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Invited review

A review of electrophysiology in attention-deficit/hyperactivity disorder: I. Qualitative and quantitative electroencephalography

Robert J. Barry , Adam R. Clarke and Stuart J. Johnstone

Department of Psychology and Brain & Behaviour Research Institute, University of Wollongong, Northfields Avenue, Wollongong, NSW 2522, Australia

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Abstract

Objective: This article reviews the electroencephalography (EEG) literature in relation to attention-deficit/hyperactivity disorder (AD/HD).

Methods: The review briefly outlines the history of the disorder, focusing on the changing diagnostic systems which both reflect and constrain research into AD/HD. Both qualitative and quantitative EEG studies are examined, and their results are discussed in relation to various models of AD/HD. Implications of these data for future research and development in AD/HD are considered.

Results: In terms of resting EEG, elevated relative theta power, and reduced relative alpha and beta, together with elevated theta/alpha and theta/beta ratios, are most reliably associated with AD/HD. Theta/alpha and theta/beta ratios also discriminate diagnostic subgroups of AD/HD. Recent studies of EEG heterogeneity in this disorder indicate the existence of different profiles of cortical anomalies which may cut across diagnostic types.

Conclusions: The research to date has identified a substantial number of EEG correlates of AD/HD which hold promise for improving our understanding of the brain dysfunction(s) underlying the disorder. Further work in this field may benefit from a broader conceptual approach, integrating EEG and other measures of brain function.

Author Keywords: Attention-deficit/hyperactivity disorder; Electrophysiology; Electroencephalography; Review

Article Outline

1. Introduction

This paper reviews the field of electroencephalography (EEG) in attention-deficit/hyperactivity disorder (AD/HD). Here, and in the companion paper reviewing the field of event-related potentials (ERPs) in AD/HD (Barry et al., 2003), we examine current knowledge of the electrophysiology of AD/HD. We first provide a brief overview of the syndrome, and outline the shifting perspectives which have both reflected and informed research in the field, up to and including the present international differences in diagnostic systems. These shifting perspectives impose a particular burden when considering data in this field, as differences in diagnostic criteria, and the consequent grouping of children into categories with different symptom clusters, can be expected to contribute substantially to different research outcomes, making the sifting of meaningful data difficult. In this regard, we report data using the diagnostic categories of the particular piece of research under discussion, but attempt to separate out the systematic effects relatable to symptom clusters in the modern diagnostic categories. It should be noted that even simple aspects of the disorder, such as its prevalence rate, are further impacted upon by issues of different types of AD/HD, as well as comorbidity, age and gender differences, and these variables serve to further cloud our understanding of the electrophysiology of AD/HD.

2. The syndrome of attention-deficit/hyperactivity disorder

AD/HD refers to a variable cluster of hyperactivity, impulsivity, and inattention symptoms, the occurrence of which substantially affects normal cognitive and behavioural functioning of the individual. Children and adolescents with AD/HD are at risk for later delinquency problems (e.g. Satterfield and Weiss), and some symptoms may persist through the lifespan. Over the last 30 years, substantial changes have occurred in the conceptualization of AD/HD, and unfortunately, these changes impede understanding of the electrophysiological studies of the disorder.

2.1. Historical changes in definition

Early accounts described defects in moral control, mischievousness and destructive behaviour (Hoffman and Still), regarded as resulting from traumatic brain injury (e.g. Goldstein and Meyer), influenza-related encephalitis (e.g. Hohman and Kennedy), or various childhood central nervous system (CNS) infections (e.g. Bender, 1942). Strauss and Lehtinen (1947) termed it the ‘minimal brain dysfunction’ (MBD) syndrome. This was followed by ‘hyperkinetic impulse disorder,’ with symptoms of hyperactivity, short attention span, variability, impulsiveness, irritability, explosive anger fits, and poor school work (Laufer and Denhoff, 1957). Clements and Peters (1962) re-introduced the MBD terminology, broadly defined to include specific learning deficits, perceptual-motor deficits, general coordination deficits, hyperkinesis, impulsivity, emotional lability, short attention span and/or distractibility, and equivocal neurological signs.

The disorder was first listed in the second edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-II; APA, 1968) as 'hyperkinetic reaction of childhood,' emphasizing inattention, impulsivity and motor activity. DSM-III (APA, 1980) renamed it 'Attention Deficit Disorder' (ADD), shifting emphasis from motor activity to attention, with two types: with hyperactivity (ADDh) and without hyperactivity (ADDwo). In the DSM-III-R (APA, 1987), it was renamed 'Attention Deficit Hyperactivity Disorder' (ADHD), and considered unidimensional in nature, with a single diagnostic checklist. A second category, 'Undifferentiated Attention Deficit Disorder' (U-ADD), featured marked inattention without specific diagnostic criteria. Subsequent studies suggested that the disorder was multidimensional (Bauermeister; Lahey and Morgan), characterized by inattention and hyperactivity/impulsivity. In the DSM-IV (APA, 1994), the criteria changed again to reflect these findings, with 3 main types: Predominantly Inattentive (AD/HDin); Predominantly Hyperactive-Impulsive (AD/HDhyp); and Combined Type (AD/HDcom).

2.2. International perspectives

Hyperkinetic Disorder (HKD) in the 10th revision of the International Classification of Diseases (ICD-10; WHO, 1993) lists similar criteria for a childhood disorder characterized by inattention, impulsivity and hyperactivity. However, ICD-10 requires symptoms from each of the 3 behavioural categories. Both systems use the same 18 behavioural items, but the two systems group the items differently, and have different diagnostic thresholds. Children with an ICD-10 HKD diagnosis are most likely AD/HDcom, but a child may meet minimum criteria for HKD yet fail the hyperactivity/impulsivity criteria in DSM-IV, resulting in a diagnosis of AD/HDin.

2.3. Prevalence of AD/HD

AD/HD is one of the most common disorders treated by child and adolescent psychiatrists in America, comprising as much as 50% of child psychiatry clinic populations (Cantwell, 1996). The DSM-IV (APA, 1994) estimated prevalence at approximately 3–5% of school-age children, and studies based on these criteria have found prevalence to range from 3 to 6% (Pelham and Lindgren). AD/HD is more common in males (James and Taylor, 1990), with relative rates of up to 9:1 in clinical samples, and 4:1 in epidemiological studies (APA, 1994), although community-based studies have found ratios as low as 2:1 (Szatmari and Taylor). AD/HD is also a highly comorbid disorder, often co-occurring with conduct disorder (CD) and oppositional defiant disorder (ODD) (Bird et al., 1994), anxiety disorders (August and Anderson), major depressive disorder or dysthymia (Anderson; Alessi and Woolston) and learning difficulties (LD) (August and Silver).

More-recent studies have also found that between 50 and 70% of children with AD/HD will continue to suffer from the disorder as adults (Mannuzza and Bellak). In adults, the disorder is typified by poor concentration, explosive outbursts, impulsivity, restlessness, as well as non-medical drug use, court referrals, incarceration, and personality disorders (Hechtman; Hechtman; Loney and Wender).

3. Electroencephalographic studies in AD/HD

EEG provides information about the electrical activity of the brain, but due to the intervening media, the scalp-recorded signal provides a diffuse picture of that underlying activity. Nevertheless, that record can provide valuable information on the brain, with high temporal

(but poor spatial) resolution. From our perspective, the EEG is a useful source of information on the background state of the brain, indexing the substrate of cognition and behaviour. Basic research has demonstrated explicit relations between the momentary brain state, indicated by parameters of the EEG, and the event-related potential signature of the processing of a stimulus (e.g. Basar and Barry). Despite this obvious interdependence, the electrophysiological investigation of AD/HD has largely examined these aspects in isolation, historically beginning with EEG studies.

3.1. Qualitative EEG studies

One of the earliest studies to identify EEG abnormalities in children with MBD was Jasper et al. (1938). Seventy-one children aged 2–16 years, in an institution for behaviour problems, most with IQ above 70, showed 3 types of symptom clusters: predominantly hyperactive and impulsive, withdrawn and emotionally immature, and delinquent in nature. Over half had EEG abnormalities, predominantly an increase in slow wave (2–6 Hz) activity in one or more regions, often frontal. Lindsley and Cutts (1940) compared EEG records from 50 children identified by their parents as having behavioural problems, and 36 normal controls, and found that 2–5 Hz activity was 2–3 times more common with behavioural problems. Kennard (1949) studied 131 children with various behavioural disorders and found that 60% had EEG abnormalities. Green (1961) reported 4 case studies of normal intelligence children with behavioural problems, all showing focal spike wave activity in the occipital regions, despite not experiencing seizures and responding poorly to anticonvulsant medication. Anderson (1963) investigated 30 children aged 8–12 years with a hyperkinetic behaviour disorder, and found EEG abnormalities in 26: unspecified focal abnormalities in 6 children, and nonfocal abnormalities in the other 20. Capute et al. (1968) studied 106 MBD children aged 2–16 years old. Fifty percent showed EEG abnormalities: 45 with slight to moderate abnormalities and 8 with very abnormal recordings. Focal abnormalities were found in 14; the most common non-focal abnormality was increased bilateral slow wave activity in the posterior regions. Wikler et al. (1970) found more slow wave activity, and more abnormal transient discharges in the EEGs of 25 hyperactive or aggressive children than in non-hyperactive subjects.

All of these studies used visual evaluation of paper recordings of the EEG, and many reported percentage differences in abnormalities between clinical and control groups rather than identifying the exact nature of the underlying abnormality. Despite limitations in comparison to later studies that use computer-aided analysis, the most common finding with this methodology was an increase in activity in the delta and theta bands, which is largely consistent with modern data.

3.2. Quantitative EEG studies

With the advance of computer-aided spectral analysis, a number of approaches have been used to assess changes in the EEG of children with normal development, and in those with a range of disorders. This has included the analysis of waveform amplitude (Matousek and Petersen, 1973), absolute and relative power (John; Gasser; Gasser; Clarke and Clarke), dominant and subordinate frequency analysis (Katada and Katada), mean frequency (Chabot and Serfontein, 1996), the wave percentage time (Matsuura et al., 1985), ratio coefficient analysis between waveforms (Matousek and Matthis), and coherence of the EEG waveform between regions (Chabot and Barry). The most commonly-used of these procedures in AD/HD research are discussed below.

3.2.1. Waveform amplitude

One of the earliest computer-aided analyses of the EEG to be undertaken used waveform amplitude, either absolute amplitude (calculated by averaging the amplitude of every wave in a given frequency band), or relative amplitude (calculated by dividing the absolute amplitude of one frequency band by the sum of the absolute amplitudes of all the calculated frequency bands).

Some of the earliest electrophysiological research into hyperactivity was undertaken by James Satterfield. These studies primarily investigated EEG, ERP and skin conductance level (SCL) differences between good and poor responders to Methylphenidate (Satterfield; Satterfield; Satterfield; Satterfield and Satterfield). The good responders to stimulant medication had higher mean resting amplitude ranges and higher mean resting power in the 0–8 Hz frequency range than the poor responders.

Matousek et al. (1984) investigated 38 children with MBD (defined as marked attention deficit with substantial gross motor, fine motor or perception dysfunction, without cerebral palsy or mental retardation) or ADD (defined as marked attention deficit without other signs of MBD), and control subjects. EEG was recorded during an eyes-closed resting condition. Results indicated that the highest correlating measures with MBD were relative delta in posterior regions, and the theta/alpha ratio.

Matsuura et al. (1993) conducted a cross-cultural EEG study in Japan, China and Korea of 153 children with deviant behaviour, and 91 children with a DSM-III-R diagnosis of ADHD. Results indicated that the ADHD group had a higher average amplitude of delta, higher percentage time of delta and slow theta, and lower percentage time of alpha, than control subjects. In the ADHD group, mean maximum amplitude was found at 8 Hz, whereas in control subjects, it was at 9 Hz.

Janzen et al. (1995) studied EEG differences in 8 children with a DSM-III-R diagnosis of ADDwo and 8 controls, recorded with eyes-open, eyes-closed, and a number of different cognitive tasks. They found that children with ADDwo had higher amplitude theta than control subjects, during an eye-closed resting condition. No differences in amplitude in the beta band were found between subjects.

3.2.2. Power studies

The most commonly-used form of EEG analysis in studies of AD/HD has been the calculation of absolute and relative power estimates. These provide an easily-interpreted and reliable method of quantifying changes in the EEG under different conditions, as well as differences between various clinical and normal groups (Matthis et al., 1981). Relative power measures, recorded under an eyes-closed resting condition, have also shown good test-retest reliability (John et al., 1980).

Dykman et al. (1982) used principal component analysis to investigate EEG differences in 4 groups: hyperactive, learning-disabled, hyperactive/learning-disabled or mixed, and normal children. A visual search task was used during the recording of the EEG. The EEG was Fourier-transformed into 1 Hz frequency bands, with results indicating that the hyperactive group had lower loadings than the control group on a factor reflecting the 7–10 Hz (theta/alpha bands) and 16–20 Hz (beta band) ranges. Callaway et al. (1983) investigated ERP

and EEG spectral differences between 18 hyperactive and 18 age-matched normal subjects. The EEG was recorded from 3 posterior electrode sites during both eyes-open and eyes-closed resting conditions. In all bands except delta, the eyes-closed condition showed a greater level of power than the eyes-open condition. Hyperactive children had lower power in the alpha and beta bands than control subjects. Satterfield et al. (1984) conducted a longitudinal study of 138 hyperactive boys. Results indicated that, with increasing age, EEG power decreased faster in control subjects than in hyperactive subjects.

Chabot and Serfontein (1996) reported EEG differences in 407 children diagnosed using DSM-III criteria for ADD, compared to a normative database. Children with ADD had an increase in absolute and relative theta, primarily in the frontal regions and at the frontal midline. A slight elevation in relative alpha, and a diffuse decrease in mean frequencies in the alpha and beta bands, were also found in some children with ADD. Interhemispheric asymmetries were found in the parietal and posterior temporal areas. Intrahemispheric abnormalities were found with asymmetries between frontal/temporal and frontal/occipital regions.

Diamond (1997) failed to find any EEG differences between ADHD and control subjects in a pilot study. Significant results in other studies were considered to have resulted from comorbid learning disabilities.

Lazzaro et al. (1998) investigated EEG differences between 26 male adolescents with a DSM-IV (APA, 1994) diagnosis of AD/HD, and 26 age- and sex-matched controls during an eyes-open resting condition. The AD/HD group had increased absolute theta and alpha1 activity in frontal regions and reduced relative beta in posterior regions. This study is one of the few to use an adolescent population rather than children.

Clarke et al. (1998) carried out the first study of EEG differences between children with different DSM-IV types, comparing 20 AD/HDcom, 20 AD/HDin and 20 control subjects, using an eyes-closed resting condition. The AD/HD groups had increased power levels across all sites in absolute and relative theta, and reductions in relative alpha and beta. In the posterior region, relative delta increases were able to differentiate between all 3 experimental groups.

In a follow-up of our 1998 study with larger independent subject groups (each n=40) and a wider range of measures, Clarke et al. (2001d) found AD/HD children to have increased absolute and relative theta, and decreased relative alpha and beta, and these effects differentiated AD/HDcom from AD/HDin. Results also indicated that effects in relative power were more stable between the two studies than absolute power effects.

Bresnahan et al. (1999) was the first study to investigate the EEG profiles of adult AD/HD subjects, using 3 age groups (each n=25): children, adolescents and adults, with age- and sex-matched controls. The results indicated that absolute and relative theta activity remained elevated through adolescence into adulthood, but there was a decrease in relative beta activity with age. Bresnahan and Barry (2002) examined whether this EEG profile was specific to adult AD/HD patients. EEGs were recorded at rest in an eyes-open condition and used to compare 50 adult patients diagnosed with AD/HD with 50 non-AD/HD subjects (who presented for AD/HD assessment but failed to meet the diagnostic criteria) and 50 control subjects. The AD/HD group differed from both the non-AD/HD group and the control group on the basis of elevated absolute and relative theta power.

Lazzaro et al. (1999) studied 54 unmedicated adolescent AD/HD males and age- and sex-matched normal control subjects, using simultaneously-recorded EEG and electrodermal measures in a resting eyes-open condition. AD/HD adolescents showed increased absolute and relative theta and alpha1 activity, reduced relative beta activity, reduced skin conductance level (SCL), and a reduced number of non-specific skin conductance responses compared with the control subjects. Their findings were taken to indicate the continuation of increased slow wave activity in AD/HD adolescents and the presence of a state of autonomic hypoarousal in this clinical group.

Although EEG and ERP studies in AD/HD have generally been separate, Lazzaro et al. (2001) examined these measures simultaneously in 54 unmedicated AD/HD adolescent males, and age- and gender-matched normal controls during an auditory oddball paradigm. Compared with controls, AD/HD patients showed increased pre-stimulus EEG theta activity, which was interpreted to contribute to their ERP differences (described in more detail in Barry et al., 2003).

Clarke et al. (2002b) investigated differences between 20 children with AD/HD, 20 comorbid AD/HD and reading disabilities, and 20 control subjects. The clinical groups had less absolute and relative alpha and beta, more absolute theta, and more relative delta and theta than the control group. The patient groups also had less absolute alpha and beta, and less relative delta, theta and alpha, in the posterior regions, and less relative beta in frontal regions than the control group. The theta/alpha and theta/beta ratios also differentiated between the clinical groups and the control group. The AD/HD group with reading disabilities had more relative theta, less relative alpha, and a higher theta/alpha ratio than the group with AD/HD alone.

3.2.3. Ratio coefficients

The ratio between power in different frequency bands has been used to evaluate changes in the EEG that occur due to normal maturation (Matousek and Petersen, 1973) and as a measure of cortical arousal (Lubar, 1991), which are both theoretically pertinent to AD/HD.

Matousek et al. (1984) found that the theta/alpha ratio was a good predictor of group differences between children with MBD, ADD and control subjects. In a longitudinal EEG study of 264 children Woerner et al. (1987) found that a mixed group of hyperkinetic and conduct-disordered children had an abnormal theta/alpha ratio at age 8, but not at age 13.

Lubar (1991) calculated theta/beta ratios for 25 ADHD and 27 control subjects during a drawing task. The ADHD subjects had a greater ratio at all sites compared to the control subjects, with the greatest difference in the frontal electrode sites. Janzen et al. (1995) also reported that children with ADHD had a higher theta/beta ratio than control subjects.

Ucles and Lorente (1996) reported that children with a DSM-III diagnosis of ADD had a higher ratio coefficient in the occipital leads than control subjects during an eyes-closed resting condition. This was considered to reflect a reduction in alpha activity resulting from a localized deficit in cortico-cortical or thalamo-cortical systems. Delayed maturation in the alpha rhythm circuits was seen as the most plausible explanation.

Monastra et al. (1999) calculated a theta/beta ratio from 482 individuals aged 6–30 years old. Results indicated that the theta/beta ratio was higher in AD/HD subjects than control subjects. In a follow-up to this study by Monastra et al. (2001), using 469 subjects between 6 and 20

years old, the theta/beta ratio was again found to discriminate between AD/HD and control subjects.

Clarke; Clarke and Clarke found that both the theta/alpha and theta/beta ratios can differentiate between groups of normal children and children with AD/HD. In addition, ratio differences were found between the AD/HDin and AD/HDcom groups in the first two studies, and between children with AD/HD and AD/HD plus reading disability in the third.

Bresnahan et al.'s adult studies have confirmed that the theta/beta ratio remains elevated in AD/HD from children to adults (Bresnahan and Bresnahan). Further, the ratio distinguished adults who met AD/HD criteria from those with some symptoms of the disorder who failed to meet those criteria (Bresnahan and Barry, 2002), indicating some specificity for this marker in AD/HD.

3.2.4. Coherence studies

The coherence of the EEG activity between two sites, conceptualized as the correlation in the time domain between two signals in a given frequency band (Shaw, 1981), provides information about the coupling of brain activity between different recording sites. A two-process model of cortico-cortical associations (Thatcher et al., 1986), in which short and long neuronal fibres contribute differentially to coherence as a function of inter-electrode distance, allows interpretation – e.g., elevated short-range coherence in children with intellectual impairment and reading disability (Gasser and Marosi) is interpreted as indicating decreased cortical differentiation.

EEG coherence has not been investigated thoroughly in the AD/HD context. An early study by Montagu (1975) found interhemispheric coherences were slightly reduced in hyperkinetic children, while intrahemispheric coherences were significantly elevated. Chabot and Chabot reported on a mixed group of attention disorder children (43.9% ADHD, 40.5% ADD, and 15.6% not meeting those criteria), some of whom had learning disabilities. They found that attention deficit disorder was associated with interhemispheric and intrahemispheric hypercoherence in frontal and central regions. There was also generally-reduced coherence parietally. Chabot et al. (1999) reported pre-medication coherence data from a similar patient mix, using a subset of patients from their previous studies, and again noted increased frontal interhemispheric coherence, particularly in the theta and alpha bands, and increased intrahemispheric coherence bilaterally in fronto-temporal regions.

Our recent study (Barry et al., 2002) found differences in intrahemispheric and interhemispheric coherences in AD/HD. These suggest reduced cortical differentiation and specialization in AD/HD, particularly in cortico-cortical circuits involving theta activity.

3.2.5. DSM type differences

Both the DSM-III (APA, 1980) and DSM-III-R (APA, 1987) identified a hyperactive and an inattentive type of disorder, with the DSM-IV (APA, 1994) expanding this further, listing 3 types of AD/HD. While the majority of studies have investigated only children with a hyperactive component to their diagnosis, a few studies have examined the EEG of inattentive children, and conducted comparisons of hyperactive and inattentive children under various DSM criteria.

Mann et al. (1992) studied EEG differences between 27 normal children and 25 children with a DSM-III diagnosis of ADDwo. EEG was recorded during a baseline eyes-open condition, a reading condition and a drawing condition. The ADDwo group had an increase in absolute power in the theta band, predominantly in the frontal regions, and showed a greater increase in theta activity in frontal and central regions during cognitive tasks, and a greater decrease in beta activity in posterior and temporal regions with tasks requiring sustained attention.

In their study described above, Chabot and Serfontein (1996) also noted EEG differences between children with the hyperactive and inattentive types of ADD. The differences between the two ADD groups were mainly in the degree of abnormality, not the type, with the EEG measures from the inattentive type falling between those obtained from the hyperactive and normal children.

Kuperman et al. (1996) used DSM-III-R criteria to study quantitative EEG differences between 16 children with ADHD, 12 U-ADD and 12 normal children. For relative power, main effects of band were found, with the control group having more delta than the U-ADD subjects and less beta than both groups of children with ADHD. The U-ADD group had hemispheric differences, with decreased delta and increased beta in the left hemisphere. In relative alpha and beta, the U-ADD group had more extreme EEG results, in comparison to the control group, than the ADHD group.

Clarke and Clarke investigated differences between children with AD/HDcom and AD/HDin. In most measures, the inattentive group was found to have EEG abnormalities that were similar to those found in children with AD/HDcom, except that they were not as extreme. However, in the Clarke et al. (2001d) study, results for absolute and relative theta, in the frontal regions, indicated the presence of qualitative differences in frontal lobe function between the two AD/HD groups. This was further investigated in a follow-up study that examined age-related changes in the EEG of 160 children with AD/HDcom or AD/HDin types, and 80 controls (Clarke et al., 2001b). Total power, relative alpha, and the theta/alpha and theta/beta ratios differentiated between all 3 groups. With increasing age, the EEG of the AD/HDin group was found to change at a similar rate to the changes found in the control group, with the differences in power levels remaining constant. In the AD/HDcom group, power was found to change at a greater rate than in the AD/HDin group, with power levels of the two AD/HD groups becoming similar with age.

In an investigation of EEG differences between 24 children with Hyperkinetic Disorder (HKD), 24 with HKD sub-threshold attention deficit (HKDsub) using ICD-10 (WHO, 1993) criteria, and 24 control children, Clarke et al. (in press) found that the HKD group had greater total power and absolute delta and theta, more relative theta, and less relative alpha and beta than the control group. The HKDsub group had EEG profiles which were different from both control children and HKD children, with the HKDsub group generally placed between the other two groups. A number of topographic differences in the frontal regions were also found, suggesting the presence of independent EEG components in the two clinical groups.

Barry et al. (2002), discussed above, also found differences in coherence patterns between AD/HDcom and AD/HDin types, with AD/HDin being less deviant than AD/HDcom. This was interpreted as indicating a simple increase in the degree of departure from normality with the larger number of symptoms in AD/HDcom.

No studies have reported EEG profiles for the DSM-IV predominantly hyperactive/impulsive type of AD/HD.

3.2.6. Summary of EEG findings

Although these studies have used a number of different diagnostic categories for their clinical groups, and several different methods to quantify the EEG differences between clinical groups and normal children, a number of commonalities were found. Most studies have reported that AD/HD groups show elevated levels of slow wave activity in comparison to normal children. The most reliable measure of this has been relative theta power, irrespective of whether an eyes-open or eyes-closed condition was used. Reduced amounts of relative alpha and beta have also been found in most power studies, while absolute alpha and beta are less reliable discriminators. Increased delta activity in both absolute and relative measures has also been found in AD/HD, but with far less consistency. In general, anomalies appear to be more pronounced in children with AD/HDcom than AD/HDin. Both the theta/alpha and theta/beta ratios also appear to be reliable measures differentiating between AD/HD and control subjects, as well as between the DSM-IV types of the disorder, with neither measure demonstrating greater sensitivity than the other, although the theta/beta ratio is preferred by some researchers (e.g. Lubar, 1991). These results are illustrated in Fig. 1, which shows topographic distributions of these measures in 8–12-year-old children, based on published data from our laboratory. To date, there are insufficient studies to evaluate the reliability of coherence differences.

Full-size image (98K)

Fig. 1. Topographic comparisons of AD/HDcom and AD/HDin children with controls for total power, relative delta, theta, alpha and beta, and the theta/alpha and theta/beta ratios.

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3.2.7. EEG in diagnosis

A number of researchers have investigated the utility of EEG measures in the diagnosis of AD/HD. With discriminant function analysis, Mann et al. (1992) found that EEG measures could predict group membership with approximately 80% accuracy. Chabot and Serfontein (1996) reported that discriminant function analysis, utilizing 9 EEG variables, produced approximately 95% correct classification of normal children and 93% correct classification of children with attentional problems. Monastra et al. (1999) found that the theta/beta ratio could

discriminate AD/HD from control subjects with 86% sensitivity and 98% specificity. Kovatchev et al. (2001) reported that an EEG-derived *Consistency Index* correctly classified 88% of boys and 67% of girls, but this became less reliable with increasing age. However, it was proposed that this could be useful in young boys.

4. EEG-based models of AD/HD

While reasonably consistent EEG results have been found across a number of studies, the interpretation of what these results represent remains contentious within the literature. Two main models of AD/HD have been proposed, based on EEG studies.

4.1. The Maturational Lag model of AD/HD

The Maturational Lag model proposes that AD/HD results from a developmental lag in CNS functioning: Children with AD/HD are developmentally inappropriate for their age, but act in a way that would be normal in younger children (Kinsbourne, 1973). From an electrophysiological perspective, this model requires that EEG measures from a child with AD/HD would be considered normal in a younger child (John et al., 1990).

Satterfield et al. (1973a) found that hyperactive children who responded well to stimulant medication were those who had increased slow wave activity in their EEG, and longer latencies and lower amplitudes in evoked cortical responses. These results were considered to support a model of delayed maturation in such children, rather than being indicative of some form of brain damage. The cross-cultural EEG study by Matsuura et al. (1993) in children with deviant behaviour found that the ADHD group had higher average amplitude delta, higher percentage time of delta and slow theta, and lower percentage time of alpha than normal control subjects. Hypothetical EEG age was calculated for the clinical groups, using the procedures outlined by John et al. (1987). This indicated that the children with ADHD showed signs of a maturational lag in brain functioning.

Clarke et al. (1998) interpreted their findings of elevated theta and reduced beta as supporting the maturational lag model in children with AD/HD. Lazzaro et al. (1998) also found increased absolute theta and alpha1 activity in frontal regions, and reduced relative beta in posterior regions, and interpreted these as representing a maturational lag in adolescents with AD/HD.

4.2. Developmental Deviation Model of AD/HD

In the Developmental Deviation model, AD/HD is conceptualized as resulting from an abnormality in the functioning of the CNS. Electrophysiological measures from these children are not considered to be normal in children of any age, and the EEG is not considered likely to mature in a normal fashion.

Klinkerfuss et al. (1965) found 90% of children with hyperactivity had abnormalities in their EEGs and 30% had markedly-disordered traces. When the EEGs were examined within age groups, the percentage of slowing of the EEG did not increase or decrease with increasing age. This indicated that the EEG of these children was not maturing, and was supportive of a developmental deviation model. Wikler et al. (1970) investigated EEG abnormalities in 25 children between the ages of 5 and 15 years during an eye-closed, resting condition. The EEGs were visually appraised and rated on the activity in each frequency band, using

calculations of percent time. Hyperactive children were found to have increased slow wave activity in comparison to normal controls. It was also noted that the abnormally-slow EEG activity of the hyperactive children did not increase or decrease with age.

Chabot and Serfontein (1996) used a paradigm described by John et al. (1988) whereby EEG measures were converted to *Z* scores and compared to a normative data base (John et al., 1980. E. John, H. Ahn, L. Princhep, M. Trepetin, D. Brown and H. Kaye , Developmental equations of the electroencephalogram. *Science* **210** (1980), pp. 1255–1258. View Record in Scopus | Cited By in Scopus (167)John et al., 1980). If the measures obtained from a subject fell within a statistically-determined band derived from a group of younger normal children, the EEG was deemed to represent a maturational lag. If the results fell outside these parameters, the EEG was viewed as a developmental deviation (John et al., 1983). From this analysis, Chabot and Serfontein (1996) concluded that their results represented a deviation from normal development, as the EEGs could not be considered normal in children of any age.

Clarke et al. (2001d), in replicating and extending their 1998 study, also included mean frequency measures from each of the traditional bands. Group differences in the patterning of frequency shifts led them to conclude that the data were not compatible with the maturational lag model, but instead pointed to a developmental deviation.

The atypical EEG coherence effects reported by Chabot's group and Barry et al. (2002) described earlier are difficult to interpret in the absence of clear age-norms for coherences between different brain regions, and point to the need for further developmental data in this area.

4.2.1. Hypoarousal model of AD/HD

While the studies cited immediately above proposed that AD/HD results from some form of developmental deviation, they have not defined this deviation. A model that can be classed under the term ‘developmental deviation’ is the hypoarousal model, which proposes that AD/HD results from cortical underarousal (Satterfield and Cantwell, 1974). This model is supported by electrodermal (Satterfield and Dawson, 1971), regional cerebral blood flow and positron emission tomography studies (Lou; Lou and Zametkin), which have found indications of cortical underarousal in this disorder. From EEG studies, a number of researchers have also found results which are consistent with a hypoarousal model (Satterfield; Satterfield; Satterfield and Grunewald). A specific link between increased theta and decreased beta activity in AD/HD has been noted in some studies (Lubar, 1991), while alpha activity remains at normal levels (Clarke and Clarke). Beta activity increases during both physical and mental activity (Andreassi; Ackerman and Ackerman), and children with ADHD have been found to have lower levels of beta activity during cognitive tasks (Lubar and Mann), which is consistent with the hypoarousal interpretation. This decrease in beta activity, or the sensory motor rhythm (12–14 Hz), which is at the lower end of the beta band, has been used in biofeedback training in this disorder (Lubar; Shouse; Lubar and Lubar). The hypoarousal model has also been used to explain the action of stimulant medications on children with AD/HD, with small doses of medication acting to increase arousal (e.g. Satterfield and Cantwell, 1974).

4.3. Limitations of the Maturational Lag and Developmental Deviation models of AD/HD

Both of these models fail to adequately explain results from behavioural studies of AD/HD. The hyperactive/impulsive behaviours found in children have been found to decrease with age (Kinsbourne, 1973), and this can be explained by a maturational lag model. As a child with AD/HD becomes older, the CNS matures to an age-appropriate level and a subsequent reduction in hyperactivity occurs. A major problem with the maturational lag model is that AD/HD is found in adults (Bellak and Black, 1992). Conceptually, it is not possible to have a maturational lag that persists into adulthood, and consequently this would have to be considered part of a more pervasive developmental deviation. Studies of adults with AD/HD have found that the gross motor activity of childhood diminishes with age, but the inattentive symptoms remain (APA, 1994). This change in behaviour cannot be explained adequately by either model.

Bresnahan and colleagues' EEG study (Bresnahan et al., 1999), covering children, adolescents and adults, concluded that the maturational model accommodated the behavioural hyperactivity and reduced beta activity noted in children and diminishing with age, while the inattention and elevated theta activity, which remained apparent in adults, evidenced a developmental deviation. The developmental AD/HD study by Clarke et al. (2001b) found compatible results, in that different aspects of the AD/HD EEG deviations from normal controls changed differently with age. Criticism of the models has also arisen from a combined EEG and ERP study (Callaway et al., 1983), which proposed that both explanations were too simplistic. These findings, together with problems arising from the different conclusions drawn by Clarke and Clarke, suggest that these models are too simple to adequately account for the symptom profile encountered in AD/HD, and that further model development is required.

4.4. EEG-defined subtypes of AD/HD

A limitation of most EEG studies is that they assume their clinical groups are homogenous. If this is not so, the reported group differences may not accurately reflect the nature of EEG deviance in individual children with AD/HD. Several studies have reported distinct EEG groups within their AD/HD samples. Clarke; Clarke and Clarke found between 15 and 20% of children with AD/HDcom had significantly elevated levels of beta activity in their EEG. This group was also found to have a behavioural profile slightly different from other children with AD/HDcom, with an increased rate of temper tantrums and moody behaviours. Chabot and Serfontein (1996), in their investigation of 407 children with a DSM-III (APA, 1980) diagnosis of ADD, found EEG subtypes: 38% had excess theta activity, 28% excess alpha activity, and 13% excess beta. Subtypes of children with ADD characterized by excess relative alpha and beta were also found in Chabot et al. (1999). These studies suggest that children with a diagnosis of AD/HD may constitute a heterogeneous group with different underlying electrophysiological abnormalities.

In a new approach, Clarke et al. (2001c) explored EEG-defined subtypes in a large sample (n=184) of boys with AD/HDcom. Comparison of the total sample with the control group found results similar to other studies described above: Children with AD/HD had increased theta and deficiencies of alpha and beta activity. Cluster analysis identified 3 distinct EEG-defined subtypes. One cluster had increased total power, relative theta and theta/beta ratio, and decreased relative delta and beta across all regions, considered indicative of cortical hypoarousal. Another was characterized by increased slow wave and deficiencies of fast wave activity, indicating a maturational lag in CNS development, although their theta levels were slightly higher than expected, suggesting an additional dysfunction. The third cluster had

excess beta activity, and was labelled an over-aroused group. In a follow-up study (Clarke et al., 2002c), a replication was conducted in children with AD/HDin (*n*=100), and identified two clusters. The first was characterized by reduced frontal relative delta and an increase in relative theta, with a reciprocal decrease in relative beta across the scalp. Alpha activity was at normal levels, suggesting a primary deficit associated with cortical hypoarousal. The second cluster had increased frontal and decreased posterior total power, increased centro-posterior relative delta, increased relative theta and decreased relative alpha across the scalp, and a decrease in fronto-central relative beta activity, indicative of a maturational lag. Comparison of the data from the two studies suggested that the clusters in the AD/HDcom group may have had some degree of cortical hypoarousal above those in the AD/HDin group.

From this research a new model of AD/HD was proposed (Clarke et al., 2002c), focusing on the underlying dysfunction rather than the behavioural profile. The model posits 3 distinct subtypes within the AD/HD diagnosis, largely independent of the DSM-IV diagnostic category. They consist of a cortical-hypoarousal subtype and a maturational-lag subtype, both of which are found in groups of children with either AD/HDcom or AD/HDin. A third EEG subtype, with excess beta activity, appears to occur in AD/HDcom, but not AD/HDin. From this model, novel hypotheses can be derived regarding the different medication responses and developmental pathways found within the population, but these have not yet been tested.

5. Future directions

In the context of the studies reviewed above, we briefly sketch future directions for research and development in the applications of EEG in the AD/HD field.

5.1. Types and subtypes

The research reviewed above has been constrained by the diagnostic criteria in effect at the time the research was carried out, and the types of AD/HD identified within the particular diagnostic system. In the present context, it is readily apparent that the DSM-IV types differ substantially in their EEG profiles. Thus it is imperative that studies should focus on identifiable types of AD/HD rather than using mixed diagnostic categories. Differences noted above support the independence of the combined and inattentive types of AD/HD, but nothing is currently known of the electrophysiology of the DSM-IV hyperactive/impulsive type, a group which appears to be missing from the current literature.

A useful approach is suggested by the reports of EEG-defined subtypes of AD/HD (Clarke and Clarke) which appear to cut across the DSM-IV types. Further investigations of these subtypes, in terms of their electrophysiological responding in a range of ERP paradigms, would appear promising, as they allow specific predictions to be made about the developmental time course of the disorder and medication responses.

5.2. Comorbidity

One of the major issues not adequately addressed to date is that of comorbidity, and its effects in determining or modulating the EEG outcomes discussed above. Isolated studies have reported studies with adequate control groups, but none appear to be optimal. Maximum information regarding the impact of some comorbid disorder (say X) in the AD/HD arena would require 4 experimental groups: AD/HD, AD/HD+X, normal controls, and X alone. Planned comparisons of such groups would allow the determination of effects due to AD/HD,

those due to X, and their interaction. Thus, although some studies have examined learning (or reading) disabilities (e.g. Ackerman; Ackerman and Clarke), ODD (Clarke et al., 2002a), and delinquency (Satterfield and Schell, 1984), the effects on EEG profiles of a range of other common comorbid conditions, particularly depression, anxiety, compulsive disorders and Tourettes, await parametric investigation.

5.3. Specificity

Another question which has not been fully addressed in the literature discussed above is that of the specificity of the EEG findings reported for AD/HD. That is, although a deviation from normal functioning might be associated with children, adolescents or adults with AD/HD versus normal age- and gender-matched controls, most studies have not addressed whether this deviation is specific to AD/HD. This requires the use of controls other than normal individuals. Bresnahan and Barry (2002), described in Section 3.2.2 above, appears to be the first to have addressed specificity issues in adult AD/HD patients. They found elevated theta to be AD/HD-specific within their comparison groups. Other fragmentary evidence exists because some studies have included inattentive or hyperactive individuals who did not meet full diagnostic criteria for AD/HD. Nevertheless, future research needs to actively pursue this question in a planned fashion. Perhaps this might be done most fruitfully in conjunction with comorbidity studies, as the optimal control group procedures outlined above can generate information useful in this regard.

5.4. EEG in diagnosis

At present, there is considerable concern regarding over-diagnosis and subsequent over-medication of children for this disorder, both in the scientific and popular press. One of the major problems with current diagnostic approaches is that they rely, almost exclusively, on the observations and perceptions of the child's parents, and (sometimes) their teachers. There are few objective assessment procedures available. Since AD/HD is considered to result from a CNS dysfunction, and EEG provides a direct measure of brain functioning, it appears to be an appropriate tool for assessing this disorder.

While the studies mentioned in Section 3.2.7 suggest that moderate classification accuracy can be achieved, we consider that the EEG has the potential to provide better group membership prediction, given the reliable patterns of group differences emerging from the literature considered above.

This approach to improving diagnosis has previously been criticized on the basis of poor sensitivity and specificity (Levy; Rey and Nuwer), and is not currently recommended for use in diagnosis by any major advisory body in the world. But it is clear from this review that robust group differences have now been identified, and that these provide a good foundation for individual subject classification (Binnie; Hoffman and Hughes). This objective approach to diagnosis has a number of advantages that warrant further development. Complementary findings in the ERP literature reviewed in the companion paper (Barry et al., 2003) suggest that if selected ERP data were used in concert with the EEG, we could expect improved classification accuracy. Clinically, the procedure is safe, non-invasive and relatively inexpensive in comparison to other imaging procedures. For these reasons, further research and development is warranted in the clinical use of EEG as a diagnostic tool in AD/HD.

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Corresponding author. Tel./fax: +61-2-4221-4421

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