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EEG-defined subtypes of children with attention-deficit/hyperactivity disorder

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Abstract

Objectives: This study investigated the presence of EEG clusters within a sample of children with the combined type of attention-deficit/hyperactivity disorder (ADHD).

Methods: Subjects consisted of 184 boys with ADHD and 40 age-matched controls. EEG was recorded from 21 sites during an eyes-closed resting condition and Fourier transformed to provide estimates for total power, and relative power in the delta, theta, alpha and beta bands, and for the theta/beta ratio. Factor analysis was used to group sites into 3 regions, covering frontal, central and posterior regions. These data were subjected to cluster analysis.

Results: Three distinct EEG clusters of children with ADHD were found. These were characterized by (a) increased slow wave activity and deficiencies of fast wave, (b) increased high amplitude theta with deficiencies of beta activity, and (c) an excess beta group.

Conclusions: These results indicate that children with ADHD do not constitute a homogenous group in EEG profile terms. This has important implications for studies of the utility of EEG in the diagnosis of ADHD. Efforts aimed at using EEG as a tool to discriminate ADHD children from normals must recognize the variability within the ADHD population if such a tool is to be valid and reliable in clinical practice.

Keywords: Attention-deficit/hyperactivity disorder; Children; EEG; Subtype; Diagnosis

1. Introduction

Attention-deficit/hyperactivity disorder (ADHD) is one of the most common disorders treated by child and adolescent psychiatrists in America, with this group of children comprising as much as 50% of child psychiatry clinic populations (Cantwell, 1996). Studies based on DSM-IV criteria (American Psychiatric Association, 1994) have found the prevalence of children with ADHD to range from 3 to 6% (Pelham et al., 1992; Lindgren et al., 1990), with the DSM-IV estimating prevalence at approximately 3–5% of school-age children. A major concern with this population is the level of subjectivity which is involved in diagnosis. At the present time, no reliable objective measures of ADHD exist. Diagnosis is almost always based on the observations and perceptions of the child's parents, which assumes that a parent has an accurate knowledge of what is normal age-appropriate behaviour.

EEG research over the last 30 years has found fairly consistent group differences between children with or without ADHD. These include increased theta activity (Satterfield et al., 1972; Janzen et al., 1995; Clarke et al., 1998, 2001b,c) which occurs primarily in the frontal regions (Mann et al., 1992; Chabot and Serfontein, 1996; Lazzaro et al., 1998), increased posterior delta (Matousek et al., 1984; Clarke et al., 1998, 2001b,c) and decreased alpha and beta activity (Dykman et al., 1982; Callaway et al., 1983), also most apparent in the posterior regions (Mann et al., 1992; Clarke et al., 1998, 2001b,c; Lazzaro et al., 1998). Increases in the theta/alpha (Matousek et al., 1984; Ucles and Lorente, 1996; Clarke et al., 1998, 2001b,c) and theta/beta (Lubar, 1991; Janzen et al., 1995; Clarke et al., 1998, 2001b,c) ratios have also been found in children with ADHD compared to normal children. Although detailed discussion is beyond the scope of this paper, these EEG differences may contribute substantially to the auditory and visual event-related potential differences which are reported from such children (e.g. Johnstone et al., 2001; Johnstone and Barry, 1996; Steger et al., 2000).

Following these studies, a number of researchers have investigated the utility of discriminant function analysis of

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such EEG measures in the diagnosis of ADHD (Lubar et al., 1985; Mann et al., 1992; Chabot and Serfontein, 1996; Chabot et al., 1999; Hughes and John, 1999; Hoffman et al., 1999). However, this procedure has been criticized on the basis of poor sensitivity and specificity (Levy and Ward, 1995; Rey, 1997; Nuwer, 1997).

One problem with the majority of these studies is that they have conceptualized their clinical groups as being homogenous, which may not be an accurate assumption. It is possible that the mean group differences reported may not accurately reflect the nature of the EEG deviance found in individual children with ADHD. Several studies have reported distinct EEG groups within their clinical samples. Clarke et al. (1998, 2001c,d) found between 15 and 20% of children with a diagnosis of ADHD combined type (ADHDcom) had significantly elevated levels of beta activity in their EEG. Chabot and Serfontein (1996) and Chabot et al. (1999) also reported the existence of distinct subsets of children with ADHD, separately characterized by excess theta, alpha and beta activity. These studies suggest that children with a diagnosis of ADHD may constitute a heterogeneous group with different underlying electrophysiological abnormalities.

This study aimed to investigate EEG similarities and differences within a group of boys with ADHDcom to determine whether their EEG profiles clustered into meaningful groups. Such clusters could form the basis for an EEG-defined subtyping of ADHD children and assist our understanding of brain dysfunction in the disorder.

2. Method

2.1. Subjects

Subjects in this study consisted of 184 children with a diagnosis of ADHDcom and 40 age-matched control subjects. All children were between the ages of 8 and 12 years and were right-handed and right-footed. Subjects had a full-scale Weschler Intelligence Scales for Children (WISC)-III IQ score of 85 or higher. The children with ADHD were drawn from new patients presenting at a Sydney-based paediatric practice for an assessment for ADHD. The clinical subjects had not been diagnosed as having ADHD previously, had no history of medication use for the disorder, and were tested before being prescribed any medication. All children between the ages of 8 and 12 years were invited to participate, with no patients refusing. All patients who presented to the practice over a 3 year period, and met the inclusion criteria, were used as subjects in this study. The control group consisted of children from local schools and community groups.

Inclusion in the ADHD group was based on clinical assessments by a paediatrician and a psychologist; children were included only where both agreed on the diagnosis. DSM-IV criteria were used and children were included only if they met the full diagnostic criteria for the diagnosis of ADHD, combined type, which includes hyperactive, inattentive and impulsive behaviours. A structured clinical interview was used which 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, assessment for neurological 'soft signs', review of school reports for the past 12 months seeking behavioural/learning problems, reports from any other health professionals, and behavioural observations during the assessment. Children were also assessed using the WISC-III, Neale Analysis of Reading and the Wide Range Achievement Test (WRAT-R) spelling test. The Conners' Rating Scale was also used (Conners, 1990). Children were excluded from the clinical groups if they had a history of a problematic prenatal, perinatal or neonatal period, a disorder of consciousness, a head injury with cerebral symptoms, a history of central nervous system 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 central nervous system diseases, obvious somatic diseases, convulsions, history of convulsive disorders, paroxysmal headache, enuresis or encopresis after the fourth birthday, tics, stuttering, pavor nocturnes or excessive nail-biting, obvious mental diseases, conduct disorders, and no deviation with regard to mental and physical development. Control subjects had to also score in the normal range on the measures of accuracy and comprehension on the Neale Analysis of Reading, and have a standard score of 90 or above on the WRAT-R spelling test. Assessment for inclusion as a control was based on a clinical interview with a parent or guardian similar to that of the ADHD subjects, utilizing the same sources of information, and the same psychometric assessment as was used for the clinical subjects.

Any children who showed signs of depression, anxiety, oppositional behaviour or syndromal disorders were excluded from this study. Children were also excluded if spike wave activity was present in the EEG.

2.2. Procedure

Both the ADHD and control subjects were tested in a single session lasting approximately 2.5 h. Subjects were first assessed by a paediatrician, where a physical examination was performed and a clinical history was taken. Subjects then had a psychometric assessment consisting of a WISC-III, Neale Analysis of Reading and WRAT-R (spelling). At the end of this assessment, subjects had an electrophysiological assessment consisting of a visual-auditory oddball evoked potential and an EEG. The EEG was recorded at the end of this session in an eyes-closed resting

condition, while subjects were seated on a reclining chair. Electrode placement was in accordance with the International 10–20 system, using an electrocap produced by Electrocap International. Activity in 21 derivations was recorded from Fp1, FP2, Fpz, F3, F4, F7, F8, Fz, C3, C4, Cz, T3, T4, T5, T6, P3, P4, Pz, O1, O2 and Oz. A single electrooculogram (EOG) electrode referenced to Fpz was placed beside the right eye and a ground lead was placed on the left cheek. A linked ear reference was used with all EEGs, and reference and ground leads were 9 mm tin disk electrodes. Impedance levels were set at less than 5 kΩ.

The EEG was recorded and Fourier transformed by a Cadwell Spectrum 32, software version 4.22, using test type EEG, montage Q-EEG. The sensitivity was set at 150 μV/cm, with a low frequency filter 0.53 Hz, a high frequency filter of 70 Hz and a 50 Hz notch filter. The sampling rate of the EEG was 200 Hz and the Fourier transformation used 2.5 s epochs.

Thirty 2.5 s epochs were selected from the live trace and stored to floppy disk. Epoch rejection was based on both visual and computer selection. Computer reject levels were set using a template recorded at the beginning of the session and all subsequent epochs were compared to this. The EOG rejection was set at 50 μV. The technician also visually appraised every epoch and decided to accept or reject it. These were further reduced by a second technician to 24 epochs (1 min) for Fourier analysis. The EEG was analyzed in 4 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), for relative power, as well as the total power of the EEG (1.5–25 Hz). The theta/beta ratio coefficient was also calculated by dividing the power in the theta band by the power in the beta band.

2.3. Statistical analysis

Initially, the data from the ADHDcom group were converted to *Z* scores based on the data from the control group. This gave comparable estimates of excesses or deficiencies of power for each frequency band at each site for each ADHD child compared to normal children.

Principal component analysis with varimax rotation was then performed on the *z*-transformed power estimates at the 21 electrode sites in each frequency band, in order to explore ways of reducing the number of variables by grouping sites into regions. Each EEG measure was then averaged in each region for further analysis. In the next stage, subjects were grouped with Ward's method of cluster analysis using the squared Euclidean distance as the measure of dissimilarity. The variables used in the cluster analysis were regional averages for total power and power in each of the 4 frequency bands, as well as the child's age (included in the analysis to control for maturational effects). Discriminant function analysis was performed on the subject clusters identified in the cluster analysis to determine the level of correct classification of subjects based on the EEG data.

Finally, independent sample *t* tests were used to compare the activity in each region for total power and power in each frequency band, as well as for the theta/beta ratio, between the subgroups and the control subjects (to determine how each group differed from the control subjects), and one-sample *t* tests between the ADHD cluster subgroups and the total ADHD group were used to determine the amount of variability within the ADHD group, using full-head topographic maps to assist in illustrating these differences.

3. Results

Principal component analysis identified two similar factors within each frequency band (see Table 1). The first factor primarily loaded on the frontal electrode sites and the second factor loaded on the posterior sites. However, there was a relatively high but inconsistent loading of the central sites and T3 and T4 on both factors. Rather than exclude these sites, it was decided to include them as a third regional grouping. The factor analysis thus suggested the grouping of scalp sites into 3 sagittal regions, frontal (Fp1, Fp2, Fpz, F3, F4, F7, F8, Fz), central (T3, T4, C3, C4, Cz), and posterior (T5, T6, P3, P4, Pz, O1, O2, Oz). There was no suggestion of any grouping in the lateral dimension. EEG measures were averaged across electrodes within each of these regions for further analysis.

The frontal, central and posterior regional means for total power, relative power in the delta, theta, alpha, and beta bands, and the age of the child were subjected to cluster analysis. This identified 3 main groups which accounted for 95.1% of the total variance. No significant differences in age were found between any of the ADHD clusters and the total ADHD sample, or between the total ADHD sample, ADHD clusters, and the control group.

Cluster 1 consisted of 42.3% of the sample of children with ADHD. Compared to control subjects, this cluster of children had increased total power, relative theta and theta/beta ratio, as well as decreased relative delta and beta across all regions (see Table 2 and Figs. 1 and 2). In comparison to the total sample of ADHD children, the group had increased relative alpha and decreased relative delta and beta activity across all regions, decreased posterior theta, and increased central and posterior total power. Cluster 2 contained 37.5% of the ADHD sample. These children had increased relative theta activity, increased theta/beta ratio, a decrease in relative alpha across all regions, decreased fronto-central beta activity, increased central/posterior delta, and a decrease in posterior total power, compared to the control group. In comparison to the total sample of children with ADHD, the group had increased slow wave activity (relative delta and theta), increased theta/beta ratio, decreased fast wave activity (relative alpha and beta), and decreased total power across all regions. Cluster 3 accounted for 20.2% of the sample. Compared to the control group, this cluster had an increase in relative beta, decreased relative alpha activity,

Table 1
Factor loadings are shown at each electrode site[a]

Site	Total power		Relative delta		Relative theta		Relative alpha		Relative beta	
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
Fp1	**0.848**	0.344	**0.902**	0.077	**0.893**	0.324	**0.899**	0.315	**0.882**	0.320
Fpz	**0.902**	0.338	**0.910**	0.282	**0.907**	0.324	**0.898**	0.373	**0.937**	0.274
Fp2	**0.858**	0.311	**0.888**	0.093	**0.883**	0.278	**0.893**	0.287	**0.892**	0.268
F7	**0.865**	0.335	**0.855**	0.227	**0.856**	0.366	**0.888**	0.346	**0.875**	0.322
F3	**0.900**	0.356	**0.874**	0.372	**0.890**	0.389	**0.890**	0.394	**0.937**	0.303
Fz	**0.876**	0.374	**0.866**	0.366	**0.886**	0.371	**0.876**	0.405	**0.936**	0.256
F4	**0.632**	0.181	**0.870**	0.337	**0.884**	0.373	**0.877**	0.408	**0.959**	0.235
F8	**0.879**	0.339	**0.853**	0.248	**0.835**	0.419	**0.867**	0.371	**0.898**	0.295
T3	*0.690*	0.525	*0.126*	0.122	*0.651*	0.510	*0.741*	0.478	0.578	*0.679*
C3	0.622	*0.687*	0.620	*0.644*	0.610	*0.656*	*0.683*	0.568	*0.783*	0.547
Cz	*0.664*	0.606	*0.628*	0.597	0.602	*0.660*	*0.672*	0.596	*0.783*	0.502
C4	*0.672*	0.654	*0.643*	0.628	0.609	*0.689*	*0.669*	0.601	*0.747*	0.577
T4	*0.727*	0.533	*0.660*	0.472	*0.636*	0.597	*0.709*	0.516	0.517	*0.634*
T5	0.457	**0.818**	0.421	**0.781**	0.441	**0.816**	0.480	**0.766**	0.360	**0.884**
P3	0.485	**0.789**	0.390	**0.847**	0.354	**0.894**	0.405	**0.848**	0.427	**0.869**
Pz	0.479	**0.743**	0.375	**0.846**	0.334	**0.881**	0.377	**0.850**	0.430	**0.849**
P4	0.470	**0.746**	0.356	**0.870**	0.335	**0.902**	0.438	**0.831**	0.379	**0.882**
T6	0.393	**0.746**	0.329	**0.844**	0.400	**0.821**	0.481	**0.761**	0.319	**0.893**
O1	0.235	**0.882**	0.146	**0.885**	0.289	**0.893**	0.291	**0.883**	0.174	**0.922**
Oz	0.192	**0.890**	0.125	**0.897**	0.317	**0.868**	0.307	**0.872**	0.204	**0.928**
O2	0.234	**0.882**	0.04	**0.903**	0.310	**0.878**	0.297	**0.882**	0.205	**0.930**

[a] Loadings in bold are consistent across measures with the top and bottom sections representing a frontal grouping (Factor 1) and a posterior grouping (Factor 2) in each measure, respectively. Loadings in italics are the largest for that measure, indicating the variability in segregation of the central sites in the two factors.

and a decreased theta/beta ratio across all sites, and increased total power and decreased relative delta in the frontal and central regions. In comparison to the total ADHD sample, these children had a general increase in relative beta activity, decreased relative theta activity, decreased theta/beta ratio, and decreased frontal and central relative delta.

The total sample of children with ADHD had a general

Table 2
Mean Z scores for each cluster and the total sample[a]

Region	Cluster 1 ($N = 78$)	Cluster 2 ($N = 69$)	Cluster 3 ($N = 37$)	Total ADHD group ($N = 184$)
Total power frontal	$1.693^{\uparrow con}$ ***	$0.383^{\downarrow ADHD}$ ***	$1.876^{\uparrow con}$ ***	$1.239^{\uparrow con}$ ***
Total power central	$0.915^{\uparrow con}$ ***, $^{\uparrow ADHD}$ *	$-0.149^{\downarrow ADHD}$ ***	$0.732^{\uparrow con}$ **	$0.479^{\uparrow con}$ **
Total power posterior	$0.768^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	$-0.580^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	0.142	0.136
Delta frontal	$-0.793^{\downarrow con}$ ***, $^{\downarrow ADHD}$ **	$0.203^{\uparrow ADHD}$ ***	$-1.046^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$-0.4705^{\downarrow con}$ *
Delta central	$-0.629^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$0.446^{\uparrow con}$ *, $^{\uparrow ADHD}$ ***	$-0.477^{\downarrow con}$ *, $^{\downarrow ADHD}$ *	-0.195
Delta posterior	$-0.326^{\downarrow con}$ *, $^{\downarrow ADHD}$ ***	$1.021^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	0.048	0.254
Theta frontal	$2.067^{\uparrow con}$ ***	$2.627^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	$-0.156^{\downarrow ADHD}$ ***	$1.830^{\uparrow con}$ ***
Theta central	$1.375^{\uparrow con}$ ***	$2.292^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	$0.045^{\downarrow ADHD}$ ***	$1.451^{\uparrow con}$ ***
Theta posterior	$0.766^{\uparrow con}$ **, $^{\downarrow ADHD}$ ***	$2.550^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	$0.343^{\downarrow ADHD}$ ***	$1.350^{\uparrow con}$ ***
Alpha frontal	$-0.174^{\uparrow ADHD}$ ***	$-1.292^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$-0.762^{\downarrow con}$ ***	$-0.711^{\downarrow con}$ ***
Alpha central	$-0.028^{\uparrow ADHD}$ ***	$-1.296^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$-0.455^{\downarrow con}$ *	$-0.589^{\downarrow con}$ ***
Alpha posterior	$-0.065^{\uparrow ADHD}$ ***	$-1.761^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$-0.564^{\downarrow con}$ **	$-0.801^{\downarrow con}$ ***
Beta frontal	$-0.591^{\downarrow con}$ **, $^{\downarrow ADHD}$ ***	$-0.488^{\downarrow con}$ *, $^{\downarrow ADHD}$ ***	$4.100^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	0.390
Beta central	$-0.733^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$-0.5873^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$2.247^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	-0.079
Beta posterior	$-0.812^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$-0.224^{\downarrow ADHD}$ **	$1.796^{\uparrow con}$ ***, $^{\uparrow ADHD}$ ***	-0.067
Theta/beta frontal	$2.994^{\uparrow con}$ ***	$2.742^{\uparrow con}$ ***	$-1.656^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$1.96^{\uparrow con}$ **
Theta/beta central	$1.956^{\uparrow con}$ ***	$1.988^{\uparrow con}$ ***	$-0.997^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$1.37^{\uparrow con}$ ***
Theta/beta posterior	$2.319^{\uparrow con}$ ***	$2.584^{\uparrow con}$ ***	$-0.516^{\downarrow con}$ ***, $^{\downarrow ADHD}$ ***	$1.84^{\uparrow con}$ ***

[a] Significant cluster differences from the total ADHD group and control group are indicated. ↑, increased power compared to; ↓, decreased power compared to; con, significant difference between the cluster group and the control group; ADHD, significant difference between the cluster group and the total ADHD sample; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$. For example, for total power in the frontal region, cluster 1 shows significantly ($P < 0.001$) increased activity relative to the control group.

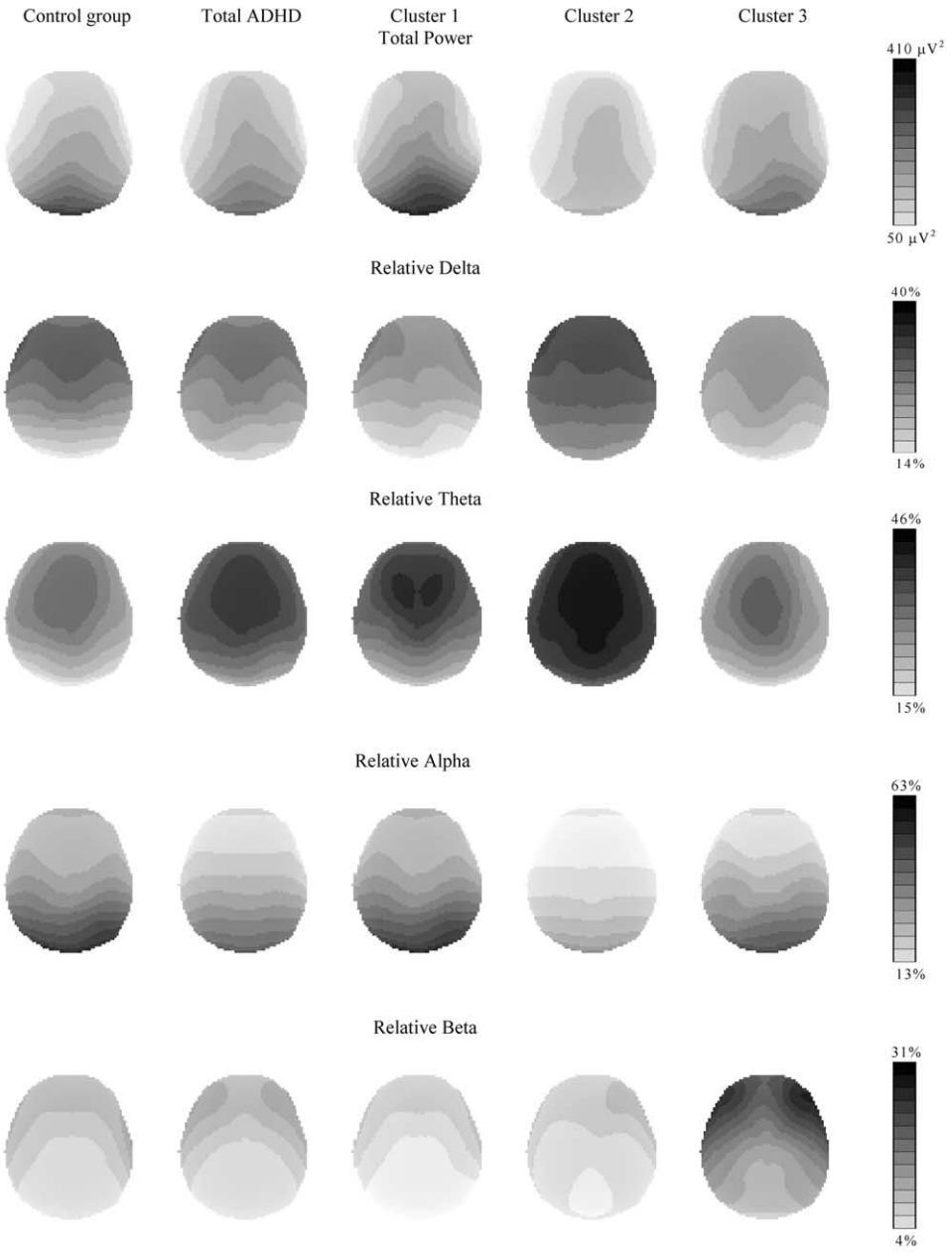

Fig. 1. Topographic group differences in total power and relative power.

increase in theta and decease in alpha activity, increased theta/beta ratio, decreased frontal delta and increased frontal and central total power relative to the control group.

The data set was also cluster analyzed using 4 and 5 clusters. The 4 cluster analysis split cluster 1, identifying a small subgroup (6% of the total sample) characterized by identical topography to the original cluster, except for more extreme EEG abnormalities in comparison to control subjects. The 5 cluster analysis resulted in the same groups as the 4 cluster analysis, except that another small subgroup (3.8% of the total sample) was split from cluster 3, again on the basis of the extremity of the EEG abnormality. As these two additional clusters contained only a small number of children, and had identical topographies to the larger clusters they were drawn from, the 3 cluster analysis was retained. Essentially, little additional information was gained by further subdivision.

4. Discussion

EEG studies of children with ADHD have typically found increased theta activity (Satterfield et al., 1972; Mann et al., 1992; Janzen et al., 1995; Chabot and Serfontein, 1996;

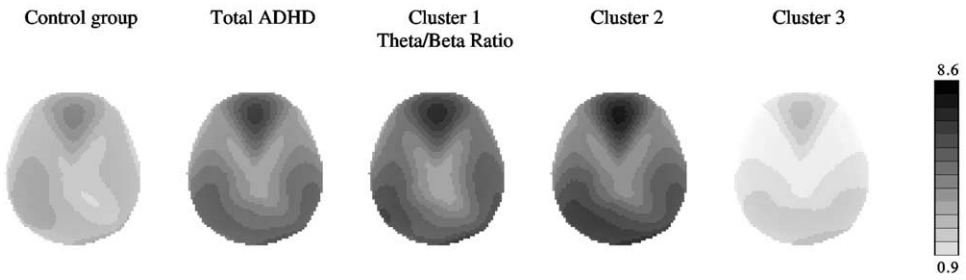

Fig. 2. Topographic group differences in theta/beta ratio coefficients.

Lazzaro et al., 1998; Clarke et al., 1998, 2001b,c), increased posterior delta (Matousek et al., 1984; Clarke et al., 1998, 2001b,c), decreased alpha and beta activity (Dykman et al., 1982; Callaway et al., 1983; Mann et al., 1992; Clarke et al., 1998, 2001b,c; Lazzaro et al., 1998), and an increase in the theta/beta ratio (Lubar, 1991; Janzen et al., 1995; Clarke et al., 1998, 2001b,c) compared to normal children. In the present study, the total sample of children with ADHD had a generalized increase in theta and decease in relative alpha activity, increased theta/beta ratio, decreased frontal delta and increased frontal and central total power. These results are typical of other studies that have presented group means. However, as can be seen from this study, group means may not accurately portray individual differences within the diagnosis. The cluster analysis identified 3 groups, with each cluster having components which were significantly different from the mean of the total sample. This indicates that the combined type of ADHD does not represent a homogenous group of children, as different electrophysiological components appear to be present in each of the 3 groups. These groups did not differ on age, so that simple maturational differences do not underlie this heterogeneity.

The DSM-IV lists criteria for ADHD based exclusively on behaviour, not on aetiology. This means that a number of different causes, which could be reflected in the different EEG profiles, may result in similar behaviours. It is important to note that all groups did have EEG profiles that were substantially different from the control group. This would suggest that although there may be different underlying causes for the obtained behaviour profiles, the disorder is based in central nervous system dysfunction.

Cluster analysis indicated the presence of 3 electrophysiologically distinct groups of children with ADHD of the combined type. The first two groups were highly consistent with the typical profile found in ADHD, with both groups having increased theta and decreased beta activity. However, the profiles of each group were different.

Cluster 1 had a predominance of high amplitude theta activity, particularly in the frontal regions, and reduced amounts of delta and beta activity. In this group, alpha activity was at a normal level. A specific link between power in the theta and beta bands has been found in other studies of ADHD, which is the basis for a number of researchers using calculations of the theta/beta ratio to differentiate ADHD and normal children, rather than separate frequency bands (Lubar, 1991; Janzen et al., 1995). Beta activity increases during both physical and mental activity (Andreassi, 1995; Ackerman et al., 1994, 1995), and a number of studies have found that children with ADHD have lower levels of beta activity during cognitive tasks (Lubar, 1991; Mann et al., 1992). This decrease in beta activity has been interpreted as cortical hypoarousal (Lubar, 1991), which is supported by studies that have assessed ADHD children using skin conductance (Satterfield and Dawson, 1971), as well as regional cerebral blood flow and positron emission tomography (Lou et al., 1984, 1989, 1990; Zametkin et al., 1990). From these results, cluster 1 appears to be associated with cortical hypoarousal.

Cluster 2 had increased slow wave activity in both the delta and theta bands, and reduced fast wave activity. While this cluster has some of the features of cluster 1 (increased theta and decreased beta), the EEG abnormality in this cluster has other features that are congruent with a maturational lag. Maximal differences were found between the cluster and the control group in the posterior regions in relative delta and alpha, and central regions in relative beta. The topography of these differences is typical of the results that would be obtained from normal younger children, with delta and alpha maturing earliest in the posterior regions and beta maturing earliest in the central regions (Gasser et al., 1983; Clarke et al., 2001a). However, the amount of theta activity in this group is slightly higher than would normally be expected in younger normal children. In a previous study (Clarke et al., 2001b) we found that there were two distinct components in the EEG of children with ADHDcom. The first was associated with the inattentive component of the diagnosis, which did not normalize with age. The second component was associated with the hyperactive/impulsive aspect of the diagnosis, which did mature with age. These two components appeared to overlay as additional levels of EEG abnormality, resulting in children with both components of the diagnosis having more abnormal EEGs than children with a single component. As the children in this study had both the hyperactive/impulsive and inattentive aspects of the disorder, it is possible that when the inattentive component of the EEG is taken into account, a maturational lag can still account for some of the EEG abnormality found in this group.

The third cluster was characterized by high power beta activity, with deficiencies in delta and alpha activity. Excess beta activity has been reported in other studies (Chabot and Serfontein, 1996; Clarke et al., 1998, 2001c,d) with prevalence rates of between 13 and 20% being reported. Clarke et al. (2001d) found that children in this group were more prone to temper tantrums compared to ADHD children with the more typical profile of excess theta activity. The present study found that 20.2% of the sample had this profile. The dominant beta band in this cluster has similar topography to the dominant theta band in cluster 1. This would suggest that similar systems are being identified in the two clusters but they are functioning in very different ways. If cluster 1 had a deficiency of beta activity, which is possibly associated with hypoarousal, then cluster 3 may be associated with cortical hyperarousal. Hyperarousal could easily cause the hyperactive and inattentive problems found in ADHD, which was what Satterfield and Dawson (1971) initially expected to find in their skin conductance study. This hypothesis needs to be tested.

Chabot and Serfontein (1996) and Chabot et al. (1999) reported that nearly one-third of their sample of ADD children had excess alpha activity. No children in the present sample were found to have this profile, and it has not been reported in other studies. This group may have resulted from some demand characteristic of their studies and needs further investigation in other independent samples.

The present results have important implications for the use of EEG in the diagnosis of ADHD. A number of studies have reported high sensitivity and specificity using EEG measures in discriminant function analyses (Lubar et al., 1985; Mann et al., 1992; Chabot and Serfontein, 1996; Chabot et al., 1999; Hughes and John, 1999; Hoffman et al., 1999). However, EEG measures of ADHD have been criticized on the grounds of showing poor sensitivity and specificity, and are not recommended for use in clinical practice (Levy and Ward, 1995; Rey, 1997; Nuwer, 1997). This is understandable if studies seek to identify ADHD individuals based on the assumption that all ADHD children will show the same EEG profile, an assumption falsified by our findings. The present results did indicate that all groups had EEG abnormalities, and as such, should be identifiable by an EEG assessment. For optimal sensitivity to be obtained, the present results suggest that any discriminant function analysis would need to accommodate more than one electrophysiological subtype of the disorder. This may mean that multiple discriminant functions should be applied to the same person. This would not be without precedent in medicine as many disorders have multiple subtypes which require independent testing for correct classification.

A second approach may be to find measures that are discrepant in all children with ADHD. The theta/beta ratio has been found to differentiate between children with and without ADHD (Lubar, 1991; Janzen et al., 1995; Clarke et al., 1998, 2001b,c). In this study, the theta/beta ratio was abnormal in all 3 of the ADHD clusters, although it was abnormally high in two and abnormally low in the third cluster (see Fig. 2). This may prove to be a useful marker of ADHD which can be used to identify cases from a single discriminant analysis.

In the initial stage of the data analysis, factor analysis was performed on the 21 electrode sites for each frequency band. Subsequently we chose to group the electrodes into 3 clusters, frontal, central and posterior. This has important implications for clinical use. Within research settings, there is an ever-increasing move towards the use of greater numbers of electrodes in data acquisition. In contrast to this, many clinicians are choosing to use relatively small units, with only 2, 4, or 8 recording channels. From the present results, a small number of channels would still provide the clinician with a substantial amount of information, and could be satisfactory for clinical use.

This study investigated the presence of EEG subtypes of children with the combined type of ADHD. Results indicated the presence of 3 distinct EEG-defined clusters of children, characterized by increased slow wave activity and deficiencies of fast wave, increased high amplitude theta with deficiencies of beta activity, and a beta-excess group. The identification of these groups has important implications for studies of the utility of EEG in the diagnosis of ADHD. Efforts aimed at developing EEG into a tool to identify individual ADHD children must recognize the variability within the ADHD population if such a tool is to be valid and reliable in clinical practice. These clusters may also have significantly different causes underlying their behaviour, may differ slightly on their behavioural profiles within the classification system, and may respond differentially to medication, possibilities which merit further investigation.

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References

Ackerman P, Dykman R, Oglesby D, Newton J. EEG power spectra of children with dyslexia, slow learners, and normally reading children with ADD during verbal processing. J Learning Disabil 1994;27:619–630.

Ackerman P, Dykman R, Oglesby D, Newton J. EEG power spectra of dysphonetic and nondysphonetic poor readers. Brain Lang 1995;49:140–152.

American Psychiatric Association. DSM-IV. Diagnostic and statistical manual of mental disorders, 4th ed. Washington, DC: American Psychiatric Association, 1994.

Andreassi J. Psychophysiology, human behavior and physiological response, 3rd ed. Hillsdale, NJ: Lawrence Erlbaum Associates, 1995.

Callaway E, Halliday R, Naylor H. Hyperactive children's event-related potentials fail to support underarousal and maturational-lag theories. Arch Gen Psychiatry 1983;40:1243–1248.

Cantwell D. Attention deficit disorder: a review of the past 10 years. J Am Acad Child Adolesc Psychiatry 1996;35:978–987.

Chabot R, Serfontein G. Quantitative electroencephalographic profiles of children with attention deficit disorder. Biol Psychiatry 1996;40:951–963.

Chabot R, Orgill A, Crawford G, Harris M, Serfontein G. Behavioural and electrophysiological predictors of treatment response to stimulants in children with attention disorders. J Child Neurol 1999;14:343–351.

Clarke A, Barry R, McCarthy R, Selikowitz M. EEG analysis in attention-deficit/hyperactivity disorder: a comparative study of two subtypes. Psychiatry Res 1998;81:19–29.

Clarke A, Barry R, McCarthy R, Selikowitz M. Age and sex effects in the EEG: development of the normal child. Clin Neurophysiol 2001a;112:806–814.

Clarke A, Barry R, McCarthy R, Selikowitz M. Age and sex effects in the EEG: differences in two subtypes of attention-deficit/hyperactivity disorder. Clin Neurophysiol 2001b;112:815–826.

Clarke A, Barry R, McCarthy R, Selikowitz M. EEG differences in two subtypes of attention-deficit/hyperactivity disorder. Psychophysiology 2001c;38:212–221.

Clarke A, Barry R, McCarthy R, Selikowitz M. Excess beta in children with attention-deficit/hyperactivity disorder: an atypical electrophysiological group. Psychiatry Res 2001d;103:205–218.

Conners C. Conners' rating scales manual, New York: Multi-Health Systems, 1990.

Dykman R, Holcomb P, Oglesby D, Ackerman P. Electrocortical frequencies in hyperactive, learning-disabled, mixed, and normal children. Biol Psychiatry 1982;17:675–685.

Gasser T, Mocks J, Bacher P. Topographic factor analysis of the EEG with applications to development and mental retardation. Electroenceph clin Neurophysiol 1983;55:445–463.

Hoffman D, Lubar J, Thatcher R, Sterman M, Rosenfeld P, Striefel S, Trudeau D, Stockdale S. Limitations of the American Academy of Neurology and American Clinical Neurophysiology Society paper on QEEG. J Neuropsychiatry Clin Neurosci 1999;11:401–407.

Hughes J, John E. Conventional and quantitative electroencephalography in psychiatry. J Neuropsychiatry Clin Neurosci 1999;11:190–208.

Janzen T, Graap K, Stephanson S, Marshall W, Fitzsimmons G. Differences in baseline EEG measures for ADD and normally achieving preadolescent males. Biofeedback Self-Regul 1995;20:65–82.

Johnstone S, Barry R. Auditory event-related potentials to a two-tone discrimination paradigm in attention deficit hyperactivity disorder. Psychiatry Res 1996;64:179–192.

Johnstone S, Barry R, Anderson J. Topographic distribution and developmental timecourse of auditory event-related potentials in two subtypes of attention-deficit hyperactivity disorder. Int J Psychophysiol 2001;42:73–94.

Lazzaro I, Gordon E, Whitmont S, Plahn M, Li W, Clarke S, Dosen A, Meares R. Quantified EEG activity in adolescent attention deficit hyperactivity disorder. Clin Electroenceph 1998;29:37–42.

Levy F, Ward P. Neurometrics, dynamic brain imaging and attention deficit hyperactivity disorder. J Paediatr Child Health 1995;31:279–283.

Lindgren S, Wolraich M, Stromquist A, Davis C, Milich R, Watson, D. Diagnostic heterogeneity in attention deficit hyperactivity disorder. Presented at the Fourth Annual NIMH International Research Conference on the Classification and Treatment of Mental Disorders in General Medical Settings, Bethesda, MD, 1990.

Lou H, Henriksen L, Bruhn P. Focal cerebral hypoperfusion and/or attention deficit disorder. Arch Neurol 1984;41:825–829.

Lou H, Henriksen L, Bruhn P, Borner H, Nielsen J. Striatal dysfunction in attention deficit and hyperkinetic disorder. Arch Neurol 1989;46:48–52.

Lou H, Henriksen L, Bruhn P. Focal cerebral dysfunction in developmental learning disabilities. Lancet 1990;335:8–11.

Lubar J. Discourse on the development of EEG diagnostics and biofeedback for attention-deficit/hyperactivity disorders. Biofeedback Self-Regul 1991;16:201–225.

Lubar J, Bianchini K, Calhoun W, Lambert E, Brody Z, Shabsin H. Spectral analysis of EEG differences between children with and without learning disabilities. J Learning Disabil 1985;18:403–408.

Mann C, Lubar J, Zimmerman A, Miller C, Muenchen R. Quantitative analysis of EEG in boys with attention deficit hyperactivity disorder: controlled study with clinical implications. Pediatr Neurol 1992;8:30–36.

Matousek M, Rasmussen P, Gilberg C. EEG frequency analysis in children with so-called minimal brain dysfunction and related disorders. Adv Biol Psychiatry 1984;15:102–108.

Nuwer M. Assessment of digital EEG, quantitative EEG and EEG brain mapping: report of the American Academy of Neurology and the American Clinical Neurology Society. Neurology 1997;49:277–292.

Pelham W, Gnagy E, Greenslade K, Milich R. Teacher ratings of DSM-III-R symptoms for the disruptive behaviour disorders. J Am Acad Child Adolesc Psychiatry 1992;31:210–218.

Rey J. Child and adolescent psychiatry. In: Beumont P, Andrews G, Boyce P, Carr V, editors. Psychological medicine: a companion guide to the management of mental disorders, Sydney: World Health Organisation Collaborating Centre for Mental Health and Substance Abuse, 1997.

Satterfield J, Dawson M. Electrodermal correlates of hyperactivity in children. Psychophysiology 1971;8:191–197.

Satterfield J, Cantwell D, Lesser M, Podosin R. Physiological studies of the hyperkinetic child: 1. Am J Psychiatry 1972;128:103–108.

Steger J, Imhof K, Steinhausen H, Brandeis D. Brain mapping of bilateral interactions in attention deficit hyperactivity disorder and control boys. Clin Neurophysiol 2000;111:1141–1156.

Ucles P, Lorente S. Electrophysiologic measures of delayed maturation in attention-deficit hyperactivity disorder. J Child Neurol 1996;11:155–156.

Zametkin A, Nordahl T, Gross M, King A, Semple W, Rumsey J, Hamburger S, Cohen R. Cerebral glucose metabolism in adults with hyperactivity of childhood onset. N Engl J Med 1990;323:1361–1366.