Functional connectivity correlates of attentional networks in insomnia disorder

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RESEARCH ARTICLE

Functional connectivity correlates of attentional networks in insomnia disorder: A pilot study

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Summary

Insomnia disorder has been associated with poor executive functioning. Functional imaging studies of executive functioning in insomnia are scarce and inconclusive. Because the Attentional Network Test relies on well-defined cortical networks and sensitively distinguishes different aspects of executive function, it might reveal brain functional alterations in relatively small samples of patients. The current pilot study assessed functional connectivity during the Attentional Network Test performed using magnetic resonance imaging in 12 participants with insomnia and 13 self-defined good sleepers. ANCOVAs were used to evaluate group differences in performance and functional connectivity in the regions of interest representing the attentional networks (i.e. alerting, orienting and executive control) at $p < 0.05$, uncorrected. During the orienting part, participants with insomnia showed weaker connectivity of the precentral gyrus with the superior parietal lobe (false discovery rate-corrected), while they showed stronger connectivity between premotor and visual regions. Individual differences in connectivity between premotor and visual regions correlated inversely with reaction time. Reaction times suggested more efficient executive control in participants with insomnia compared with good sleepers. During the executive control part, participants with insomnia showed stronger connectivity of thalamic parts of the arousal circuit with the middle frontal and the occipital gyri. Conversely, connectivity between the inferior and superior frontal gyri was weaker. Participants with insomnia seem to recruit more cortical resources in visuomotor regions to orient attention than good sleepers do, and seem to have enhanced executive control that relates to stronger connectivity of arousal-related thalamic areas. This latter result should be treated with caution and requires confirmation.

KEYWORDS
attentional network test, executive control, frontal gyrus, hyperarousal, task-based functional magnetic resonance imaging

1 | INTRODUCTION

Insomnia disorder (ID) is frequent in the general population, with a prevalence of about 6%– to 10% in industrialized countries (Calem et al., 2012; Ohayon, 2002; Pallesen et al., 2014). ID generates a high socioeconomic burden, notably due to reduced work productivity, as well as poor mental health consequences (Van Someren, 2020). In contrast to the profound effects of experimental sleep deprivation on cognitive performance in GS, people with ID perform normal on most cognitive domains. Performance deficits seem mostly limited to tasks that assess memory and executive functioning (Fortier-Brochu et al., 2012; Fortier-Brochu & Morin, 2014; Wardle-Pinkston et al., 2019). Understanding of deficits in executive functioning in insomnia is of particular importance as such deficits have been associated with increased emotional problems and rumination in the general population (Yang et al., 2017) and in participants with ID (Ballesio, Ottaviani, & Lombardo, 2019).

As meta-analysed and reviewed (Fortier-Brochu & Morin, 2014), results from previous studies investigating executive functioning in participants with ID are still mixed. Some studies have shown performance decrement while others did not or even highlighting better performance in participants with ID (Ballesio, Aquino, et al., 2019; Brownlow et al., 2020; Wardle-Pinkston et al., 2019). Possibly, different tasks tap into different vulnerabilities and strengths characteristic of people with insomnia. To address these issues, a comprehensive assessment of the different brain networks involved in executive functioning would be valuable. The Attentional Network Test (ANT) was specifically designed to distinguish different brain networks, that partially overlap, involved in executive functioning (Fan et al., 2005), and has shown sensitivity to executive difficulties in ID (Li, Liu, et al., 2016; Liu et al., 2014; Perrier et al., 2015). The ANT relies on the attentional networks as defined by Posner and colleagues, namely the alerting, orienting and executive control networks (Fan et al., 2005). The *alerting* network is located around frontal and parietal regions. The *orienting* network involves the posterior parietal lobe, the thalamus, as well as the middle frontal gyrus and premotor regions. Finally, the *executive control* network is based on anterior regions of the frontal cortex, including the anterior cingulate cortex, the lateral prefrontal cortex and the thalamus. The ANT may thus be particularly appropriate to study the neural correlates of deviations in executive functioning in ID due to its reliance on well-defined cortical networks and demonstrated sensitivity to ID.

Functional magnetic resonance imaging (fMRI) is well suited to investigate the neural correlates of task performance. Task-based fMRI data can be investigated in terms of task-related activation of specific regions (Yang et al., 2019) or in terms of task-related changes in functional connectivity (FC) between specific regions. Previous fMRI studies in ID, although scarce, addressed neural correlates of executive functioning using task-related activation (Altena, Van Der Werf, Sanz-Arigita, et al., 2008; Drummond et al., 2013; Hwang et al., 2019; Son et al., 2018). Altena, Van Der Werf, Strijers, and Van Someren (2008) assessed neural correlates of executive functioning in ID using fluency tasks to reveal better performance in spite of hypoactivation of the inferior frontal gyrus. Two studies using the N-back task in ID found intact performance but altered cortical activation patterns (Drummond et al., 2013; Son et al., 2018). While Drummond et al. (2013) reported hypoactivation of the right dorsolateral prefrontal cortex and reduced deactivation of the default mode network, Son et al. (2018) instead found hyperactivation in the inferior frontal cortex and in the temporal pole. Both the dorsolateral prefrontal cortex and the inferior frontal cortex are part of the executive control network, and are known to play a role in executive functioning. Finally, one study using the Stroop task (Hwang et al., 2019) did not find deviations in brain activation in ID compared with GS, and concluded that the Stroop task might not be the most appropriate task to address deviations in executive functioning related to insomnia.

Altogether, these previous findings suggest executive functioning alterations, as assessed behaviourally and using task-related activation, in ID. However, the previous studies were also limited in their scope by only evaluating working memory performance and only addressing activation of specific brain regions, not their FC. Consequently, the neuronal correlates of altered executive functioning in ID remain scarcely investigated and require further attention (Tahmasian et al., 2018). Given recent studies indicating altered FC during resting-state imaging in ID (Leerssen et al., 2018; Li et al., 2014), we considered it of particular interest to investigate FC in ID during performance of a task relying on well-defined cortical networks and with demonstrated sensitivity to ID. We hypothesized that altered executive functioning in ID would be accompanied by altered FC, particularly in the prefrontal regions known to be involved in executive control.

2 | METHODS

2.1 | Participants

This study included 25 participants, of whom 13 self-acclaimed good sleepers (GS; 1 male/12 females) and 12 diagnosed by clinical interview to fulfill the diagnostic criteria for ID according to the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) and the International Classification of Sleep Disorders (ICSD-3; 12 females). Exclusion criteria for all participants were: (a) diagnosed current or past neurological or psychiatric disorders; (b) current sleep disorders other than insomnia, including signs of frequent hypopnea or leg movements; (c) shift work; (d) use of sleep medications within the prior 2 months; (e) MRI contraindications.

2.2 | Design and general procedure

The MRI included anatomical scans and functional scans during the ANT task that consisted of three sessions separated by a B0 scan to assist with data preprocessing, and by a small break inside the scanner to minimize head movements or muscle tension that would increase with extended performance (see Section 2.4 for more details).

Following the task, participants rated their sleepiness level and effort invested in the task as described in detail below (Section 2.3). All MRI scans took place between 13:30 hours and 15:00 hours in the afternoon. Participants were asked to refrain from alcohol, drugs as well as caffeinated beverages during the day of the assessment. Participants' characteristics as well as information related to arousal and fatigue were collected through questionnaires in the Netherlands Sleep Registry (NSR; Benjamins et al., 2013; Blanken et al., 2019) during the week of the assessment visit. All participants provided written informed consent. The study protocol was approved by the Ethics Review Board of the University of Amsterdam (Ethic approval N° 2015-EXT-4429).

2.3 | Questionnaires

Insomnia complaints were measured using the Insomnia Severity Index (ISI; Bastien et al., 2001; Morin, 1993), which consists of seven items about the nature, severity and impact of insomnia. Arousal was measured using the hyperarousal scale (HA; Pavlova et al., 2001) and the Pre-Sleep Arousal Scale (PSAS; Nicassio et al., 1985). The HA is a 26-item questionnaire that measures information processing, tendencies to introspection, thinking about feelings and intense responses to unexpected stimuli, which are all commonly reported in insomnia. One global hyperarousal score was computed. The PSAS describes bedtime arousal, both at the physical and mental levels, using 16 items. Fatigue was measured using the Fatigue Severity Scale (FSS; Krupp et al., 1989) that reflects how fatigue interferes with day-to-day functioning and quality of life using nine items. For all questionnaires, higher scores indicated more severe symptoms.

Following the ANT task, participants were asked to report their sleepiness level using the Karolinska Sleepiness Scale (KSS), a Likert scale that is a validated measure of sleepiness (Åkerstedt et al., 2014; Akerstedt & Gillberg, 1990), and the mental effort required to perform the task using a visual analogue scale between 0 (not demanding at all) and 100 (extreme demanding). Higher scores indicated more sleepiness and mental effort, respectively.

2.4 | Attentional Networks Task

The ANT used in the current study has been described previously (Fan et al., 2002, 2005). The participants' task was to identify the direction of a central arrow (i.e. target) flanked by two arrows on each side (i.e. flankers) using a button box.

Each trial was as follows: (1) a fixation cross appeared in the centre of the screen; (2) then, a cue was presented for 200 ms; (3) finally, after a variable duration (300–11,800 ms), the target (central arrow) appeared and was flanked by two arrows left and right. After the participant's answer, the stimulus disappeared and a post-target fixation period lasts for a variable duration (the delay from the onset of the target and the start time of the next trial is between 3000 and 15,000 ms). If no answer was given after 2000 ms, another trial began automatically.

Cue types included: central cue, an asterisk that appeared at the fixation cross; spatial cue, that appeared either below or above the fixation cross according to the position of the subsequent target; or no cue, with a blank screen showing only the fixation cross. The flankers could point either to the same direction as the target (congruent condition) or to the opposite direction (incongruent condition). In addition, the stimulus could appear either below or above the fixation cross. Total task duration was 20 min with nine runs (three per session) of 36 trials plus two buffer trials.

The following variables were computed: mean reaction time (RT), alerting RT (RT no cue minus RT centre cue), orienting RT (RT centre cue minus RT spatial cue) and executive control RT (RT incongruent flanker minus RT congruent flanker) as previously instructed. Incorrect responses and omissions were excluded as well as outliers defined as greater than the mean for each subject plus or minus two standard deviations.

2.5 | Functional imaging acquisition

Participants were scanned using a 3-Tesla MRI scanner (Achieva, Philips Medical Systems, Best, the Netherlands) with 32-channel head coils in the Spinoza Centre for Neuroimaging, Amsterdam, the Netherlands.

The task-based fMRI acquisition was done with a single-shot echo-planar imaging gradient echo sequence with the following scanning parameters: repetition time = 2500 ms, echo time = 28 ms, phase-encoding direction = AP/RL, flip angle = 77.2°, field of view = 240 × 240 × 118 mm^3 (AP × RL × FH), voxel size = 2.5 × 2.5 × 2.5 mm^3, slice gap = 10%, SENSE factor = 2 (AP).

Additionally, T1-weighted images were acquired from a 3D Turbo Field Echo sequence with the following scanning parameters: repetition time = 8.3 ms, echo time = 3.8 ms, phase-encoding direction = RL, flip angle = 8°, field of view = 240 × 188 × 220 mm^3 (AP × RL × FH), voxel size = 1 × 1 × 1 mm^3, SENSE factors = 2.5 (RL), 2 (FH).

2.6 | Functional imaging preprocessing and analysis

2.6.1 | Image preprocessing

Preprocessing was performed using FMRIPREP version stable (Esteban et al., 2019; SciCrunch Research Resource Resolver RRID: SCR_016216). For more details of the pipeline, see https://fmriprep.readthedocs.io/en/stable/workflows.html. A summary is provided below, for a detailed version of the preprocessing steps, please see Supplemental material.

Following spatial normalization (ANTS) and brain tissue segmentation (FAST) of each T1w scan, functional data were preprocessed including motion correction (FLIRT) and distortion correction (FUGUE). Then, data were co-registered to the T1w. Independent

component analysis-based automatic removal of motion artefacts was used to generate data that were non-aggressively denoised, and physiological noise regressors were extracted applying CompCor.

2.6.2 | Regions of interest (ROIs) to ROIs analysis using the Conn toolbox

The ROI analyses were performed using the Matlab CONN toolbox 15.g implemented in SPM12 (Whitfield-Gabrieli & Nieto-Castanon, 2012). Following pre-processing from FMRIPREP (see Section 2.6.1 and Supplemental material), we imported preprocessed images into the Conn toolbox. Then, we performed the denoising step using signals from GM, WM and CSF images and confounds extracted from FMRIPREP (i.e. six movement parameters – trans and rot, the five first aCompCor and the five first tCompCor) that were removed by linear regression. A band-pass filter was applied to each voxel (0.008–0.09 Hz) in order to reduce non-neurophysiological noise. Framewise displacement was also examined to quantify head motion across groups and ANT sessions. Groups did not significantly differ in head motion (Wilcoxon tests: Block 1: $W = 84$, $p = 0.77$; Block 2: $W = 88$, $p = 0.61$; Block 3: $W = 94$, $p = 0.41$).

The ROIs from the FSL Harvard-Oxford Atlas Maximum Likelihood provided by the CONN toolbox were selected based on previous reports of activation during the ANT (Fan et al., 2005; Russman Block et al., 2020) and were tested for each relevant network of interest (i.e. only regions relevant for each network were entered in the dedicated analysis). The central coordinates for each spherical ROI of 10 mm radius are given below.

- The *alerting network* included the right superior temporal gyrus: [57, −1; −10]; the left inferior and superior parietal gyri: [−54, −46, 33] and [−29, −49, 57], respectively; the left fusiform: [−26, −76, −13]; the left inferior frontal gyrus: [−49, 28, 8]; as well as the bilateral thalamus: right: [10, −18, 6], left: [−9, −19, 6].
- The *orienting network* included bilateral fusiform: right: [27, −75, −12], left: [−26, −76, −13]; the left precentral gyrus: [−33, −11, 49]; the right postcentral: [37, −26, 52]; the left superior frontal gyrus: [−14, 18, 56]; the bilateral superior parietal lobe: right: [29, −47, 58], left: [−29, −49, 57].
- The *executive control network* included the anterior cingulate cortex: [1, 18, 24]; the bilateral thalamus: right: [10, −18, 6], left: [−9, −19, 6]; the bilateral inferior frontal gyrus: right: [51, 27, 7], left: [−49, 28,8]; the right middle frontal gyrus: [39, 18, 42]; the left superior frontal gyrus: [−14, 18, 56]; and the left fusiform: [−26, −76, −13].

Using the CONN toolbox, we calculated the Pearson's correlation coefficients (*r*-values) of time courses of BOLD signals for all combinations of ROIs, and then quantified the FC as the Fisher's transformed *r*-values. In order to highlight significant differences in group-level comparisons for each ANT contrast, a general linear model analysis was performed. Results are reported both at $p < 0.05$, uncorrected level and using false discovery rate (FDR) correction. Considering our small sample size, results that did not survive multiple comparisons correction will be considered as exploratory, while results that do survive multiple corrections have to be considered as to be confirmed in larger samples than in the current pilot study. Both education level and mean RT were entered as nuisance covariates. The *alerting* contrast was defined as the linear contrast of centre cue compared with baseline, thus centre > no cues. The *orienting* contrast was defined as the linear contrast of spatial cue compared with centre cue, thus spatial > centre cues. The *executive control* contrast was defined as the linear contrast of incongruent targets compared with congruent targets, thus incongruent > congruent flankers.

2.7 | Behavioural statistical analyses

Statistical analyses were performed using R software (www.r-project.org). Participants' characteristics and questionnaires scores were compared between groups using unpaired *t*-tests and non-parametric Wilcoxon tests in case of non-normality defined by Shapiro–Wilk test. Because mean RT has been shown to influence network RTs during the ANT (Macleod et al., 2010), ANCOVAs were conducted to examine group differences in RTs associated with specific network RTs, controlling for overall mean RT and education level. In order to investigate whether FC differences between the groups were related to ANT RTs, Spearman's correlations were conducted using "cor.test" and the package "corr.plot" to generate maps. In order to control for group effect, partial Spearman's correlations were conducted using the "ppcor" package for correlations that showed significant results. The threshold significance was set at $p < 0.05$.

3 | RESULTS

3.1 | Participants' characteristics and questionnaire results

Participants' characteristics and questionnaires scores are shown in Table 1. GS were significantly higher educated than ID, while age did not differ between the groups. Participants with ID reported more severe insomnia than GS and suffered from these complaints for at least 6 years. Regarding questionnaire scores, ID reported more hyperarousal, more mental and physical pre-sleep arousal and more fatigue than GS did (Table 2).

3.2 | ANT and questionnaires related to the task behavioural results

Following task completion, ID did not report either more sleepiness or mental effort to complete the task than GS did. ANCOVA analyses, accounting for education level and mean RT, did not reveal significant differences between groups for the alerting and orienting network

TABLE 1 Participants' demographical characteristics and questionnaires results

	GS ($n = 13$)	Participants with ID ($n = 12$)	Statistics (df)	p-Values related to group effect
Age (years)	47 ± 12.36	50.58 ± 12.82	$t = -0.71$ (22.68)	0.48
Education (years)	11.61 ± 3.73	8.58 ± 3.50	$t = 2.10$ (23)	0.047*
Insomnia duration (years)	NA	20.47 ± 15.14	NA	NA
ISI[a]	4.15 ± 3.36	12.58 ± 3.73	$t = -5.92$ (22.23)	< 0.001*
HA, total score[a]	38.69 ± 8.01	51 ± 13.54	$t = -2.74$ (17.58)	0.014*
PSAS_M[a]	12.92 ± 2.75	18.73 ± 7.17	$t = -2.54$ (12.50)	0.025*
PSAS_P[a]	10.69 ± 1.65	14.27 ± 5.59	W = 33.5	0.026*
FSS[a]	2.1 ± 1.08	2.83 ± 2.75	$t = -2.89$ (16.56)	0.009*

Note: Scores were compared between groups using unpaired *t*-tests and non-parametric Wilcoxon procedure in case of non-normality defined by when normality hypothesis could not be rejected by the Shapiro–Wilk test.
Abbreviations: df, degree of freedom; FSS, Fatigue Severity Scale; GS, good sleepers; HA, hyperarousal scale; ID, insomnia disorder; ISI, Insomnia Severity Index; PSAS_M/P, Pre-Sleep Arousal Scale, mental and physical.
*$p < 0.05$.[a]Higher scores indicate greater difficulties.

TABLE 2 Questionnaire findings and reaction times for the Attentional Networks Task

	GS ($n = 13$)	Participants with ID ($n = 12$)	Statistics (df)	p-Values group effect
Mental effort[a]	42.67 ± 18.98	38.82 ± 24.19	$t = 0.46$ (20.92)	0.65
Sleepiness – KSS[a]	5.58 ± 2.35	4.73 ± 2.10	W = 101	0.21
Mean RT (ms)[b]	571.10 ± 73.57	571.19 ± 76.37	$t = 0$ (1)	0.99
Alerting network RT[b]	20.27 ± 12.65	21.83 ± 12.88	$t = 0.13$ (1)	0.73
Orienting network RT[b]	23.91 ± 18.23	26.47 ± 20.94	$t = 0.099$ (1)	0.76
Executive control network RT[b]	94.23 ± 21.12	81.09 ± 20.15	$t = 5.51$ (1)	0.029*

Note: Questionnaire scores were compared between groups using unpaired *t*-tests and non-parametric Wilcoxon procedure in case of non-normality defined by when normality hypothesis could not be rejected by the Shapiro–Wilk test. ANCOVAs were conducted to examine group differences of networks RTs, controlling for mean RT and education level.
Abbreviations: GS, good sleepers; ID, insomnia disorder; KSS, Karolinska Sleepiness Scale; RT, reaction time.
*$p < 0.05$.[a]Higher scores indicate greater difficulties.
[b]Lower RTs indicate better performance.

performance RTs. The mean RT also did not differ between groups. A significant group effect was found for executive control network performance with faster RTs in ID compared with GS, indicating better executive control in participants with ID than in GS.

3.3 | ANT ROIs to ROIs results

The between-group comparison did not reveal any significant difference in FC between ROIs involved in the alerting network.

Regarding the orienting network, compared with GS, participants with ID had stronger FC between premotor and visual regions. More precisely, participants with ID had stronger FC of the left precentral gyrus with both the left occipital fusiform gyrus and the right temporal fusiform gyrus. These results survived correction for multiple comparisons. Their FC between the right postcentral gyrus and right temporal fusiform gyrus was also stronger than in GS. In contrast, participants with ID showed weaker FC of the right parietal lobe, involved in the attentional shifting of attention, with the left precentral gyrus. Both results did not survive correction for multiple comparisons.

Regarding the executive control network, participants with ID had stronger FC of the left thalamus, involved in arousal circuits, with both the left occipital fusiform gyrus and the right middle frontal gyrus. In contrast, participants with ID showed weaker FC between the right inferior frontal gyrus pars triangularis and the left superior frontal gyrus. Both results did not survive correction for multiple comparisons.

3.4 | Correlations among FCs and with RT performance

Figure 1 shows correlations among FCs and of FCs with RT performance across all participants. Below, correlations are reported firstly without accounting for group effect and secondly after controlling for group differences (i.e. partial correlations; Table 3).

The FC between the inferior frontal and superior frontal gyri (executive control network) was negatively associated with FC in the orienting network between premotor and visual regions. This correlation survived when accounting for group effects ($p = 0.026$). FC

FIGURE 1 Correlations among FCs and of FCs with RT performance, across all participants. FC, functional connectivity; MFG, middle frontal gyrus; OFG; occipital fusiform gyrus; PostCG, precentral gyrus; RT, reaction time; TFG, temporal fusiform gyrus; Thal, thalamus. Significant correlations are highlighted using black boxes, i.e. $p < 0.05$

between the thalamus and the middle frontal gyrus (executive control network) was positively correlated with the FC between the thalamus and the occipital fusiform gyrus (executive control network). This correlation did not survive when controlling for group effects ($p = 0.17$).

The FC between the precentral and occipital fusiform gyri (orienting network) was negatively associated with orienting RTs. The stronger the connectivity, the lower the RTs (i.e. better performance). This correlation survived when accounting for group effects ($p = 0.016$). The FC between the precentral and occipital fusiform gyri (orienting network) was positively correlated with the FC between the precentral and temporal fusiform gyri (orienting network). This correlation did not survive when accounting for group effects ($p = 0.14$).

4 | DISCUSSION

The aim of this pilot study was to evaluate the use and sensitivity of assessing FC in attentional networks in order to better understand alterations in executive functioning in ID. Shorter RTs specifically on the executive control part of the ANT in ID suggested more efficient executive control, while people with ID did not differ from GS with respect to RTs reflecting functionality of the alerting and orienting networks. Participants with ID showed stronger FC between thalamic parts of the arousal circuit with both the middle frontal and occipital gyri. Conversely, FC between the inferior and superior frontal gyri, involved in executive functioning, was weaker. During orienting, participants with ID showed weaker FC between the superior parietal lobe involved in attention shifting and the precentral gyrus, while they showed stronger FC between premotor and visual regions. Moreover, individual differences in FC between premotor and visual regions correlated inversely with orienting RTs. No difference in FC was highlighted between groups during the alerting part of the task. Of note, solely the stronger FC between premotor and visual regions survived correction for multiple comparisons and was correlated with behavioural performance. Other findings should thus be interpreted with caution and need replication.

In accordance with previous reports showing integrity of both the alerting and orienting networks in participants with ID (Li, Ma,

TABLE 3 Significant differences in FC between participants with ID and GS in orienting and executive control networks

Seeds ROIs	Beta	t_{21}	*p*-Uncorrected	*p*-FDR corrected	Group comparisons
Orienting network					
Left precentral gyrus					
Left occipital fusiform gyrus	0.56	2.85	0.005*	0.033*	ID > GS
Right temporal fusiform gyrus	0.47	2.43	0.012*	0.048*	ID > GS
Right postcentral gyrus					
Right temporal fusiform gyrus	0.56	2.19	0.020*	0.16	ID > GS
Left precentral gyrus					
Right superior parietal lobule	−0.37	−1.89	0.036*	0.29	ID < GS
Executive control network					
Left inferior frontal gyrus pars triangularis					
Left superior frontal gyrus	−0.61	−2.15	0.022*	0.18	ID < GS
Left thalamus					
Left occipital fusiform gyrus	0.58	2.25	0.018*	0.092	ID > GS
Right middle frontal gyrus	0.55	2.12	0.023*	0.092	ID > GS

Note: No significant group differences were found for FC during the alerting part of the network task.
Abbreviations: FDR, false discovery rate, applied within each network; ID, insomnia disorder; KSS, Karolinska Sleepiness Scale; ROI, region of interest; RT, reaction time.
*$p < 0.05$.

et al., 2016; Perrier et al., 2015), none of the alerting and orienting component RTs of the ANT differed between groups. Despite a lack of significant difference in RT for the orienting network, imaging results highlighted FC differences between participants with ID and GS during the orienting part of the task. Firstly, participants with ID had stronger FC between pre-motor and visual regions than GS, in line with previous findings showing altered functional activity during resting-state in ID in visuo-motor regions (Li et al., 2018; Zhou et al., 2016). This result did survive correction for multiple comparisons, suggesting its robustness, although replication studies are needed. Participants with ID seem thus to recruit more cortical resources in visuo-motor regions to direct attention than GS do, leading to an unaffected task performance in line with the compensatory recruitment hypothesis already proposed in ID (Muscarella et al., 2019; Orff et al., 2007). This hypothesis postulates that the lack of behavioural impairment may be the result of greater recruitment of cortical resources to perform the task as good as GS. In support of this hypothesis, results highlighted significant relationships between better efficiency of the orienting network and stronger FC in visuo-motor regions. Such higher recruitment of cortical resources may have induced larger feelings of fatigue as reflected by questionnaire scores in the current study (i.e. FSS). Fatigue is known as a perpetuating factor for insomnia, and should thus be further considered in participants with ID particularly when people are performing cognitive challenging tasks (Ellis et al., 2021).

Secondly, participants with ID had weaker FC than GS between the precentral gyrus and the superior parietal lobule. The superior parietal lobule contributes to selective attention by shifting the focus of attention between spatial location and objects (Corbetta & Shulman, 2002; Molenberghs et al., 2007; Spadone et al., 2021). This result thus suggests lower efficiency in abilities to shift spatial attention in ID, despite the lack of performance impairment.

Behavioural results indicate more efficient executive control in ID than in GS in the current study. While faster RTs in ID have been found in previous work (Altena, Van Der Werf, Strijers, & Van Someren, 2008; Edinger et al., 1997), our findings contrast with previous behavioural reports suggesting both conflict resolution deficit (Perrier et al., 2015), that involves executive control, and altered executive control network (Li, Liu, et al., 2016; Liu et al., 2014) in ID using the ANT *outside* of the MRI-scanner. This discrepancy between behavioural findings outside of the MRI-scanner and current results obtained using ANT inside the MRI-scanner may result from the MRI-scanner environment. Previous reports have found faster RTs during perceptual decision-making tasks performed inside the MRI-scanner compared with outside the MRI-scanner. Authors have proposed that stress-induced arousal during the scanner sessions could have led to increased performance (van Maanen et al., 2016). Indeed, the scanner environment has been linked to higher cortisol level (i.e. one of the hyperarousal physiological markers), particularly in people exposed to the scanner for the first time (Peters et al., 2011; Tessner et al., 2006). Moreover, several studies have highlighted that the noise of the MRI-scanner is associated with higher cognitive control and more activation in attentional areas, potentially leading to preservation of behavioural performance (Hommel et al., 2012; Tomasi et al., 2005). In the current study, the noise of the MRI-scanner could have impacted executive control performances differentially in participants with and without insomnia. Hyperarousal, notably at the cortical level, is known as a core feature of ID. A previous report concluded that stronger FC between the prefrontal cortex and the thalamus could reflect greater cortical excitability and hyperarousal in participants with ID (Lee et al., 2018). Seemingly, in the current study, stronger thalamus to

frontal gyrus connectivity may reflect greater cortical hyperarousal in ID that could have contributed to more efficient executive control during the ANT. Structural alterations in the thalamus have been linked to ID in previous studies (Kang et al., 2018; Li, Tian, et al., 2016), which may impact the integrity of FC between the thalamus and other structures in this pathology.

During the executive control part of the task, results also highlighted weaker FC between the inferior and superior frontal gyri in participants with ID than in GS, which is in line with previous reports. One study showed altered activation of the inferior frontal gyrus during a letter fluency task and a two-back task (Altena, Van Der Werf, Sanz-Arigita, et al., 2008; Son et al., 2018), and another study reported hypoconnectivity between the inferior frontal gyrus and the parietal regions during resting-state in ID (Li et al., 2014). Knowing the crucial role of the inferior frontal gyrus in executive functioning, notably inhibitory control (Collette et al., 2006; Salehinejad et al., 2021), our results suggest lower inhibitory control in ID during the ANT. Still, this altered connectivity did not appear to interfere with task performance, as it was not correlated with executive control RTs and because ANT performance was not impaired in participants with ID compared with GS.

The main limitation of the current pilot study is the sample size, which prevents the generalizability of the results. Only results related to the stronger FC between pre-motor and visual regions reach statistical significance after correction for multiple comparisons. Other results require replication and should be considered as exploratory. Furthermore, larger sample sizes would have allowed us to use a more stringent threshold for fMRI analyses. However, our results highlight that the ANT task might be of great interest to investigate various components of attention in insomnia. In contrast to tasks used in previous studies, the ANT did show performance differences between participants with ID and GS (Son et al., 2018). Future research could include polysomnography measures to correlate the greater executive control RT as well as the FC underlying hyperarousal with sleep architecture and microstructure (e.g. Beta power spectrum). In addition, the current study included only female participants with ID, which may have impacted our results. Indeed, recent studies have shown brain activity differences between males and females in ID (Dai et al., 2016; Wang et al., 2020; Yang et al., 2022). Future studies combining both male and female participants may better inform about such differences. Finally, the current sample of participants with ID had a long insomnia duration while a rather low ISI score. The fact that participants with ID in the current sample had insomnia difficulties for a long time could have masked differences between groups. One may expect that the inclusion of participants with more recent ID could have led to significant FC differences surviving for multiple comparisons correction in the executive control network.

In conclusion, our results suggest enhanced executive control in participants with ID compared with GS. This might be related to greater cortical hyperarousal as reflected by increased thalamic FC in ID. Moreover, the current study brings in new elements in accordance with the compensatory recruitment hypothesis in insomnia by showing that participants with ID may rely more on spatial information in relationship with motor activation during the ANT, which could have helped them perform the task in a similar way to GS. Future studies using the ANT in combination with neuroimaging in larger samples are needed to confirm our results, and increase our understanding of executive and orientation functioning in insomnia.

AUTHOR CONTRIBUTIONS

Joy Perrier designed the study, analysed data and wrote the manuscript, Jessica Bruijel helped in writing the article, and recruiting participants and collecting the data. Mikaël Naveau and Nicolas Delcroix provided feedback for data analyses. Jennifer Ramautar, Diederick Stoffers and Joris Coppens helped with data collection and designing the study. Diederick Stoffers also provided MRI sequences. Oti Lakbila-Kamal helped in data collection. Nicolas Bessot and Eus JW Van Someren helped in designing the study, obtained funding and supervised the work. All authors have corrected and approved the current version of the manuscript.

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CONFLICT OF INTEREST

None of the authors has a conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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