. Besides, no VBM study was found to be eligible according to our inclusion and exclusion criteria (Table 1).

Importantly, the included studies were mainly assessed for higher activation in SD than NS (SD > NS) or the lower activation in SD compared to NS (SD < NS). We identified several studies with the same/overlapping samples. Therefore, in order to minimize the within group effects, the data was organized by subject groups rather than by specified functional tasks, as suggested before [28]. Similarly, if publications used the same or overlapping group of subjects and reported several experiments, those were combined. Accordingly, we have merged the experiments from various publications [2,9,10,29–31]. Notably, through the entire current study, the word “study” is referred to an individual scientific publication and the word “experiment” is used as a specific contrast (e.g., SD < NS or SD > NS).

Activation likelihood estimation (ALE)

ALE meta-analysis is a canonical CBMA procedure, which is utilized to integrate the reported coordinates from different experiments [28,32,33]. In this approach, the spatial convergence could be described as a consistent functional or structural

Table 1
Demographic and imaging information of the included papers.

	Author, year	Study design	Number of subjects (before, control/after, case)	Number of female subjects	Age (mean ± standard deviation)	Hours of deprived sleep	Imaging modality	Normalizing Software	Reported standard space	Task
1	Albouy et al. (2013) [72]	case–control	16/15	14	24 ± 3	24	Task-related fMRI	SPM2	MNI	Motor adaptation task
2	Benedict et al. (2012) [81]	before-after	12/12	0	23.3 ± 0.6	24	Task-related fMRI		MNI	Food stimuli
3	Bell-McGinty et al. (2004) [82]	before-after	15/15	NS	25.05 ± 2.7 in 19 subjects	48	Task-related fMRI	SPM99	Talairach	Non-verbal recognition task
4	Chee et al. (2004) [9]	before-after	14/14	5	23	24	Task-related fMRI	Brain Voyager v 4.9	Talairach	Verbal working memory
5	Chee et al. (2008) [10]	before-after	17/17	NS	22.5 ± 1.6	one night	Task-related fMRI	Brain Voyager QX	Talairach	S H congruent and incongruent stimuli
6	Chee et al. (2010) [30]	before-after	20/20	15	21.5 ± 2	one night	Task-related fMRI	Brain Voyager QX	Talairach	S H congruent and incongruent stimuli
7	Choo et al. (2005) [31]	before-after	12/12	NS	21.8 ± 0.8	24	Task-related fMRI	Brain Voyager QX	Talairach	N back
8	Czisch et al. (2012) [83]	before-after	20/20	19	25.5 ± 2.5	36	Task-related fMRI	SPM8	MNI	Oddball task
9	Dai et al. (2012) [84]	before-after	16/16	8	22	24	Resting-state fMRI	SPM5	MNI	
10	Drummond et al. (2005) [85]	before-after	32/32	14	27.6 ± 6.6	35.7 ± 0.8	Task-related fMRI	AFNI	Talairach	Verbal learning task
11	Gao et al. (2015) [86]	before-after	16/16	8	22.1 ± 0.8	24	Resting-state fMRI	SPM8	MNI	
12	Gujar et al. (2010) [8]	case–control	12/14	NS	22.3 ± 2.8	35.2 ± 0.95	Task-related fMRI	SPM2	MNI	Memory encoding task
13	Greer et al. (2016) [87]	case–control	15/14	case 10, control 7	(1) Sleep rested & 10R/10R: n = 7,20.86 ± 2.9 (3) Sleep rested and 9R: n = 8, 19.63 ± 1.2 (2) Sleep deprived and 10R/10R: n = 7, 20.86 ± 1.8 (4) Sleep deprived and 9R: n = 7, 20.57 ± 1.3	24	Task-related fMRI	SPM8	MNI	Monetary incentive delay task trials
14	Habeck et al. (2004) [88]	case–control	14/17	NS	26.3 ± 4.9 in 18 subjects	49	Task-related fMRI	SPM99	Talairach	Delayed-match-to-sample task
15	Klumpers et al. (2015) [16]	before-after	12/12	6	females 29.2 ± 10.2, males 28.5 ± 4.8	22	Task-related fMRI, PET	SPM8	MNI	Semantic emotional classification
16	Kong et al. (2012) [12]	before-after	22/22	11	20 ± 1.3	22	Task-related fMRI	Brain Voyager QX	Talairach	Attending face vs. house
17	Lythe et al. (2012) [89]	before-after	20/20	0	26.7 ± 6.7	31	Task-related fMRI	SPM5	MNI	N back
18	Menz et al. (2012) [4]	before-after	22/22	0	26.6 ± 4.22	24	Task-related fMRI	SPM8	MNI	Risky choice task
19	Mu et al. (2005) [90]	before-after	33/33	0	28.6 ± 6.6	30	Task-related fMRI	SPM2	MNI	Verbal working memory
20	Mullin et al. (2013) [3]	before-after	25/25	16	23.1 ± 1.6	25.5–27	Task-related fMRI	SPM8	MNI	Monetary Reward Task
21	Muto et al. (2012) [11]	before-after	12/12	7	21	25–33	Task-related fMRI	SPM8	MNI	The attentional network task
22	Rauchs et al. (2008) [91]	before-after	12/12	6	23.2 ± 2.9	30	Task-related fMRI	SPM2	MNI	Virtual environment and navigation tasks
23	Reichert et al. (2017) [92]	before-after	31/32	18	24.68 ± 3.32	41	Task-related fMRI	SPM9	MNI	Visual n back
24	Thomas et al. (2003) [15]	before-after	17/17	0	24.7 ± 2.8	24	PET	SPM95	Talairach	Serial addition subtraction task
25	Vartanian et al. (2014) [93]	before-after	13/13	3	32.23 ± 8.45	24	Task-related fMRI	SPM8	MNI	Divergent thinking task cognitive information processing (AUT)
26	Vandewalle et al. (2009) [94]	before-after	15/15, 12/12	PER3 4/4:7, PER3 5/5:5	24.13 ± 0.95 (genotype PER3 4/4), 24.17 ± 1.17 (genotype PER3 5/5)	25	Task-related fMRI	SPM5	MNI	N back
27	Venkatraman et al. (2007) [2]	before-after	26/26	12	21.3 ± 1.6	24	Task-related fMRI	Brain Voyager QX	Talairach	Gambling task
28	Venkatraman et al. (2011) [29]	before-after	29/29	14	22.34 ± 1.23	22	Task-related fMRI	FSL FEAT 5.63	Talairach	Decision making
29	Wang et al. (2016) [95]	before-after	16/16	8	24.51 ± 2.75	24	Resting-state fMRI	DPARSF	MNI	
30	Wu et al. (2006) [96]	before-after	32/32	17	28.3 ± 9.4	29–34	PET	SPM99	Talairach	Visual vigilance task
31	Xu et al. (2016) [97]	before-after	22/22	9	22.5 ± 1.7	24	PET	SPM8	Talairach	Mathematical processing task

disturbance [32]. This has been used in various neuropsychiatric conditions [34–40]. In order to identify consistent brain regions related to SD across different experiments, the revised ALE algorithm implemented in MATLAB is utilized here [18]. In the ALE algorithm, the reported foci from experiments were identified as centers for 3D Gaussian probability distribution to consolidate the spatial uncertainty linked to either focus. The width of uncertainty was determined between-subject variations, differences between imaging procedures and normalizing methods. Clearly, the foci of experiments with smaller sample size had a smaller effect on modeled 3D Gaussian probability distributions [18,32]. The probability of all foci of each experiment was then aggregated for each voxel to form a modeled activation (MA) map of every experiment. The unions of modeled activations of all experiments were calculated to obtain an ALE map, which described the convergence of each resulted brain regions. This ALE map was assessed against null-distribution of random spatial association using non-linear histogram integration. Statistical significance threshold was set at $p < 0.05$ family-wise error at the cluster level (cFWE) to correct for multiple comparisons and avoid false positive findings as suggested previously [20,41]. Each ALE analysis should be conducted if at least 17 experiments are available to achieve 80% power for moderate effects [27]. Anatomy toolbox version 3 [42] and JuBrain cytoarchitectonic atlas (jubrain.fz-juelich.de) were utilized in labeling the observed brain regions [43].

Functional decoding

The region resulting from the ALE analysis was then functionally characterized based on the meta-data from the BrainMap database [42–45], using forward inference, as performed in previous studies [44,45]. The main idea behind this approach is to identify all experiments that activate a particular region of interest and then analyze the experimental meta-data describing the experimental settings that were employed in these areas. This allows statistical inference on the type of tasks that evoke activation in a particular region.

Using the BrainMap database, behavioral domains (BD) are extracted to describe the cognitive processes probed by an experiment. The functional profile of the particular ROI was determined by identifying taxonomic labels for which the probability of finding activation in the respective region/set of regions was significantly higher than the overall chance across the entire database. That is, we tested whether the conditional probability of activation given a particular label [P(Activation|Task)] was higher than the baseline probability of activating the region(s) in question *per se* [P(Activation)]. Significance was established using the binomial test [$p < 0.05$, corrected for multiple comparisons using false discovery rate (FDR)]. Significance (at $p < 0.05$, corrected for multiple comparisons using FDR) was then assessed by means of the chi-squared test.

Task-based and resting-state functional connectivity analysis

Both resting-state and task-based FC have been reported in several meta-analyses [34,46,47]. Meta-analytical connectivity modeling (MACM) was used to characterize the whole-brain connectivity of the seed region during the execution of experimental tasks through the identification of significant co-activations with the seed across many individual experiments [32,48]. First, all experiments that feature at least one focus of activation in a particular seed region were identified in the BrainMap database. Next, the retrieved experiments were subjected to a quantitative meta-analysis using the revised ALE algorithm [18,28,32]. This algorithm treats the activation foci reported in the experiments as spatial probability distributions rather than single points, and aims at identifying brain areas that show convergence of activation across experiments. Importantly, convergence was assessed across all the activation foci reported in these experiments. Consequently, any significant convergence outside the seed indicates consistent co-activation and hence FC. Statistical significance was assessed at $p < 0.05$ after correction for multiple comparisons.

We also conducted voxel-wise seed-based FC analysis in a resting-state database of healthy brains, using the regions determined in the ALE analysis as seeds. Seed-based FC analysis assesses synchronous fluctuation of blood oxygen level-dependent signals between the seed and other brain voxels. Here, resting-state fMRI data from 192 healthy adult subjects (65% female, age range 20–75, mean ± SD age = 46.4 ± 16.7 y) from the Nathan Kline Institute/Rockland sample (NKI/Rockland sample) available online via (http://fcon_1000.projects.nitrc.org/indi/pro/nki.html) was used [49]. Data were preprocessed in SPM12 and in-house script implemented in MATLAB. The first four scans were excluded prior to further analyses and the remaining EPI images were corrected for head movement using a two-pass (alignment to the initial volume followed by alignment to the mean after the first pass) affine registration. The mean EPI image for each subject was then spatially normalized to the ICBM-152 reference space using the "unified segmentation" approach [50]. The resulting deformation was applied to the individual EPI volumes, which were then smoothed with a 5 mm FWHM Gaussian kernel to improve signal-to-noise ratio and to compensate for residual differences in anatomy. The time-course of each seed region was then extracted per subject by computing the first eigenvariate of the time-series of all voxels within that seed. Variance explained by the mean white matter and cerebral spinal fluid signal were removed from the time-series to reduce spurious correlations. The signal was then band-pass filtered to preserve frequencies between 0.01 and 0.08 Hz. The processed time-course of each seed was then correlated with the time-series of all other gray matter voxels in the brain (identically processed) using Pearson coefficient resulting in the resting-state FC of each seed region. The voxel-wise correlation coefficients were then transformed into Fisher's Z-scores and were entered in a second-level ANOVA for group analysis including age and gender as covariates of no interest. The results for all three seeds were corrected by cFWE for multiple comparisons ($p < 0.05$), which have been used in several meta-analyses [34,46,47].

Conjunction between task-based and resting-state functional connectivity patterns

We performed conjunction analyses for the identified seed from ALE analysis across task-based and resting-state FC maps to delineate the consensus connectivity patterns, as suggested before [51].

Results

In this meta-analysis, from 305 retrieved papers, 31 studies consisting 45 experiments and 811 subjects were eligible to be included in this meta-analysis (Fig. 1, Table 1). These 31 studies included 36 task fMRI, four resting-state fMRI and five PET experiments, which comprised 24 SD > NS and 21 SD < NS experiments.

Convergence of experiments in SD

Testing for significant convergence across all 45 experiments comparing SD and NS conditions, all SD < NS (24 experiments) and all SD > NS (21 experiments) together yielded non-significant results ($P = 0.257$, cFWE). Separate analyses for all SD < NS or all SD > NS also provided non-significant results (Table S1).

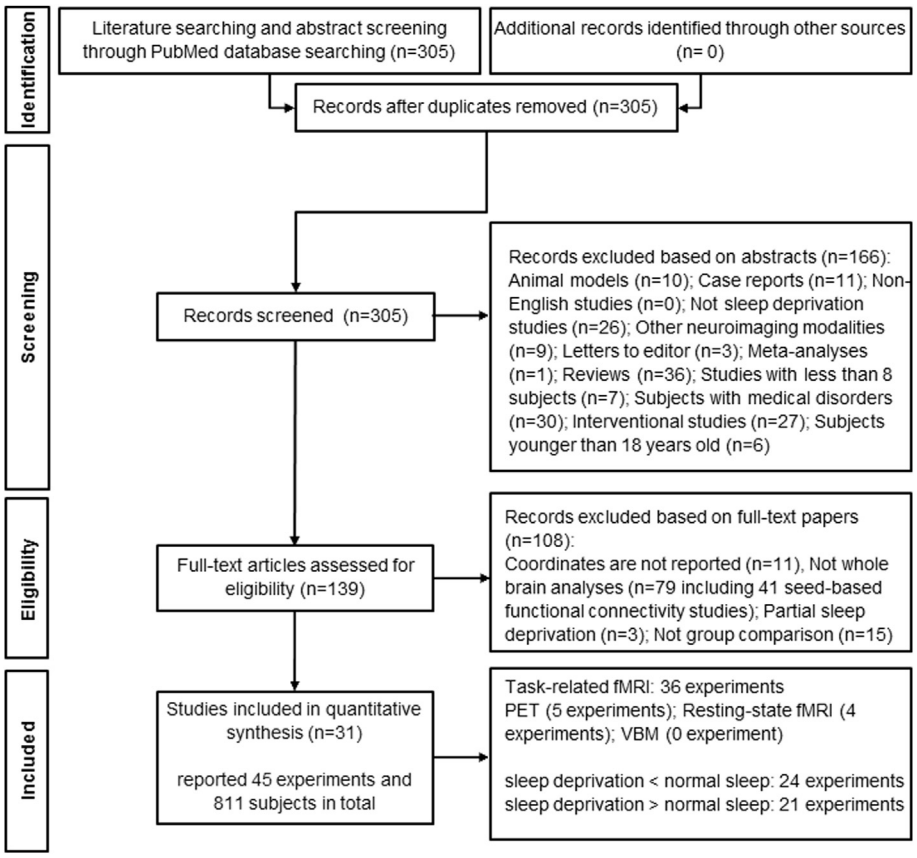

Fig. 1. Paper selection strategy flow chart based on preferred reporting items for systematic reviews and meta-analyses statement.

ALE analyses combining resting-state and task fMRI (using only SD < NS condition (20 experiments) demonstrated that subjects with SD had consistent hypoactivity in the superior parietal lobule (SPL), mainly in the right IPS (local maximum: 30–52 48 in MNI space, 98 voxels, P < 0.030, cFWE) (Fig. 2A). In this analysis, seven task-based studies including memory, attention, decision making, and motor tasks contributed and none of the resting-state fMRI experiments contributed here [3,9,10,12,30,31,91]. This region is allocated 66% to the right hIP3 (anterior part of the medial wall of the IPS) using the Anatomy toolbox in SPM (version 3.0) and JuBrain cytoarchitectonic atlas [42,43].

Further separate ALE analyses on the 36 task-based fMRI experiments regardless of the contrasts (SD > NS or SD < NS) and 18 task fMRI experiments with the contrast of SD < NS have indicated

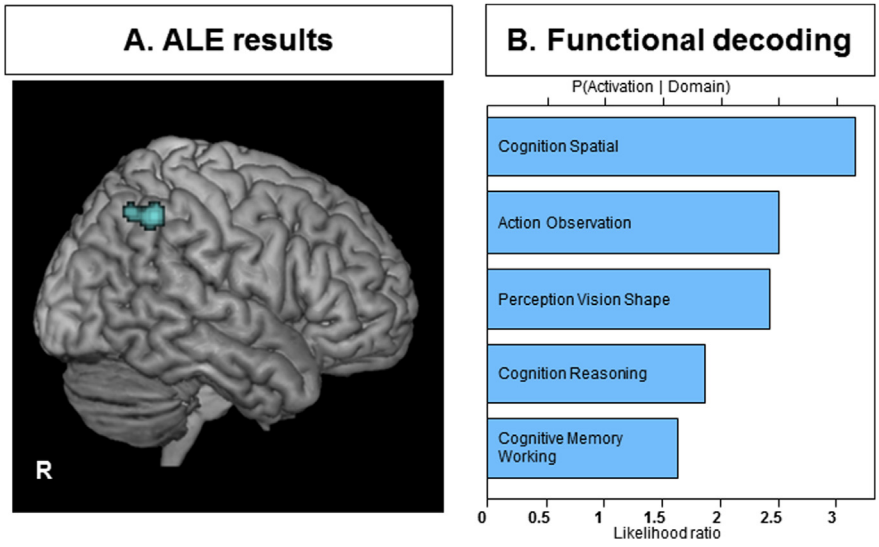

Fig. 2. A) Convergence of decreased activity in SD compared to NS based on both task and resting-state fMRI experiments in the right intraparietal sulcus and superior parietal lobule. All activations are significant at P < 0.05 corrected for multiple comparisons using the family-wise error rate in cluster level (cFWE); B) behavioral characterization of the significant cluster (p < 0.05, corrected for multiple comparisons).

consistent regional abnormality in the right IPS, mainly in the right hIP3 ($P < 0.05$, cFWE). Notably, we also combined 41 PET and task fMRI studies and result was not significant ($p = 0.198$, cFWE). In summary, the reduced activation in the IPS was mainly driven from the task fMRI experiments. More details regarding all sub-analyses are provided in the Supplementary file.

Functional decoding

By applying functional decoding analyses for each seeds (obtained from ALE analyses) in the BrainMap database, we found that these regions were functionally related to cognition (spatial), action (observation), vision-related perception (shape), cognition (reasoning) and cognition (working memory) ($p < 0.05$, FDR corrected for multiple comparisons) (Fig. 2B).

Combined findings of task-based and resting-state functional connectivity analyses

Task-based and resting-state FC analyses have been conducted for the identified regions from ALE analyses (Fig. 3 and Supplementary file). Firstly, the MACM analysis was done in order to identify regions that feature significant task-based co-activation with the seed, based on ALE results from both task and resting-state fMRI experiments in SD < NS experiments. Here, we observed significant co-activation in the hIP3 in IPS [52], hOc4lp (located in caudal and dorsal portions of lateral occipital cortex [53], precentral gyrus [54], insula [55], cerebellum [56] (Fig. 3A). The resting-state FC analysis of the mentioned seed showed significant connectivity with the more extended regions including SPL [57], IPS [52], inferior frontal gyrus (IFG) [58], precentral gyrus [54], insula [55], hOc4lp (located in caudal and dorsal portions of lateral occipital cortex [53], fusiform gyrus [59], cerebellum [56], thalamus [60] (Fig. 3B).

As the last step, we combined the results of task-based and resting-state FC, which depicted co-activation in the SPL, IPS, insula, IFG, precentral, occipital and cerebellum (Fig. 3C). We also have done the other conjunction analyses combining task-based and resting-state FC related to two other seeds, obtained from ALE analyses on the 36 task fMRI experiments regardless of the contrasts (SD > NS or SD < NS) and 18 task fMRI experiments with the contrast of SD < NS (Supplementary file).

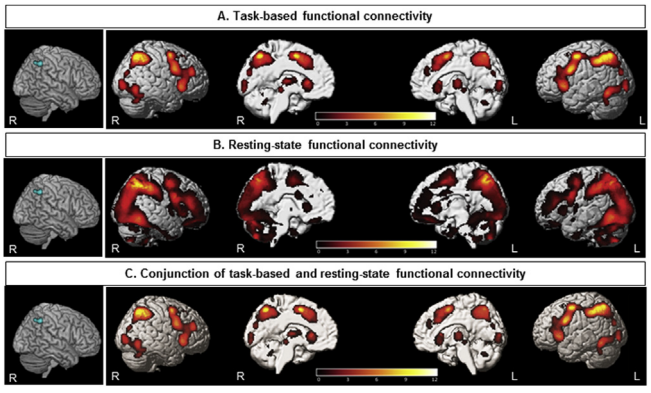

Fig. 3. A) The results of task-based functional connectivity analysis of the seed obtained from ALE findings using the BrainMap dataset; B) the results of resting-state functional connectivity of the seeds obtained from ALE findings in a healthy participants' dataset; C) conjunction analysis demonstrated regions significantly co-activated with the seed in both task-based and task-independent datasets ($p < 0.05$ corrected for multiple comparisons using the family-wise error rate in cluster level (cFWE)).

Discussion

We have integrated findings from 31 neuroimaging studies in SD and found convergent reduced activity predominantly in the right intraparietal sulcus and superior parietal lobule. The contribution of this area in the neurocircuitry fingerprint of SD was further explored. The functional decoding analysis indicated possible dysfunction of visual perception, memory and reasoning in SD. The task-based and resting-state FC of this region revealed a network comprising from the left superior parietal lobule, intraparietal sulcus, insula, IFG, precentral, cerebellum, occipital cortex, fusiform gyrus and thalamus.

It has long been known that damage to right parietal regions can cause the hemispatial neglect syndrome, even though this region lacks spatial maps. The findings of our study indicate that there are abnormalities in the right parietal cortex following SD, and, more specifically, they point to altered neural activity in the right IPS and SPL. These two regions are located in the superior parietal cortex (SPC) (Fig. 1), which is known to demonstrate rich, functional heterogeneity across its subregions, including during mnemonic and numerical decision tasks [61]. Its role in a large variety of cognitive tasks, such as spatial attention, perceptual decision making, visual categorization, saccadic eye movements, processing of information in working memory, episodic memory and numerical cognition has been proposed and demonstrated over the years [61]. Our functional decoding analysis has further supported its role in a range of cognitive processes such as spatial cognition, action observation, vision-related perception, reasoning, working memory. More specifically, the co-activation of IPS and SPL in task-based FC analysis was observed to occur with the left SPL, IPS, fusiform gyrus, bilateral occipital cortex and thalamus (Fig. 3A). On the other hand, resting-state FC analysis suggests that underlying functional neurocircuitry may also include the SPL, IPS, IFG, precentral gyrus, insula, occipital cortex, fusiform gyrus, and cerebellum (Fig. 3B). When these results were combined, the co-activation was also suggested in the SPL, IPS, IFG, insula, IFG, precentral, cerebellum, bilateral occipital cortex, left fusiform gyrus and thalamus (Fig. 3C). Taken together, our results point to a multi-component model of SPC functional organization and highlight the central role for IPS and SPL in SD.

The role of superior parietal cortex in sleep deprivation

Following sleep deprivation, our findings suggest abnormal activity in deeper recesses of an anterior part of the medial wall of the IPS and SPL. In that respect, of note are findings of a recent single-neuron study of two tetraplegic subjects. Here, encoding of two types of memory retrieval signals has been demonstrated in this region: familiarity of stimuli, and retrieval confidence [62]. Traditionally, it has been proposed that lateral IPS activity may increase with the familiarity, whilst SPL/medial IPS activity reacts to uncertainty, being stronger when subjects are less confident in their memory decisions. However, findings of Rutishauser and colleagues point to a more complex and richer tapestry of neuronal functional subphenotypes of the region, raising the possibility that this is the critical node where multiple parietal cortex computations enable our choosing of an action—even though the coding of action execution itself may occur somewhere else [63]. Given that our major finding indicates lower activity of both IPS and SPL in sleep deprived subjects, it is then perhaps unsurprising that this region has also been implicated in poorer decision-making in SD people [29]. It is impossible to deduce if demonstrated lower activity in this region is due to a generalized lower activity of all neuronal subpopulations in this region, or if there might be preferential inducement of certain subgroup of neurons, with net lower

activity due to significantly reduced activity of other subgroups. Arguably, either scenario might have significant functional repercussion. For example, it has been previously suggested that transient synchronization of theta oscillations across multiple regions, such as retrosplenial cortex may occur during autobiographical memory retrieval, may enable integration of the ground-truth memory-based evidence encoded in medial temporal lobe to SPC regions [64,65]. Similar integration may occur with information from the cerebellum, another region that was suggested to co-activate with IPS and SPL in our study. False and erroneous transfers might be facilitated by sleep deprivation and may underlie some of previously reported sleep deprivation-associated neuropsychiatric deficits. Indeed, dysmetria of thought and affect is now accepted to occur in cerebellar disorders [65]. Thus, improper decision-making observed in SD might be due to the differential pattern of activity in IPS and SPL. Behavioral decoding of this region also indicated the contribution of this region in working memory, observation and reasoning, which may be taken to further support this hypothesis. The other function of IPS is in passive observation and imitation, which might be related to mirror neurons within this region involving in perspective taking [66]. For example, Yamazaki et al. have demonstrated that mirror neurons in this region are involved in encoding the 'semantic equivalence' of actions carried out by different agents in different contexts [67]. In this context, IPS connectivity with fusiform gyrus as one of the implicated nodes in the extended SD-affected neurocircuitry is of interest. This region has been considered an important region for semantic representations and the aberrant connectivity with IPS and its subregions may similarly underlie SD driven affective and cognitive deficits. Faulty connectivity with this computational hub for face processing might also lead to functional hypomimia noted in many affective and neuropsychiatric disorders [68].

IPS has long been suggested as a core region of attention network susceptible to SD, for more detailed review of these findings please refer to a recent review on acute SD [69]. For example, findings of a growing body of studies assessing attention paradigms in sleep deprived subjects are in keeping with the notion that the decreased activity of IPS and SPC may be a main culprit that underlies observed delays and poorer results in these individuals [12,63]. Moreover, it is widely thought that the ability to hold information across a delay is necessary to succeed at tasks that require working memory or sustained attention. It is hence of interest that feedback of sustained activity from frontal eye field to IPS within the attention network has been shown gated by task demands [70], with SD lowering this threshold significantly and leading to higher activation in perceptual load of visual processing [71] and visuomotor adaptation [72]. Thus, people with SD are more likely to utilize wider regions of the brain in order to perform optimally, and they may be inclined to perceive tasks as being more complex than those who had sufficient sleep. In that respect it is perhaps of interest to mention the effect of inadequate sleep, and notion of subacute to chronic sleep deprivation through poor sleep efficiency, that forms a severe aspect of most, if not all major sleep disorders. Our group has recently demonstrated the aberrant connectivity of the frontoparietal network, including regions corresponding to IPS and SPL, to severity of obstructive sleep apnea (OSA), one of the most prevalent sleep disorders [73]. OSA is commonly associated with poor sleep quality due to frequent arousals during sleep and arguably the aberrant connectivity of attentional network might also lead to executive and neuropsychiatric deficits in some patients with OSA. In keeping, another study has noted that in major depression disorder, there is a lower connectivity of IPS, anterior insula and dorsal anterior cingulate cortex [74]. Therefore, as the role for IPS and SPL function further emerges, it would be important to address in future studies the complex across-region neural dynamics with different information exchanges at different temporal windows as well as through interactions with broader neural systems, such as our FC analyses suggested.

Potential strengths and limitations

In this study, we found a convergent region across 31 acute SD studies comprising 45 experiments including 811 unique subjects by ALE analysis, following the recent best-practice neuroimaging meta-analysis guideline [20]. Of note, we excluded studies on less than eight subjects, ROI analysis and in order to minimize the within-group effect, we merged the studies with similar sample using pooling approach suggested by Turkeltaub and colleagues [28]. Among 11 included studies in the prior ALE meta-analysis in SD [75], six of the included studies used ROI analysis [13,71,76–79] and we excluded them due to their potential to erroneously skew results regarding any particular ROI [20]. More specifically, null-hypothesis in CBMA utilizes random spatial associations across the whole brain with the assumption that each voxel has the same chance of being activated [80]. Importantly, we used cluster-level FWE with $P < 0.05$ for multiple comparison correction to maximize the statistical accuracy [20]. Moreover, we performed behavioral characterization of the identified regions using the BrainMap database. Finding a consistent region across whole-brain task-based and resting-state studies enabled us to identify a seed for task-based and resting-state FC analyses in order to delineate regions co-activated with that seed concurrently.

Whilst every effort has been done to follow the best-practice in delivering this study, it has been acknowledged that our findings somewhat differ from the previously published meta-analysis that included a smaller cohort of 11 acute SD studies using "attention tasks" only [75]. Ma and colleagues demonstrated decreased activity in various regions including bilateral IPS, insula, right prefrontal cortex, medial frontal cortex, and right parahippocampal gyrus, as well as increased activity in thalamus [75]. In keeping, our study highlighted the importance of the IPS region, but it did not demonstrate significant changes in other reported regions. Whilst it is possible that the length of sleep deprivation, which in our studies ranged up to 49 h, and different population cohorts and tested paradigms played a role and contributed to differential outcomes, we suggest that different methodologies both groups used could have also contributed to this. For example, a false discovery rate (FDR) correction in GingerALE versions prior to 2.3.6 version, which is used in that work [75], has been reported to have a significant error to control for false positive results and could significantly affect meta-analysis outcomes, which has since been corrected [41].

The level of sample homogeneity required for a CBMA dependents on the research question of each meta-analysis. The optimal approach is to aggregate findings within each task or imaging modality and then integrates the data across them. This requires dividing the available literature into more homogeneous but inevitably also smaller subsets – to the level where valid meta-analyses cannot be carried out on these any longer due to lack of available experiments. On the other hand, including more studies, increases statistical power to detect smaller effects and provide superior evidence for the generalization across experimental and analytical procedures [33]. In the current study, our aim was to identify the spatial convergent abnormality due to sleep deprivation in various task activations and resting-state studies compared to healthy subjects with normal sleep. Of note, there was not enough experiment per task to perform a statistically sound CBMA [27].

Conclusion

Our ALE analyses indicate the reduced activity of the IPS and SPL in SD. Moreover, the functional decoding of IPS and SPL demonstrates several main cognitive functions in visual processing, memory, language, reasoning and spatial recognition. Most excitingly, this very region has recently gained some attention as a potential major hub in modality independent decision making process. We believe that taken together, these findings should inspire future explorations of the role for sleep deprivation and its modulation of the IPS and SPL regions contributions to a diverse array of functional domains and neuropsychiatric disorders.

Practice points

- Our findings have demonstrated a significant convergent functional disruption due to sleep deprivation in the region of the right intraparietal sulcus and superior parietal lobule. In addition, Functional characterization of this region suggested associated dysfunctionality in spatial cognition, observation, visual perception, reasoning and memory.
- Connectivity analyses, assessing task-based co-activation and resting-state functional connectivity patterns, have demonstrated that these regions are part of a wider network, also comprising of the left superior parietal lobule, the intraparietal sulcus, insula, inferior frontal gyrus, precentral, occipital cortex, and cerebellum.
- This study highlights the important role of parietal cortex in sleep deprivation that should be assessing more in future.

Research agenda

- Future neuroimaging studies should address our findings in larger sample sizes during acute total, as well as acute partial sleep deprivation. Comparison between findings of those experimental paradigms and that underlying subacute and chronic sleep deprivation should enable a more correct deciphering of varied diffuse and focal regional susceptibilities of corresponding neural networks.
- Resting-state neuroimaging studies following sleep deprivation should provide a more direct insight into the altered intrinsic organization of major neural networks.

Conflicts of interest

The authors do not have any conflicts of interest to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smrv.2019.03.008.

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