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Research Report

Altered spontaneous low frequency brain activity in Attention Deficit/Hyperactivity Disorder

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ABSTRACT

Background: Resting brain activity appears altered in Attention Deficit/Hyperactivity Disorder (ADHD). The default mode interference hypothesis (Sonuga-Barke and Castellanos, 2007) postulates that patterns of spontaneous very low frequency brain activity, typical of the resting brain, cause attention lapses in ADHD when they remain unattenuated following the transition from rest to active task performance. Here we test this hypothesis using DC-EEG. *Methods*: DC-EEG recordings of very low frequency brain activity (<1.5 Hz) were compared for 16 male children with ADHD and 16 healthy controls during both rest and active task performance (two choice reaction time task). *Results*: A previously identified very low frequency resting network of electrodes was replicated. At rest ADHD children showed less EEG power in very low frequency bands (i.e., .02–.2 Hz). They also showed less attenuation of power at these frequency bands during rest-to-task transition. Reduced attenuation was associated with a number of measures of performance. *Discussion*: We confirmed the existence of altered very low frequency brain activity in ADHD. ADHD children may have deficits both in maintaining a resting brain when needed and 'protecting' an active brain from the intrusion of resting state brain activity.

1. Introduction

Attention Deficit/Hyperactivity Disorder (ADHD) is the most common psychiatric disorder of childhood and adolescence (Banaschewski et al., 2009). It manifests as symptoms of developmentally inappropriate inattention, impulsivity and hyperactivity (Taylor and Sonuga-Barke, 2008). ADHD is a neuropsychological heterogeneous condition (Sonuga-Barke et al., 2008) and numerous elements of its cognitive phenotype have been characterised (Castellanos and Tannock, 2002). One of the most robust cognitive markers, affecting a large proportion of patients across different tasks and settings, is increased intra-individual reaction time variability (RTV e.g., Kalff et al., 2003; Klein et al., 2006; Scheres et al., 2001; van Meel

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Abbreviations: DM, default mode; RTV, reaction time variability; VLF, very low frequency

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et al., 2005). Indeed, Bidwell et al. (2007) have shown that RTV is also increased in unaffected dizygotic twins of children with ADHD when compared to control twin-pairs, while further evidence for the heritability of this marker comes from the molecular genetics research of Bellgrove et al. (2005) who report an association between the dopamine transporter gene and RTV in ADHD.

Traditionally, RTV was considered only in terms of the standard deviation from the mean (see Castellanos et al., 2006). More recently, Leth-Steensen et al. (2000) applied an ex-Gaussian model to the RT data of children with ADHD to delineate between the mean, 'mu' (μ) RT, and the standard deviation, 'sigma' (σ) of the normal component, and an exponential component 'tau' (τ), of the RT distribution. This approach is argued to be a more appropriate method of analysing RT data when compared with traditional parametric statistical techniques as it is less affected by outliers. Using this, they found that children with ADHD did not differ from an age-matched or younger group of control children in terms of μ or σ, but did differ significantly from both groups on the exponential component τ. These findings have been corroborated subsequently by Hervey et al. (2006), although in addition to an increased τ component, they also reported an increased σ component in children with ADHD.

The default mode (DM) interference model of RTV in ADHD explains this pattern as being due to spontaneous lapses in attention which occur periodically during task performance (Sonuga-Barke and Castellanos, 2007). These lapses are postulated to occur because of the intrusion of very low frequency (VLF) brain activity, of the kind most commonly seen in the resting brain, which interferes with information processing during task performance. It is now known that widely distributed networks of related brain regions synchronised through spontaneous VLF oscillations are active in the resting brain (<0.1 Hz, e.g., Biswal et al., 1995; Firbank et al., 2007; Fox et al., 2005, 2006; Fransson, 2005, 2006; Greicius et al., 2003; Raichle et al., 2001; Raichle, 2006; Sonuga-Barke and Castellanos, 2007). One such network, the DM network (Raichle et al., 2001) incorporates brain regions de-activated during goal directed tasks (medial prefrontal cortex and posterior cingulate cortex) and is thought to underpin self referential thought and an introspective attentional orientation (Fransson, 2005). In this way, the persistence of resting state DM brain activity into periods of goal directed task activity is postulated to be incompatible with effective task-related performance (see Eichele et al., 2008). For Sonuga-Barke and Castellanos (2007), therefore, periodic lapses of attention and cycles of impaired performance and subsequent RTV are due to a failure to effectively attenuate the VLF DM activity in the transition from rest to task.

Initial support for the DM interference hypothesis comes from a number of sources. First, periodic fluctuations in attention may have a VLF time signature in a similar range to DM neural oscillations. Castellanos et al. (2005) showed that RT data obtained from an Eriksen flanker task oscillated at around 0.05 Hz (corresponding to a cycle every 20 s), and that the power of this oscillation was significantly higher in children with ADHD group than in controls. Recent research by the same group (Di Martino et al., 2008) as well as others (e.g. Johnson et al., 2007; Vaurio et al., 2009) have also found a predictable pattern of increased power in VLF RTV (<0.1 Hz) in children with ADHD. In contrast, Geurts et al. (2008) did not find any evidence for increased RTV in children with ADHD in terms of oscillatory power after applying spectral analysis, ex-Gaussian techniques and intra-individual variability analysis. Instead, these authors suggest that comorbid conditions may play an important role in previous reports of increased variability in ADHD (Geurts et al., 2008).

Second, DM activity is correlated with response variability (Helps et al., 2009), attentional lapses (Li et al., 2007) and mind wandering during task performance (Mason et al., 2007; Smallwood et al., 2007a,b, 2008a,b). Mason et al. (2007) found that the frequency with which the participant's mind wandered and activity in the DM network, both increased for highly practised working memory tasks when compared with novel task sequences. A similar study by McKiernan et al. (2006) also reported that DM activity and the frequency of task-unrelated thought was correlated with task difficulty, such that they decreased during difficult compared to easy task conditions. Finally, DM activity has been associated with poor task performance, and has been shown to increase prior to an error during a stop-signal (Li et al., 2007) and Eriksen task (Eichele et al., 2008).

Third, studies using fMRI have reported DM network dysregulation in ADHD. Castellanos et al. (2008) reported decreased functional connectivity in ADHD both within the DM network and between the network and other regions such as the anterior cingulate cortex (ACC). Cao et al. (2006) reported reduced regional homogeneity (the similarity of the time series of a particular voxel with its neighbours) in the frontal-striatal cerebella circuits in the resting BOLD signal of boys with ADHD compared to controls. Uddin et al. (2008) have reported reduced *network homogeneity* (long-range connectivity) within the DM network in ADHD compared to controls, particularly between the precuneus and other DM network regions.

Fourth, in a more direct test of the DM interference hypothesis, Fassbender et al. (2009) found that children with ADHD exhibited less deactivation of regions implicated in the DM network than controls and that greater variability in task RT was associated with a failure to deactivate ventromedial prefrontal cortex. Thus, a failure to attenuate the DM network during task engagement was associated with increased intra-individual variability in ADHD.

DC-EEG can also be used to examine VLF neural oscillations in the resting brain, their attenuation in the transition from rest to task, and their links with performance and attention. Initial studies suggest that VLF EEG oscillations (0.06–0.2 Hz) which are spatially and temporally stable have a spatial distribution across the scalp that corresponds in some ways to the DM network locations (i.e., frontal and posterior midline, Helps et al., 2008). Adults with high levels of ADHD symptoms of inattention had less VLF power than controls (Helps et al., 2008). In general the transition from rest to task led to the attenuation of VLF EEG activity across this network and, as predicted by the DM interference hypothesis, the degree of this rest-task attenuation was inversely associated with ADHD symptoms (Helps et al., 2009). The VLF pattern of EEG in this network was associated with the VLF time signature of RTV in a simple reaction time task: participants who effectively attenuated VLF EEG from rest to task showed a lower degree

of synchrony than participants who did not attenuate this activity from rest to task (Helps et al., 2009).

Here we extend our previous study to a clinic-referred sample of adolescents with ADHD and age-matched control adolescent boys. The aims were; (i) to replicate the spatial distribution of the VLF network found in Helps et al. (2008); (ii) to compare levels of resting VLF EEG power in adolescent ADHD boys and aged matched controls; and (iii) to examine ADHD-related alterations in attenuation in VLF EEG power during the transition from rest to task performance. Our predictions were as follows. First, as in our previous study, there will be a distinct resting VLF EEG network with power maximal along the frontal midline and posterior scalp regions. Second, that VLF EEG power in this network at rest will be lower in ADHD than controls. Third, that adolescents with ADHD would show less attenuation of VLF EEG in the transition from rest to task and that these differences would persist even when controlling for overall resting power levels. Lastly, we predicted that there would be an association between rest-task attenuation and performance, so that greater rest-task attenuation was associated with better task performance. We had limited statistical power to test this and so included this as an exploratory analysis.

2. Results

2.1. Demographics and clinical characteristics

Table 1 illustrates the clinical characteristics of the control and ADHD groups. The two groups did not differ in age but the ADHD group had significantly lower IQ than the control group. Analyses were run with and without IQ as a covariate. ADHD patients displayed more emotional and conduct problems, had more difficulties in peer relationships and exhibited less pro-social behaviour than controls.

Table 1 – Group characteristics.

	Control (N=16) mean (SD)	ADHD (N=16) mean (SD)	F	p
Age	14years 8 m (11 m)	14year 7 m (11 m)	.072	.791
WISC-III IQ				
Block design (scaled score)	11.25 (2.99)	8.31 (2.35)	9.57	.004
Vocabulary (scaled score)	10.69 (2.63)	7.50 (2.19)	13.90	.001
Estimated full scale IQ	105.60 (14.50)	88.10 (11.26)	14.52	.001
Number of parent reported				
ADHD symptoms				
Inattention	0.81 (1.22)	7.88 (1.41)	229.38	<.001
Hyperactivity	0.38 (0.62)	6.81 (2.29)	118.14	<.001
Total score	1.19 (1.22)	14.69 (3.18)	251.56	<.001
Parent reported SDQ				
Emotion	0.50 (1.10)	4.75 (2.76)	32.59	<.001
Conduct	0.88 (1.15)	5.94 (2.17)	67.83	<.001
Peer relationships	1.25 (1.69)	4.25 (2.41)	16.62	<.001
Pro-social behaviour	9.25 (0.77)	6.19 (2.51)	21.76	<.001
Impact	0.06 (0.25)	5.00 (2.97)	44.01	<.001
Hyperactivity	1.69 (1.49)	8.81 (1.37)	196.90	<.001
Number of teacher reported ADHD symptoms	N=12	N=11		
Inattention	1.33 (2.27)	6.64 (2.01)	34.90	<.001
Hyperactivity	0.42 (0.90)	5.55 (2.42)	46.90	<.001
Total score	1.75 (2.60)	12.18 (2.31)	71.30	<.001

Note. WISC-III = Wechsler Intelligence Scales for children, SDQ = Strengths and Difficulties Questionnaire.

2.2. Behavioural performance on two choice response reaction time task

Table 2 shows the statistics relating to task performance. There was an effect of condition; fewer omission and directional errors were made and RTs were slower and less variable in the moderate condition. ADHD patients made more omission errors, were slower, and more variable in responding than controls. There was no significant condition (fast vs. moderate event rate) by group interactions. Controlling for the effects of IQ did not alter the group differences in performance.

2.3. Very low frequency oscillations during rest

Fig. 1 compares the electrode locations in the resting network in the present study with the resting network locations in Helps et al. (2008). There is substantial overlap between the electrode maps with frontal midline and posterior regions predominating. Table 3 reports the statistics relating to VLF EEG at rest. The ADHD group exhibited significantly less resting power in the S4 and S3 frequency bands. For each frequency band a significant effect of location emerged and within the network there was higher mean power than outside the network. No significant group by location interactions emerged for any of the frequency bands.

2.4. Very low frequency rest-task attenuation

The difference in power between rest and each of the goal directed conditions within the resting network was calculated across sub-delta frequency bands. To simplify the interpretation of this analysis we combined scores for the two frequency bands showing case–control differences (S4/S3) and those showing no difference (S2/S1). There was significant rest-to-task attenuation in both conditions of the task (fast: $F(1,23)=16.1$, $p=.001$; moderate: $F(1,24)=29.9$, $p<.001$). Greater power was observed in the S4/S3 band than in the S2/S1 band (fast: $F(1,23)=151$, $p<.001$; moderate: $F(1,24)=179$, $p<.001$). In the fast event rate condition, a frequency by condition interaction was identified ($F(1,23)=9.06$, $p=.006$) and the difference in power between rest and task was greatest in the S4/S3 band. The ADHD group exhibited less rest-task attenuation than the controls ($F(1,20)=8.25$, $p=.009$) overall (and even after controlling for IQ; $F(1,19)=7.77$, $p=.012$). Crucially this group difference in attenuation persisted after controlling for differences in resting state VLF power in the S3

Table 2 – Group Differences on two choice reaction time task, fast and moderate event rate conditions.

	Fast condition mean (SD)		Moderate condition mean (SD)		Main effect (condition)		Group effect		M×G	
	Control	ADHD	Control	ADHD	*F*	*p*	*F*	*p*	*F*	*p*
% omission errors [a]	0.84 (1.24)	4.07 (4.43)	0.09 (0.27)	2.23 (3.97)	28.25	<.001	9.89	.004	1.18	.287
% directional errors	15.50 (8.82)	20.60 (10.70)	4.72 (3.74)	8.67 (6.27)	73.07	<.001	2.59	.119	.28	.604
Mean RT (ms)	321.00 (29.70)	356.00 (35.10)	361.00 (45.50)	401.00 (56.40)	38.15	<.001	7.69	.010	.44	.513
SD of RT (ms)	74.60 (27.50)	117.10 (34.70)	57.30 (11.40)	110.00 (30.20)	4.84	.037	30.00	<.001	1.01	.324
Normalised variance	0.23 (0.09)	0.33 (0.09)	0.16 (0.03)	0.27 (0.06)	22.15	<.001	21.50	<.001	.33	.547

Main Effect = effect of condition, M×G = condition by group interaction.
[a] The mean percentage of omission errors for each group is shown in this table for illustrative purposes, however as this variable was not normally distributed, analyses were performed on the square root transformed data.

and S4 bands ($F(1,20)=8.91$, $p=.007$), see Table 4. Within the ADHD group, rest-task attenuation was more strongly correlated with symptoms of inattention than with symptoms of hyperactivity/impulsivity, in both conditions of the task. Rest-task attenuation was not correlated with either symptoms of inattention or symptoms of hyperactivity/impulsivity in the control group, see Table 5.

2.5. *Attenuation and task performance*

Table 6 shows the correlation between rest-task attenuation and performance. As predicted there was a tendency for attenuation of S4/S3 power to be negatively correlated with task performance, so that participants who attenuated least made more errors, and were slower and more variable than those who attenuated most. Statistical power was limited but a negative correlation was identified between attenuation in the S4/S3 frequency band and omission errors (significant) and measures of intra-individual variability (non-significant trend) in the moderate condition of the task.

3. Discussion

This study advances our understanding of the VLF brain activity in ADHD in a number of important ways. First, we identified a network of resting state VLF oscillations on the basis of S3 power with frontal and posterior midline and central posterior cortex electrode locations predominating. This overlapped considerably with the network previously identified by Helps et al. (2008). Second, and consistent with previous findings in non-clinical samples, ADHD was associated with less resting state VLF power (S4 and S3) in this network. Third, VLF power in this network was attenuated in the switch from rest to a goal directed task. Fourth, as predicted the ADHD group exhibited less rest-task attenuation than the control group. This group difference was

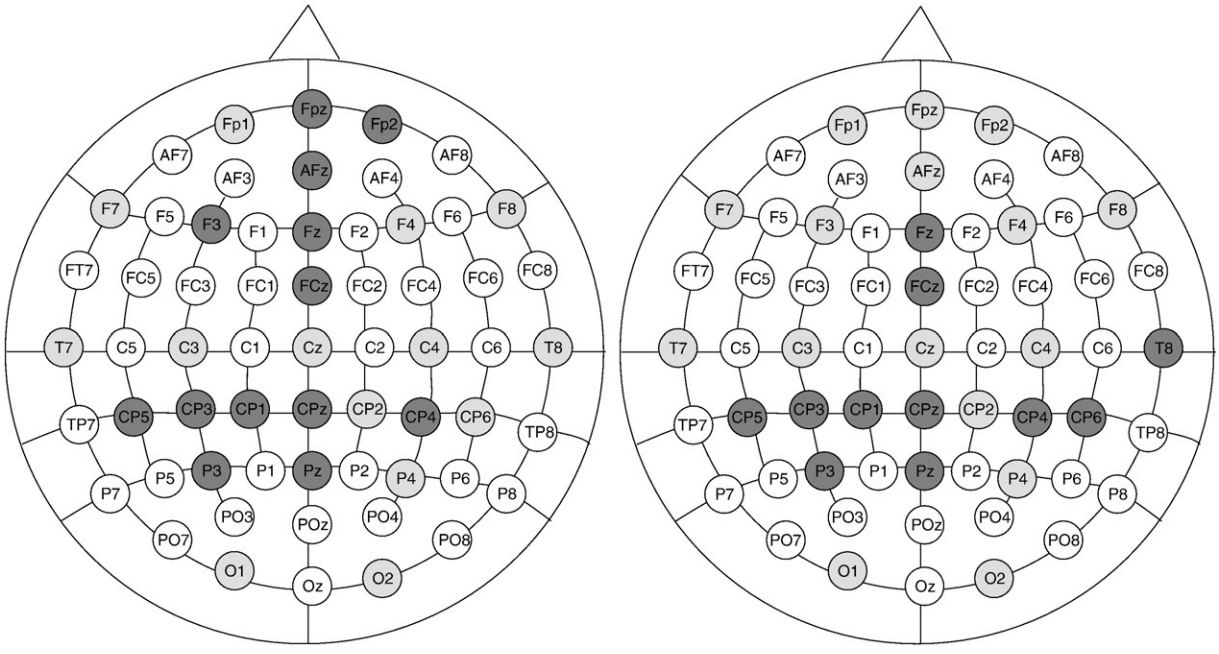

Fig. 1 – Electrodes selected for S3 network shown in dark grey in the present sample (left) and in our previous research (right; see Helps et al., 2008), all other electrodes in the montage are shown in light grey.

Table 3 – Group differences in low frequency EEG power (μV^2), within and outside of the resting network, during rest.

	Within network mean (SD)		Outside network mean (SD)		Main effect (location)		Group effect		Location × Group	
	Control	ADHD	Control	ADHD	*F*	*p*	*F*	*p*	*F*	*p*
Rest										
S4 power	5.22 (.639)	4.64 (.600)	5.04 (.565)	4.50 (.513)	8.93	.006	6.62	.016	.256	.617
S3 power	4.83 (.621)	4.34 (.504)	4.63 (.577)	4.13 (.521)	14.63	<.001	5.41	.028	.007	.937
S2 power	3.65 (.552)	3.24 (.611)	3.48 (.492)	3.05 (.574)	14.79	<.001	4.07	.055	.015	.903
S1 power	3.72 (.649)	3.28 (.758)	3.54 (.559)	3.13 (.735)	12.12	.002	2.78	.108	.122	.730
Delta power	3.30 (.649)	3.12 (.741)	3.10 (.538)	2.75 (.778)	13.16	<.001	2.04	.165	.306	.585

independent of IQ or resting (baseline) differences in VLF power and within the ADHD group rest-task attenuation was more strongly associated with symptoms of inattention than symptoms of hyperactivity/impulsivity. Finally, rest-task attenuation in VLF power tended to be negatively correlated with task performance measures, so that participants who attenuated least made the most errors and were slower and more variable than those who attenuated most, although we lacked the statistical power to test this definitively.

Identifying a VLF resting network in this way raises questions about the relationship between this S3 defined EEG network and the DM network previously identified using fMRI. We had previously demonstrated that this network is stable across time within individuals; here we show stability across samples. Furthermore, the S3 network shares some similarities with the DM network. First, scalp locations for the S3 network are consistent with a model of neural generators localised to DM network sites, notwithstanding the inverse problem of localising EEG signal to specific brain sources. Second, the frequency bands implicated most closely resemble the frequency for resting state BOLD signal coherence. However, as the limits of these VLF EEG bands have been theoretically determined, based on the assumption of a natural logarithmic relationship between successive frequency bands, the individual VLF bands (S4, S3, S2 and S1) may not represent functionally distinct frequencies, and may cross genuine functional boundaries. Given the similarity in attenuation and resting behaviour of S4 and S3, this seems likely. It will be important for future research into VLF EEG to determine functionally distinct frequency bands. Investigating a larger number of frequency bands and bands with different frequency limits may determine the most accurate physiological limits to these low frequency EEG bands and this is likely to enhance power and reliability when assessing VLF EEG and rest-task EEG attenuation.

Table 4 – Rest-task attenuation for each group.

	VLF power at rest (μV^2), mean (SD)	VLF power during task (μV^2), mean (SD)	Rest-task attenuation mean (SD)
Fast condition			
S4/S3 power			
Control	10.10 (1.21)	8.09 (1.03)	−1.97 (1.62)
ADHD	8.98 (1.05)	8.22 (1.01)	−0.70 (1.38)
S2/S1 power			
Control	7.38 (1.56)	6.05 (1.36)	−1.33 (1.67)
ADHD	6.52 (1.36)	5.77 (1.49)	−0.66 (1.59)
Moderate condition			
S4/S3 power			
Control	10.10 (1.21)	7.61 (0.92)	−2.45 (1.27)
ADHD	8.98 (1.05)	8.28 (1.58)	−0.70 (1.43)
S2/S1 power			
Control	7.38 (1.56)	5.49 (1.22)	−1.89 (1.46)
ADHD	6.52 (1.36)	5.60 (1.11)	−0.70 (1.35)

Third, there are ADHD-related abnormalities at rest in this network that may be related to altered resting state functional connectivity in ADHD as suggested by fMRI studies. Such altered connectivity is particularly apparent between the anterior (medial prefrontal cortex) and posterior (posterior cingulate/precuneus) components of the DM network (Castellanos et al., 2008; Uddin et al., 2008). Therefore, although we have not directly assessed connectivity in our studies, it is unsurprising that we also identified alterations in the resting state EEG of children with ADHD in scalp locations corresponding to these regions. Fourth, there is a pattern of deactivation from rest to task at these sites that mirrors that seen with BOLD responses (e.g., Greicius et al., 2003; Gusnard et al., 2001; McKiernan et al., 2006; Weissman et al., 2006). For example, Weissman et al. (2006) found that attentional lapses (defined by very slow RTs) were associated with reduced deactivation of DM activity, while the activation of frontal control regions increased on the subsequent trial indicating the recruitment of compensatory attentional mechanisms. Recently, Travis, et al. (in press) reported an association between 7.5–10 Hz resting state EEG activity and DM structures using source analysis (eLORETA). More commonly, research has used simultaneous fMRI-EEG recordings to correlate DM structures and EEG oscillations. One such study by Scheeringa et al. (2009) found that frontal theta (4–7 Hz) increases were correlated negatively with the BOLD signal in the DM network during a working memory task, and that increased deactivation of the DM network with increasing memory load was associated with greater increases in frontal theta power. Fifth, as in fMRI studies, failure to attenuate EEG LFO in the transition to tasks may be related to attentional lapses specifically and to ADHD symptoms more generally. Although children with ADHD are often reported to exhibit atypical resting state activity (e.g., Cao et al., 2006, 2009; Castellanos et al., 2008; Uddin et al., 2008; Zang et al., 2007; Zhu et al., 2008), recent work has also shown that these children deactivate the DM network less during a working memory (Fassbender et al., 2009) and stroop task (Peterson et al., 2009) when compared with controls. Interestingly, Peterson et al. (2009) also show that stimulant medications significantly

Table 5 – Correlations between rest-task attenuation and symptoms of ADHD (Pearson's *r*).

Rest-task attenuation	ADHD		Control	
	Inattention	Hyperactivity/Impulsivity	Inattention	Hyperactivity/Impulsivity
Fast condition				
S4/S3	−.443	−.239	−.144	−.199
S2/S1	−.589†	−.404	−.061	−.046
Moderate condition				
S4/S3	−.562†	−.371	.114	.343
S2/S1	−.640*	−.433	.434	.272

* $p<.05$.
† $p<.1$.

increased deactivation of the DM network in the ADHD group during the task, to levels comparable to the control group.

In this study we tested a number of predictions derived from the DM interference hypothesis about ADHD. Specifically, we identified a deficit in ADHD rest-task attenuation that was associated with task performance. These findings are consistent with the idea that, if VLF EEG is not properly attenuated when one engages in a goal directed task, this may interfere with goal directed brain activity, causing poorer task performance. This is consistent with our previous finding in young adults (see Helps et al., 2009) and with a recent fMRI finding in children with ADHD showing ineffectual deactivation of the ventromedial prefrontal cortex during a working memory task, which was correlated with increased RTV (Fassbender et al., 2009) However, on the basis of the current results, this appears to be only part of the picture of abnormal spontaneous VLF activity in ADHD revealed by this is and the previous study (Helps et al., 2008). Specifically ADHD patients or young adults with high ADHD symptoms—and particularly symptoms of inattention exhibited reduced VLF power in the resting network compared to controls. In light of these findings, we may need to extend the DM interference model. More specifically, our data points to the possibility of a dual deficit in VLF brain activity in ADHD. First, as predicted by the DM interference hypothesis there are deficits during goal directed task performance due to a failure to properly attenuate resting state brain activity. Second, ADHD patients may also find non-goal directed states problematic: they find both tasks and rest difficult. This has recently be suggested by Tian et al. (2008) who argue that in addition to being delay averse (see Sonuga-Barke, 2005) ADHD patients also find a conscious resting state challenging, and exhibit atypically increased levels of sensory processing at rest. It is likely that the aberrant pattern of resting state activity observed in this clinical group may be influenced by intrusions from task-unrelated stimuli in the environment.

These two characteristics, the failure to attenuate DM activity during a task and an impaired resting state, may be reconciled within the notion of a more generalised state regulation deficit affecting multiple states including both goal directed and task specific states. Under a state regulation model of ADHD (Sergeant, 2005), it has been argued that this deficit arises from a context-dependent failure to regulate energetical state (i.e., phasic levels of arousal affecting stimulus perception and tonic levels of physiological activation related to task performance, Sonuga-Barke et al., in press). In ADHD, this failed regulation has the most significant effect on the moderation of activation levels contingent on task demands: challenging tasks (e.g. fast event rates) lead to over-activation while very slow or boring tasks are thought to result in reduced activation levels. Therefore, according to this model aberrant VLF attenuation and impaired RS activity in ADHD as identified in the current study may be due to the dysregulation of physiological states with these varying context-demands. A key prediction of the state regulation models of ADHD is that performance should be affected by event rate. In the present study we employed two conditions of the two choice response reaction time (2-CR RT) task, one with a fast-(1 second ISI) and one with a moderate-event rate (3 second ISI). Consistent with fMRI research, attenuation of resting brain activity has been shown to be proportional to task difficulty (e.g. McKiernan et al., 2006). In the present study however, although participants were found to be slower, less variable and to make fewer errors in the moderate- compared to the fast-event rate condition of the task, they did not differ in their degree of attenuation from rest to task

Table 6 – Correlations between rest-task attenuation and task performance (Pearson's *r*).

Rest-task attenuation	Omission errors	Directional errors	Mean RT	SD of RT	Normalised variance
Fast condition					
S4/S3	−.202	−.085	−.257	−.188	−.129
S2/S1	.029	.077	−.219	<.001	.084
Moderate condition					
S4/S3	−.439*	−.261	−.167	−.387†	−.372†
S2/S1	−.226	.074	−.205	−.214	−.181

* $p<.05$.
† $p<.1$.

between these two conditions and these effects did not interact with ADHD status.

The inconsistency between the current results and the McKiernan et al. (2006) study may be due to differences in the ISIs employed by these studies. The McKiernan study also failed to find differences in attenuation between a 1 second ISI and a 2 second ISI event rate condition; only identifying greater attenuation in a very fast ISI condition (600 ms). Future investigations that employ a wider range of event rates will help to elucidate whether the degree of rest-task EEG attenuation is associated with event rate as predicted by state regulation models.

Some of the limitations described in our previous research also apply here, for example group sample sizes were small—especially after participants with excessive movement artifacts were excluded from the analyses. As participants within the ADHD group were recruited from more than one clinic, it is possible that there may have been some variation in diagnostic consistency. Nevertheless, to verify group membership we included an ADHD rating scale (DuPaul et al., 1998) and only participants who had a clinically significant number of symptoms were included in the ADHD group. Furthermore, by focussing only on the low frequencies, we are unable to determine associations between these low frequencies and higher frequency neuronal bands such as alpha and theta. Although beyond the scope of this paper, this will be important for understanding how this VLF EEG interacts with more traditional measures of attention. The findings of the current study require replication with much larger sample sizes. Future studies should include a larger number and more equidistant arrangement of scalp electrodes to allow for EEG source analysis. Importantly, source analysis, or co-registered EEG and fMRI, would allow future research to determine whether these VLF EEG are associated with the structures of the DM network. Further, to more accurately assess the relationship between VLF brain oscillations and variability in task performance, future research should explore this association across a range of different task demands. More specifically, future research should employ behavioural tasks that deliver a near-to continuous measure of attention in order to be able to accurately correlate behaviour with brain activity.

In summary, in this study we confirmed the existence of a VLF EEG resting network. We also showed that adolescents with ADHD exhibited differences in resting VLF EEG compared to controls and that they also exhibited less attenuation of this VLF EEG from rest to task than controls. These findings suggest deficits both at rest and in transition from rest-to-task in ADHD.

4. Experimental procedures

All methods were approved by the by the University of Southampton School of Psychology Ethics Committee and by the Southampton and South West Hampshire Research Ethics Committee B.

4.1. *Participants*

Sixteen adolescent boys with a clinical diagnosis of ADHD-combined type aged between 13 and 16 years and 16 age-matched control adolescent boys participated in the study (see Table 1). A further four adolescents performed the tasks but were excluded as they did not meet the study entry criteria (see following sections). Participants with ADHD were recruited from two clinics from the Southampton City Primary Care Trust and Child and Adolescent Psychiatry Mental Health Service. Children were invited to participate in the study if they met the following criteria: a) a formal DSM-IV diagnosis of ADHD-combined type from their psychiatrist; b) no other developmental disorder other than oppositional defiant disorder (ODD) or conduct disorder (CD); c) IQ>70; and d) no medication other than methylphenidate (which must be discontinued 24 h prior to testing). Eligible cases for the study were identified by one of the psychiatrists involved with their care. Control cases were recruited from two local schools. Inclusion criteria for controls were; a) no developmental disorder; b) IQ>70; and c) no medication. One control participant was excluded because of the presence of tic disorder. All participants received £30 to reimburse their travel expenses. ADHD cases were required to currently display 12 or more symptoms defined as 'often' or 'very often' on the ADHD rating scale (Dupaul et al., 1998). Two children in the ADHD group were excluded as current ADHD symptoms by parent ratings did not meet this threshold. Parent report on the strengths and difficulties questionnaire (SDQ; Golland et al., 2007) was used to screen for other undiagnosed adolescent psychiatric disorders (Goodman et al., 2000). No control cases were reported to experience a clinical degree of ADHD symptoms (control symptoms ranged between 0 and 3 symptoms). An estimation of full scale IQ was assessed in all children from the vocabulary and block design subsets of Wechsler Intelligence Scales for children (WISC-III, Wechsler, 1991), using the conversion reported in Sattler (1992). One participant in the ADHD group was excluded for IQ<70.

4.2. *Procedure*

Written informed consent was obtained from the parents themselves, from the parents on behalf of the participant and also from the participant. Participants completed the WISC-III IQ assessment. After this, they were seated on a comfortable chair in front of a computer monitor in the testing cubicle and an electrode cap was fitted: the researcher video-monitored the participant in an adjacent room throughout the experiment. There was a single testing session. Each participant completed three assessment periods; (i) five minute period of rest; (ii) a 2-CR RT task, with two conditions (fast and moderate event rate) and (iii) a continuous tracking task. This last task failed to record data and was dropped from the analysis. Assessments were presented in a counterbalanced order. During the rest assessment participants were instructed simply to 'rest' and to keep their eyes fixated on a fixation cross in the centre of the computer screen. Both conditions of the 2-CR RT task lasted 10 min: green arrows were presented in the centre of the computer screen and pointed either right or left, participants were asked to respond by pressing the right or left mouse button to indicate the direction of the arrow. In the fast condition the ISI was 1 second, in the moderate event rate condition the ISI was 3 seconds. The stimulus presentation time was identical in both conditions

(400 ms). In the previous study with adults this task only used a fast event rate condition. The moderate event rate condition was included in this study because on the basis of pilot data we were concerned that fast event rate condition (1 second ISI) might be too difficult for the younger participants in this study.

4.3. *Electrophysiological acquisition and processing*

Data were recorded using Neuroscan Synamps^2 70 channel EEG system, DC-coupled recording equipment. The data were sampled with a 70 Hz low pass filter at a rate of 250 Hz. An electrode cap (Easycap, Herrsching, Germany) was fitted to the participant and EEG data were recorded from twenty-seven silver/silver chloride electrodes placed according to the extended 10/20 system (Fp1, Fpz, Fp2, Afz, F7, F3, Fz, F4, F8, FCz, C7, C3, Cz, C4, T8, Cp5, Cp3, Cp1, Cpz, Cp2, Cp4, Cp6, P3, Pz, P4, O1, and O2). Furthermore, a ground electrode was positioned on Fc6 and an active (reference) electrode at Af7. A reference electrode was also placed on each mastoid for later use in re-referencing. Horizontal electro-oculogram (HEOG) was recorded from bipolar electrodes placed on the outer canthi of each eye. Vertical electro-oculogram (VEOG) was recorded from bipolar electrodes placed above and below the right eye. All impedances were kept below 10 kΩ. All data were analysed and processed using MATLAB (version 7.7.0). The data were initially re-referenced off-line to the mean mastoid signal, the linear trend caused by drift was removed from the EEG data using the 'detrend' command in MATLAB and data were downsampled to 10 Hz. Ocular and other artifacts were removed from the data using Independent Component Analysis ((ICA) the signal was reconstructed by back-projection of all artifact-free components). This was performed separately on the EEG data obtained from the rest with eyes open session, and each condition from the 2-CR RT task.

4.4. *Exclusion of participants*

One control participant and three ADHD participants were excluded because of excessive movement artifacts (movement or muscles artifacts continued to obscure the EEG after ICA had been performed). So for EEG analysis, 15 control and 13 ADHD participants were compared. Furthermore, two ADHD participants were excluded from the fast condition and one ADHD participant was excluded from the moderate condition of the task because of insufficient task engagement, these participants made >15% omission errors on the task.

4.5. *Data processing*

Fast Fourier Transformation (FFT) analysis was performed on the data from each of the 27 scalp electrodes for each participant in each test condition; 1) rest with eyes open; 2) fast event rate condition, and 3) moderate event rate condition of the 2-CR RT task. One minute Hanning windows that overlapped by 10 s were used and power (as area under the curve) in each of the VLF band (slow 4 [S4] .02–.06 Hz; [S3] .06–.2 Hz; slow 2 [S2] .2–.5 Hz; slow 1 [S1] .5–1.5 Hz; delta, 1.5–4 Hz) were calculated for each condition. Since power is not normally distributed, the values were natural log transformed (Gasser et al., 1982). In the same manner as in Helps et al. (2008), the spatial location of the resting S3 network was assessed using data only from the control group as it was assumed that the network may be abnormal in the ADHD group. Electrodes with S3 power higher than the mean were selected and considered to comprise the S3 network.

4.6. *Statistical analysis*

Differences in task performance between conditions (fast vs. moderate) were assessed using repeated measures ANOVAs for each dependent variable. Similarly repeated measures ANOVAs were used to assess differences in resting EEG power between locations (within and outside of the network); and rest-task attenuation was assessed for each condition of the 2-CR RT task using repeated measures ANOVAs with condition (rest vs. task) and frequency (S4/S3, S2/S1) entered as the within subjects factors. In all of these analyses, group differences were assessed by including group (ADHD vs. controls) as the between subjects factor. The association between rest-task attenuation and task performance was assessed using correlations (Pearson's *r*).

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