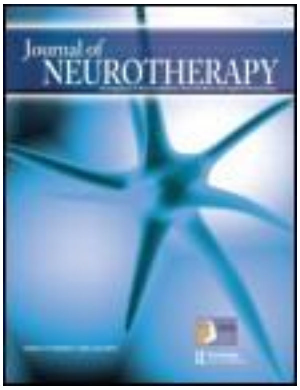

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Adam R. Clarke [a b c], Robert J. Barry [a b c], Rory McCarthy [d] & Mark Selikowitz [d]

[a] Brain & Behaviour Research Institute, University of Wollongong , Wollongong, Australia

[b] School of Psychology, University of Wollongong , Wollongong, Australia

[c] Illawarra Health and Medical Research Institute, University of Wollongong , Wollongong, Australia

[d] Sydney Developmental Clinic , Sydney, Australia

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RESEARCH ARTICLES

CORRELATION BETWEEN EEG ACTIVITY AND BEHAVIOR IN CHILDREN WITH ATTENTION-DEFICIT/HYPERACTIVITY DISORDER

Adam R. Clarke[1,2,3], Robert J. Barry[1,2,3], Rory McCarthy[4], Mark Selikowitz[4]

[1]Brain & Behaviour Research Institute, University of Wollongong, Wollongong, Australia
[2]School of Psychology, University of Wollongong, Wollongong, Australia
[3]Illawarra Health and Medical Research Institute, University of Wollongong, Wollongong, Australia
[4]Sydney Developmental Clinic, Sydney, Australia

The aim of this study was to determine whether EEG activity in specific bands correlated with the core behavioral symptoms of children with attention-deficit/hyperactivity disorder (AD/HD). Sixty boys diagnosed with AD/HD Combined type and 60 age-matched male controls participated in this study. An EEG was recorded during an eyes-closed resting condition and relative power estimates in the delta, theta, alpha, and beta bands, and the theta/beta ratio, were calculated. The EEG measures of the AD/HD group were converted to *z* scores relative to the controls, and these were correlated with scores on the Conners' Rating Scale obtained from a parent. The AD/HD group had global increases in theta activity and the theta/beta ratio, increased frontal delta, with reduced global alpha and frontal beta activity. Frontal theta activity correlated with inattention, the theta/beta ratio correlated with hyperactivity-impulsivity, and both measures correlated with a Combined type diagnosis. EEG power anomalies in AD/HD are associated with specific symptom clusters in the disorder.

INTRODUCTION

Attention-deficit/hyperactivity disorder (AD/HD) is one of the most common psychiatric disorders of childhood in the United States (Wolraich et al., 2005), with studies estimating the prevalence rate in children at approximately 5% (Polanczyk, de Lima, Horta, Biederman, & Rohde, 2007). Children with AD/HD have varying levels of hyperactivity, impulsivity, and inattention, which may change with development from preschool through adulthood (American Psychiatric Association [APA], 1994). The disorder interferes with many areas of normal development and functioning in a child's life and predisposes a child to a greater risk of social and psychiatric problems as adults (Mannuzza, Klein, Bessier, Malloy, & LaPadula, 1993).

EEG studies of children with AD/HD have consistently found that these children have greater theta activity during an eyes-closed resting condition than age- and gender-matched controls (Chabot & Serfontein, 1996; Clarke, Barry, McCarthy, & Selikowitz, 2002a; Clarke et al., 2003; Hobbs, Clarke, Barry, McCarthy, & Selikowitz, 2007; Lazzaro et al., 1998). Less consistent, but still commonly found within the literature, are increased delta activity and reduced alpha and beta activity (Barry, Clarke, & Johnstone, 2003; Callaway, Halliday, & Naylor, 1983; Clarke, Barry, McCarthy, & Selikowitz, 1998, 2001a, 2001b; Clarke et al.,

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Address correspondence to Adam R. Clarke, PhD, Brain & Behaviour Research Institute, University of Wollongong, Wollongong 2522, Australia. E-mail: ADAM_CLARKE@UOW.EDU.AU

2006; Dykman, Holcomb, Oglesby, & Ackerman, 1982; Matousek, Rasmussen, & Gilberg, 1984). Abnormalities in the theta/beta ratio have also been studied, with results indicating it to be one of the most sensitive markers of AD/HD in group studies (Barry, Clarke, Johnstone, McCarthy, & Selikowitz, 2009; Clarke, Barry, McCarthy, & Selikowitz, 2002b; Janzen, Graap, Stephanson, Marshall, & Fitzsimmons, 1995; Lubar, 1991; Monastra, Lubar, & Linden, 2001).

These EEG profiles have been interpreted as representing a number of different central nervous system (CNS) abnormalities, including a hypo-aroused CNS (Satterfield & Cantwell, 1974), and a maturational lag in CNS development (Clarke et al., 1998; Mann, Lubar, Zimmerman, Miller, & Muenchen, 1992). However, recent research has failed to fully support any of these models, with results suggesting that a child with AD/HD may have a number of these different CNS abnormalities, leading to the suggestion that the current models are too simplistic, and possibly inaccurately labeled (Clarke et al., submitted). One possible problem with the approach in many of these studies is that they have tried to fit a model of CNS abnormality based on results from the entire spectral analysis. This approach gives a wealth of data, with increases and decreases in power being evident in multiple bands. However, it does not tell us anything about the role of any discrete component of the EEG. It is possible that only a subset of the significant results obtained actually relate to the behaviors under investigation and the other EEG abnormalities relate to other CNS mechanisms. This approach also leads to an implicit assumption that when there are reciprocal changes in multiple bands, the bands may be linked as part of a state change within a single mechanism or process. However, it is possible that when simultaneous changes are seen in multiple bands, they represent functional changes in different independent systems. For this reason it may be beneficial in the development of our understanding of AD/HD to investigate the significance of EEG abnormalities in single bands. Hence, the aim of the current study was to determine whether any of the commonly found EEG abnormalities correlate with the core symptoms of this disorder.

METHOD

Participants

Participants in this study were 60 boys with a diagnosis of AD/HD Combined type and 60 age-matched male controls. All children were between the ages of 8 and 12 years and had a full-scale Wechsler Intelligence Scale for Children (3rd. ed; WISC–III) IQ score of 80 or higher. The children with AD/HD were drawn from new patients presenting at a pediatric practice for an assessment for AD/HD. The clinical subjects had not been diagnosed as having AD/HD previously, had no history of medication use for the disorder, and were tested before being prescribed any medication. The control group consisted of children from local schools and community groups.

Inclusion in the AD/HD group was based on clinical assessments by a pediatrician. A semistructured clinical interview was used that incorporated information from as many sources as were available. The interview included a description of the presenting problem and a medical history given by a parent or guardian, a physical examination, review of school reports for the past 12 months seeking behavioral/learning problems, reports from any other health professionals, and behavioral observations during the assessment. Children were also assessed using the WISC–III, Neale Analysis of Reading, and the South Australian Spelling test to assess for intellectual disabilities and learning problems. The Conners' Parent Rating Scale–Revised (L) was also administered to quantify the severity of symptoms. The clinical notes and psychometric test results were then independently reviewed by a psychologist, and children were included in the study only when both agreed on the diagnosis. *Diagnostic and Statistical Manual of Mental Disorders* (4th ed. [*DSM–IV*]; APA, 1994) criteria were used, and children were included only if they met the full diagnostic criteria for Attention-Deficit/Hyperactivity

Disorder, Combined type. Children were excluded from the clinical group if they had a history of a disorder of consciousness, a head injury with cerebral symptoms, a history of CNS diseases, convulsions or a history of convulsive disorders, paroxysmal headaches, or tics.

Inclusion in the control group was based on an uneventful prenatal, perinatal, and neonatal period; no disorders of consciousness, head injury with cerebral symptoms, history of CNS diseases, obvious somatic diseases, convulsions, history of convulsive disorders, paroxysmal headache, tics, or stuttering; and no deviation with regard to physical development. Control participants also had to score in the normal range on the measures of intellectual functioning and reading ability. Control subjects were also excluded if they met criteria for any disorder listed in the *DSM–IV* (APA, 1994). Assessment for inclusion as a control was based on a clinical interview with a parent or guardian similar to that of the AD/HD participants, utilizing the same sources of information, and the same psychometric assessment as was used for the clinical subjects.

Children were also excluded if spike wave activity was present in the electroencephalogram (EEG).

Procedure

Both the AD/HD and control participants were each tested in a single morning over approximately 2.5 hr. The EEG was recorded at the end of this session in an eyes-closed resting condition while participants were seated on a reclining chair. Electrode placement was in accordance with the international 10-20 system, using an electrode cap. Activity in 19 derivations was recorded from Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, and O2. The ground lead was placed between Fz and Cz. A linked ear reference was used with all EEG, and reference and ground leads were 9 mm tin disk electrodes. Impedance levels were set at less than 5 kOhm.

The EEG was recorded on a Lexicor NRS-24 using a sampling rate of 256 Hz. A gain of 30,000 was used, with a high pass filter of 0.5 Hz, low pass filter of 64 Hz, and a 50 Hz notch filter. The EEG was artifacted and Fourier transformed using software produced by NXLink. Initially the EEG was visually artifacted by a trained EEG technician to provide a minimum of 80 s of artifact-free trace for Fourier analyses. Artifacting included the removal of eye blinks, vertical and lateral eye movements, muscle tension artifacts, and other movement-based artifacts. The artifact-free EEG was then resampled at 100 Hz and epoched using 2.56-s epochs. Epochs were then Fourier transformed using a Hamming window. The FFT calculated estimates of four frequency bands: Delta (1.5–3.5 Hz), Theta (3.5–7.5 Hz), Alpha (7.5–12.5 Hz) and Beta (12.5–25 Hz). Relative power in each band was used in the analysis because this has been found to provide the most reliable EEG measure in test/retest conditions (John et al., 1980) and is the most robust marker of differences between children with AD/HD and control subjects (Barry et al., 2003). The theta/beta ratio was also calculated at each electrode site by dividing power in the theta band by beta power.

Statistical Analysis

Data analysis in this study was conducted in line with the first cluster study of Clarke et al. (2001b). Initially, the data from the AD/HD and control groups were converted to *z* scores based on the means and standard deviations of the control group. This was done in 2-year bands to control for maturational effects. The *z* scores allow comparable estimates of excesses or deficiencies of power for each frequency band at each site, for each AD/HD child, compared to normal children.

Each EEG measure was then averaged in two regions for further analysis. These consisted of a frontal region (Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4) and a posterior region (T5, T6, P3, P4, Pz, O1, O2). Two-tailed independent sample *t* tests were used to compare the AD/HD group with the control group, for each region, in relative power and the theta/beta ratio.

In the final stage of the analysis, one-tailed Pearson correlations were performed between the *z*-transformed EEG data in all bands and the theta/beta ratio, with the three *DSM–IV* subscales (Inattentive, Hyperactive-Impulsive, Total) of the Conners' Parent Rating Scale. It was hypothesized that increased delta, theta, and the theta/beta ratio, and reduced alpha and beta activity, would positively correlate with increased Conners' scores on each of the *DSM–IV* subscales.

RESULTS

A summary of significant results is presented in Table 1, and raw relative power data are presented in Figure 1. The AD/HD group had significantly more relative theta in the frontal, $t(118) = -6.083$, $p < .001$, and posterior, $t(118) = -6.083$, $p < .001$, regions, with reduced frontal, $t(118) = 2.172$, $p < .05$, and posterior, $t(118) = 3.58$, $p < .001$, relative alpha, and reduced frontal relative beta, $t(118) = 2.326$, $p < .05$. The theta/beta ratio was also significantly increased in both the frontal, $t(118) = -3.703$, $p < .001$, and posterior, $t(118) = -3.736$, $p < .001$, regions in the AD/HD group.

For the correlation of the EEG with the Conners' *DMS–IV* subscales, frontal theta significantly correlated with the Inattentive ($r = .246$, $p < .05$) and Total ($r = .243$, $p < .05$) subscales, and the theta/beta ratio in the frontal region correlated with the Hyperactivity-Impulsive ($r = .219$, $p < .05$) and Total ($r = .241$, $p < .05$) subscales.

TABLE 1. Mean *z* Scores for the AD/HD Group Relative to the Control Group

Region	AD/HD group
Delta frontal	–0.82
Delta posterior	0.53
Theta frontal	1.31***
Theta posterior	1.38***
Alpha frontal	−0.45*
Alpha posterior	−0.67*
Beta frontal	−0.49*
Beta posterior	−0.38
Theta/beta ratio frontal	1.18***
Theta/beta ratio posterior	1.43***

Note. AD/HD = attention-deficit/hyperactivity disorder.
*$p < .05$. ***$p < .001$.

DISCUSSION

The initial part of the analysis was a comparison of the AD/HD group with the control group. This was conducted to allow comparison of the EEG in the present sample with past studies in order to assess how representative of the wider literature is the current sample. In the present study, the AD/HD group had increased global theta activity and theta/beta ratio, increased frontal delta, with reduced global alpha and frontal beta activity. This profile of EEG abnormalities is consistent with past

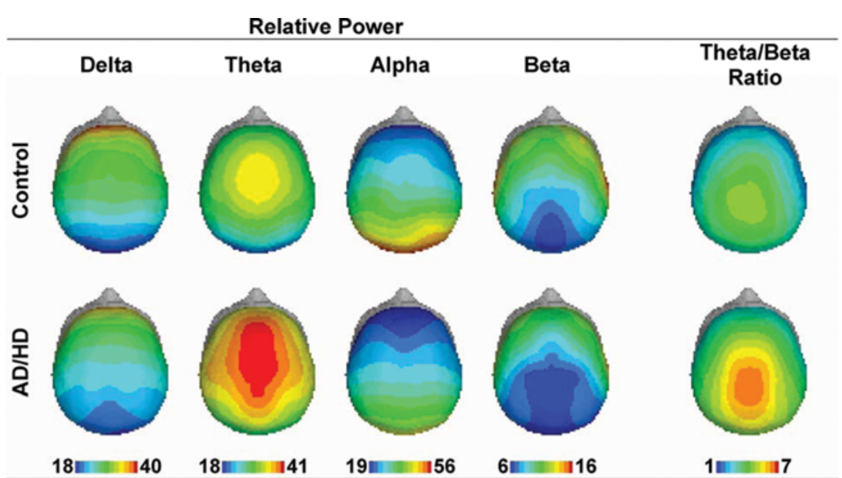

FIGURE 1. Topographic differences in relative power (%) and the theta/beta ratio for the AD/HD and control groups. (Color figure available online.)

research, indicating that this group of subjects has an EEG profile typical of this disorder.

In the second part of the analysis, Conners' scores for the three subscales most closely linked to the *DSM–IV* (APA, 1994) criteria for AD/HD were correlated with EEG activity in each band in the AD/HD group. Significant correlations in the expected direction were obtained for the theta band and the theta/beta ratio, but only for frontal regions. Frontal lobe deficits are at the core of two of the major cognitive models of AD/HD, being linked to executive-function deficits in this disorder (Barkley, 1997a, 1997b; Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003). Within these models of AD/HD, the core symptoms of inattention, hyperactivity, and impulsivity are attributed to executive-function deficits, and this is supported by the results of the current analysis.

In the theta band, frontal theta was significantly correlated with the Inattentive and Total subscales. Increased frontal theta activity is one of the most commonly reported EEG abnormalities in AD/HD and is found in all types of the disorder (Barry et al., 2003). The fact that elevated theta activity correlates with inattention helps to explain why it is found in children with both the Inattentive and Combined types of AD/HD, as both of these types have core symptoms of inattention. This is also probably why theta correlated with the Total subscale of the Conners', as this includes the inattentive symptom score. Increased theta activity has also been found in children with learning disabilities (Dykman et al., 1982), autism (Coben, Clarke, Hudspeth, & Barry, 2008), and mental retardation (Katada & Koike, 1981), as well as in younger normal children (Gasser, Verleger, Bacher, & Sroka, 1988). This has led many to speculate that theta activity might be a nonspecific marker of brain dysfunction. However, the current results suggest that increased theta might actually be a specific marker of inattention, a symptom that is present in all the groups just listed. Further research is needed to test this hypothesis.

The theta/beta ratio was the only other measure to correlate with Conners' scores, with frontal ratio scores correlating with the Hyperactive-Impulsive subscale, and again with the Total subscale. In a cross-sectional study of maturational changes in AD/HD, Clarke, Barry, McCarthy, and Selikowitz (2001b) found that the theta/beta ratio matured at a faster rate in children with the Combined type of AD/HD and became similar to levels found in children with the Inattentive type of the disorder by age 12. This was interpreted as indicating that hyperactivity was associated with the theta/beta ratio, and the reduction in the degree of abnormality of the ratio was related to a reduction in hyperactivity. This interpretation is supported by the current results with the theta/beta ratio being associated with Hyperactivity once again. However, of particular interest is the fact that theta power alone correlated with Inattention, not Hyperactivity-Impulsivity, but the theta/beta ratio correlates with Hyperactivity-Impulsivity, even though theta is a core component of the ratio. One possibility is that this result is associated with the beta component of the ratio. Bresnahan, Anderson, and Barry (1999) conducted a cross-sectional study of children, adolescents, and adults with AD/HD. Their results indicated that the abnormal beta levels of childhood normalized with increasing age. It was hypothesized that this was associated with the reduction in hyperactivity found in children with AD/HD as they get older. Beta activity is also a component of the theta/beta ratio, and possibly is a more sensitive measure of behavioral abnormalities in this disorder than beta power alone. Although relative beta did not correlate with any of the behavioral subscales of the Conners', it is possible that beta activity may be associated with hyperactivity and that the theta/beta ratio amplifies this association.

This study investigated the link between EEG activity in specific bands and ratings of the core components of the symptom profile of children with AD/HD. Results indicate that frontal theta activity correlates with Inattention, the theta/beta ratio with Hyperactivity-Impulsivity, and both measures contribute to a Combined type diagnosis. This link between EEG power in discrete bands and behavioral abnormalities in children with AD/HD may further our understanding of CNS dysfunctions in this population, and further research in this line may help provide a better understanding of the functional basis of this disorder.

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