

The Development of a Quantitative Electroencephalographic Scanning Process for Attention Deficit–Hyperactivity Disorder: Reliability and Validity Studies

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The development of a quantitative electroencephalographic (QEEG)-based procedure for use in the assessment of attention deficit–hyperactivity disorder (ADHD) was examined through a series of studies investigating test reliability and validation issues. This process, involving a spectral analysis of the electrophysiological power output from a single, midline, central location (the vertex), was conducted in 469 participants, 6 to 20 years of age, classified as ADHD, inattentive type; ADHD, combined type; or control. The results indicated that the QEEG scanning procedure was reliable ($r = .96$), was consistent with the Attention Deficit Disorders Evaluation Scale (S. B. McCarney, 1995) and the Test of Variables of Attention (L. M. Greenberg, 1994; chi-square, $p < .01$), and differentiated participants with ADHD from a nonclinical control group ($p < .001$). The sensitivity of the QEEG-derived attentional index was 90%; the specificity was 94%.

The current *Diagnostic and Statistical Manual of Mental Disorders* (4th ed.; *DSM-IV*; American Psychiatric Association, 1994) defines attention deficit–hyperactivity disorder (ADHD) as a psychiatric disorder involving pervasive symptoms of inattention and/or hyperactivity–impulsivity, which are observed in 3%–5% of children prior to the age of 7. However, examination of the *DSM-IV* reveals that a number of other clinical conditions are also characterized by symptoms of inattention, impulsivity, or hyperactivity (e.g., learning disorders, conduct disorders, and affective disorders). Diagnostic issues are still further complicated by the high levels of comorbidity between ADHD and conduct disorder or affective disorders (Anderson, Williams, McGee, & Silva, 1987; Biederman, Faraone, Keenan, Steingard, & Tsuang, 1991; Biederman, Newcorn, & Sprich, 1991; Milberger, Biederman, Faraone, Murphy, & Tsuang,

1995). As a result of the symptom overlap between ADHD and other disorders, the question of the “existence” of ADHD has even been raised for debate by both the general public (e.g., Breggin, 1998) and the scientific community (Schrag & Divoky, 1975; Carey & McDevitt, 1995).

Much of the difficulty facing clinicians seeking to diagnose ADHD stems from the absence of any laboratory test specific for attentional disorders. As a result, mental health professionals have been encouraged to use an assessment strategy incorporating a detailed review of medical, developmental, social, family, and academic histories and the use of behavioral ratings provided by multiple observers (Barkley, 1990, 1998). However, as noted by Barkley (1990, 1998) and Cantwell (1996), data derived from interview and rating scales cannot be considered diagnostic for ADHD because of rater bias. Although recently developed neuropsychological measures of attention (e.g., continuous performance tests [CPTs]) provide a more objective measure of inattention and impulsivity (Conners, 1994; Greenberg, 1994; Gordon, 1983; Sanford, 1994), these tests tend to yield a high rate of false-negative errors (Barkley, 1998; Cantwell, 1996). Consequently, as noted by Kuperman, Johnson, Arndt, Lindgren, and Wolraich (1996), the development of a “biological measure” could “help to refine diagnostic criteria and may provide more specific diagnostic tests for ADHD and other disorders of attention and self-regulation” (p. 1009).

At this time, the development of laboratory procedures for use in the evaluation and clinical management of psychiatric patients is considered to be at the early stage. In their review of laboratory and diagnostic testing in child and adolescent psychiatry over the past 10 years, Zametkin,

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Ernst, and Silver (1998) concluded that "few controlled studies on the specificity and sensitivity of any laboratory test for any specific disorder of behavior presenting in children have been conducted in children and adolescents" (p. 464). As noted by Zametkin et al. (1998), efforts to develop a laboratory test for attentional disorders began to emerge during the past decade as neuroimaging and electrophysiological techniques identified physical characteristics that differentiate individuals with ADHD from same-age peers without attentional or other neurological disorders. Researchers using a variety of neuroimaging techniques have observed metabolic (Zametkin et al., 1990; Zametkin & Rapoport, 1987), circulatory (Amen, Paldi, & Thisted, 1993), and neuroanatomical (e.g., Casey et al., 1997; Hynd et al., 1993) differences between individuals diagnosed with ADHD and same-age peers without neurological impairment. As concluded by Casey et al., the results of these neuroimaging studies have provided substantial evidence of the importance of the frontostriatal circuitry in understanding the neurological basis of ADHD.

Quantitative electroencephalographic (QEEG) examinations of the prefrontal region and the frontal lobes have likewise revealed differences between individuals diagnosed with ADHD and their peers. Evidence of electrophysiological "slowing" in these areas has been consistently reported (Chabot, Merkin, Wood, Davenport, & Serfontein, 1996; Chabot & Serfontein, 1996; Janzen, Graap, Stephanson, Marshall, & Fitzsimmons, 1995; Mann, Lubar, Zimmerman, Miller, & Muenchen, 1992; Monastra et al., 1999), and initial evaluations of QEEG-based laboratory measures for ADHD have noted high rates of classification accuracy with test sensitivity and specificity rates greater than 87% (Chabot & Serfontein, 1996; Monastra et al., 1999). Because QEEG examinations are noninvasive and pose no risk for significant injury to the patient, further investigation of reliability and validity issues, as recommended by Zametkin et al. (1998), was considered to be a critical next step in the development of a laboratory measure for ADHD.

During the past decade, several research teams have reported a series of studies that have proceeded from the establishment of normative databases and examined electrophysiological differences between patients diagnosed with ADHD and normative samples. Chabot and his colleagues (Chabot et al., 1996; Chabot & Serfontein, 1996) demonstrated the ability of a discriminant function analysis of certain QEEG characteristics (e.g., absolute power, relative power, coherence between pairs of electrodes, and power asymmetry) to distinguish individuals with ADHD from nonclinical controls and patients with learning disabilities. In a similar manner, Lubar and his colleagues have reported QEEG findings that differentiated patients with ADHD both from a matched control group (Lubar, 1995; Mann et al., 1992) and from a more extensive normative database (Monastra et al., 1999). However, unlike the studies of Chabot and his colleagues, the studies reported by Mann et al., Lubar, and Monastra et al., used a simplified QEEG analysis, examining electrophysiological power and power ratios at specific cortical locations.

Initially, Mann et al. (1992) analyzed the electrophysiological power output from a 16-channel electroencephalograph (EEG) and noted that children with ADHD displayed significantly higher levels of frontal theta (i.e., 4–7.75 Hz recorded at F3 and F4) and lower levels of beta (12.75–21 Hz) posteriorly. Lubar (1995) and Lubar, Swartwood, Swartwood, and Timmerman (1996) next reported that a ratio comparing the power output in the theta versus beta frequency bands could be used to differentiate children with ADHD from a nonclinical control group, with the highest degree of differentiation noted at the vertex (Cz) and certain frontal locations (F3, F4). Consequently, based on this initial work, a normative study was conducted by Monastra et al. (1999) to develop a database for a simplified QEEG procedure that examined power ratios obtained from a single output. Because Lubar had reported that recordings from Cz could be used as a basis for differentiating patients with ADHD from a nonclinical control group, and the preparation of a patient for this type of a QEEG study required less time than the procedures used by Mann et al., Lubar, and Chabot et al. (1996), examination of a simplified procedure seemed warranted from both a clinical and cost perspective.

In the Monastra et al. (1999) study, 482 individuals ages 6 to 30 were examined via a single-channel QEEG procedure that monitored electrophysiological power in the theta (4–8 Hz) and beta (13–21 Hz) frequencies at the vertex (Cz). Participants were classified as ADHD, inattentive; ADHD, combined type; and control on the basis of a standardized interview, behavioral rating scales, and a CPT. Similar to the other QEEG studies, in this study recordings were obtained while participants were engaged in cognitive tasks (reading, listening, and drawing). The results indicated significant differences between the ADHD groups and the control group ($p < .01$). Test sensitivity was 86%, and specificity was 98%, which are comparable to the rates noted by Chabot and Serfontein (1996).

In summary, at least three independent research teams have reported that QEEG procedures can differentiate patients with ADHD from nonclinical control groups with high levels of sensitivity and specificity. However, the development of a laboratory test requires demonstration of test reliability and validity in both research and clinical applications. The purpose of this article is to present the results of a series of studies designed to replicate prior findings and examine the reliability and validity of the "neurometric" described by Monastra et al. (1999) in a controlled research application. The first experiment was a cross-validation study intended to replicate Monastra et al.'s initial study. The second experiment examined the criterion-related validity of the simplified QEEG process by comparing classification decisions based on electrophysiological data with those derived from interview data and review of patient history, behavioral rating scales, and neuropsychological measures of attentional deficits. The third experiment investigated the test-retest reliability of the attentional index derived from the QEEG process.

Experiment 1: Cross-Validation Study

Method

Participants. One hundred twenty-nine individuals, ages 6 to 20 (98 boys and 31 girls), were evaluated using a combination of a structured clinical interview, behavioral rating scales, CPTs, and a computerized power spectral analysis of QEEG recordings. All participants were screened by The Family Psychology Institute, a private outpatient psychological clinic located in a region of upstate New York with a population of approximately 500,000 within a 50-mile radius of the clinic. Physicians, schools, and mental health professionals located near the institute referred the individuals who participated in this study.

In order to establish clinical and control groups that were free of other neurological conditions that could affect attentional functions, parents or guardians completed Barkley's ADHD Clinic Parent Interview (Barkley & Murphy, 1998). This semistructured clinical interview format provides detailed information regarding medical, developmental, social, and academic history. Individuals diagnosed with other neurological disorders (e.g., epilepsy, autism, etc.) were not included in this study. In addition, all participants had been evaluated by their primary care physicians or pediatricians prior to their involvement in this study. None reported treatment for any medical condition that has been associated with attentional deficits.

Because of the potential for confounding effects of psychotropic medication on QEEG findings, none of the members of the control group were evaluated while using any medication. In order to control for medication effects in our ADHD sample, none of the participants in this study had a history of stimulant therapy. Evaluations were conducted between the hours of 9 a.m. and 3 p.m.

Classification of individuals into clinical and nonclinical groups was identical to that reported by Monastera et al. (1999). Initially, participants were interviewed using Barkley's ADHD Clinic Parent Interview in order to determine if the individual had been diagnosed with any medical condition associated with impairment of neurological functioning. Subsequent screening included parental completion of the Attention Deficit Disorders Evaluation Scale (ADDES; McCarney, 1995) and participant completion of the Test of Variables of Attention (TOVA), a CPT developed by Greenberg (1994). The ADDES is a behavioral rating scale assessing both the type and frequency of inattentive and hyperactive-impulsive symptoms of ADHD. The TOVA was incorporated into the research design in order to provide a performance measure of attentional skills and capacity for impulse control.

Because of our intent to reduce initial classification errors, participants had to meet *DSM-IV* criteria for ADHD based on the report of the referral source and test positive for ADHD on both behavioral and CPT measures in order to be placed into one of the clinical groups. Members of the nonclinical control group were individuals who had been determined by their physician to have no medical or psychiatric disorders that could cause attentional deficits. Those participants who served as the nonclinical control group also needed to test negative for attentional deficit disorder on the behavioral and CPT measures. The specific criteria for group placement were as follows.

For the ADHD, inattentive type, group, the criteria were (a) met *DSM-IV* criteria according to a referring source (physician, school); (b) met *DSM-IV* criteria according to caretaker report on the Barkley ADHD Clinic Parent Interview; (c) obtained a positive score for inattention on the ADDES and scored in the nonclinical range for impulsivity and hyperactivity; (d) obtained a positive overall rating for ADHD on the TOVA; and (e) did not meet

DSM-IV criteria for any other type of psychiatric disorder according to caretaker report on the Barkley ADHD Clinic Parent Interview.

For the ADHD, hyperactive-combined type, group, the criteria were (a) same as Item a above for ADHD, inattentive type, group; (b) same as Item b above for ADHD, inattentive type, group; (c) obtained a positive score for Impulsivity or Hyperactivity on the ADDES; (d) same as Item d above for ADHD, inattentive type, group; and (e) same as Item e above for ADHD, inattentive type, group.

For the nonclinical control group, the criteria were (a) did not meet *DSM-IV* criteria for any psychiatric disorder based on caretaker report on the Barkley ADHD Clinic Parent Interview; (b) caretaker scores on the ADDES were in the nonclinical range for inattention, impulsivity, and hyperactivity; and (c) TOVA overall rating was negative for ADHD.

Because this study was designed as a cross-validation of the Monastera et al. (1999) study, none of the participants in Experiment 1 participated in any of our prior investigations. Similarly, none of these participants were included for data analysis in Experiment 2 or 3. Distribution of participants by age and diagnosis is presented in Table 1.

Materials. Power spectral analysis was conducted on QEEG recordings that were obtained using an Autogenics A-620 EEG with associated Assessment Software (Wood Dale, IL). This system provides researchers with a computerized analysis of EEG recordings in multiple frequency bands. For the purpose of this study, 4–8 Hz was defined as the theta band, and 13–21 Hz was defined as the beta band. As in our prior research, multiple short periods (90 s) of digitized EEG were obtained. A fast Fourier transformation algorithm was computed by the A-620 Assessment Software on the electrophysiological data. The overall electrophysiological power (in picowatts) was computed for the theta and beta bands by the Assessment System. Subsequently, a ratio (calculated by dividing the power noted within the theta band by that noted in the beta band) was computed for each condition. The average of the theta-beta power ratios was calculated over the four conditions. The resultant attention index was manually entered into the Statistica (StatSoft, 1995) statistical program for data analysis and graphic presentation.

Procedure. The QEEG procedure used in collecting data was as follows. First, the vertex (Cz) was located using the International 10-20 System of electrode placement (Andreassi, 1989).

Second, the area was cleaned using Omni prep and isopropyl alcohol. A small amount of conductive paste (Ten20) was applied to the scalp and to a Grass Gold Disc Electrode with hole (E5GH) and the sensor was attached to the scalp. A similar procedure was used for cleaning and preparing the earlobes, and one pair of Gold Disc Electrodes in Ear Clip (Grass E34 D) was attached to each

Table 1
Distribution of Participants by Age and Diagnosis

Diagnosis	Age (in years)			Total
	6–11	12–15	16–20	
ADHD-I	16	7	14	37
ADHD-H/C	42	14	3	59
Control	7	11	15	33
Total	65	32	32	129

Note. ADHD-I = attention deficit-hyperactivity disorder, inattentive type; ADHD-H/C = attention deficit-hyperactivity disorder, hyperactive-combined type.

earlobe. In order to assure quality of preparation, impedance and offset potential of the sensors were assessed via an Autogenics Electrode Tester. Impedance readings were to be below 10 k Ω . Offset potential was to be below 10 μ V before recordings were obtained.

Third, band frequencies were defined on the Assessment Software as follows: theta, 4–8 Hz; beta, 13–21 Hz. Once the sensors were tested and the band frequencies defined, the participant's EEG activity at Cz was recorded during the following tasks.

1. Eyes fixed–baseline: The participant was seated in front of the computer monitor display and instructed to focus his or her gaze on the monitor's on–off indicator light. EEG recordings were obtained for 90 s. Subsequently, the EEG record was visually inspected in 2-s intervals (*epochs*) in order to filter out epochs containing eye blinks–rolls. In addition, an electromyograph (EMG) channel on the A-620 monitored muscular activity and was used to screen excessive movement artifact. A minimum of 15 low-artifact epochs (i.e., no evidence of eye blinks–rolls and overall EMG output below 15 μ V) was required for completion of this task.

2. Silent reading: The next 90-s task was reading. Material that was consistent with the participant's reading ability was selected from the Kaufman Test of Educational Achievement (Kaufman & Kaufman, 1985) and read silently by the participant. After completion of this task, the EEG was reviewed in 2-s intervals to eliminate epochs with excessive EMG artifact. A minimum of 15 low-artifact epochs was required for completion of this task.

3. Listening: A 90-s listening task occurred next. Age-appropriate material was selected and read by the clinician (as described for Task 2). EEG review was conducted as described previously.

4. Drawing: A stable drawing surface was placed in front of the participant. He or she was instructed to copy geometric figures from the Benton Visual Retention Test (Benton, 1955). EEG was recorded for 90 s and reviewed for artifact.

Results

To test the hypothesis that significantly higher theta–beta power ratios would be obtained in the QEEG recordings of participants identified with ADHD, we obtained the power ratios for individual participants during completion of the four experimental tasks. A summary of the mean theta–beta power ratios is presented by age and diagnosis in Table 2. Initial visual inspection of the power ratio data revealed a pattern suggestive of both maturational and diagnostic effects.

The attentional indices for all participants were then transferred to StatSoft's (1995) Statistica program for sta-

tistical analysis and graphic presentation of data. The planned statistical analysis consisted of an analysis of variance (ANOVA) design. Between-subjects comparisons were made to examine the effects of diagnosis, age, and sex on the theta–beta power ratio. Within-subjects comparisons were made to examine task effects (as a repeated measure). Tukey's honestly significant difference test was used for analysis of significant main or interaction effects. An alpha level of .01 was used as a minimum level of significance for all statistical tests.

A summary of the ANOVA of all effects is presented in Table 3. As anticipated, statistical analysis indicated that the magnitude of the theta–beta power ratio was significantly affected by both the age and the diagnosis of participants ($p < .001$). There was no indication that the attention index was affected by the sex of the participant and no evidence that the effects of age and diagnosis were moderated by the sex of the participant. Within-subjects comparisons also revealed a significant effect of type of task on the resultant power ratios ($p < .01$). No significant interaction effects were noted.

As illustrated in Figure 1, post hoc examination of the main effects indicated that both the ADHD, inattentive type, and ADHD, hyperactive–combined type, groups could be differentiated from the control group on each of the four tasks ($p < .001$ on each task), regardless of age. However, no statistical differentiation between the two clinical groups was noted on any of the tasks. Although graphic depiction is suggestive of greater cortical slowing in the ADHD, hyperactive–combined type group at ages 12–15 (compared with same-age peers diagnosed with ADHD, inattentive type), statistically significant differences were not obtained ($p < .08$). Examination of task effects revealed that significantly higher power ratios were observed during the drawing task compared with all other tasks ($p < .001$).

The results of this cross-validation study were consistent with previous findings (Monastra et al., 1999) and indicated that participants with either inattentive or hyperactive–combined types of ADHD exhibit significantly higher theta–beta power ratios than peers without any psychiatric or developmental disorders. However, in order to assess the validity of the QEEG-based attention index (derived from the mean theta–beta power ratio across four tasks for each participant) in evaluating a specific patient for ADHD, a comparison between classification based on the attention index and that based on clinical interview, the ADDES, and the TOVA was needed for each participant.

Classification of QEEG scores as positive or negative for ADHD was made as follows. First, an attention index (the average theta–beta power ratio across four tasks) was calculated for each participant. Next, this index score was compared with the normative database developed by Monastra et al. (1999). If an individual's score was greater than 1.5 standard deviations above the average obtained by their same-age peers without ADHD in the normative sample, then the participant's test score was considered positive for ADHD. Otherwise, the score was considered negative for ADHD. The critical values (i.e., 1.5 standard deviations

Table 2
Mean Theta–Beta Power Ratios

Age (in years)	Diagnosis		
	ADHD-I	ADHD-H/C	Control
6–11	6.78	6.63	2.67
12–15	3.80	5.55	1.97
16–20	3.32	3.65	1.70

Note. ADHD-I = attention deficit–hyperactivity disorder, inattentive type; ADHD-H/C = attention deficit–hyperactivity disorder, hyperactive–combined type.

Table 3
Summary of All Analysis of Variance Effects

Effect	df 1	df 2	F
Age	2	111	10.06**
Sex	1	111	1.90
Diagnosis	2	111	21.66**
Task	3	333	3.91*
Age × Sex	2	111	0.19
Age × Diagnosis	4	111	1.31
Age × Task	6	333	0.77
Sex × Diagnosis	2	111	0.18
Sex × Task	3	333	0.95
Diagnosis × Task	6	333	0.64
Age × Sex × Diagnosis	4	111	0.06
Age × Sex × Task	6	333	0.08
Age × Diagnosis × Task	12	333	0.48
Sex × Diagnosis × Task	6	333	0.59
Age × Sex × Diagnosis × Task	12	333	0.66

* $p < .009$. ** $p < .001$.

above the age-peer mean) derived from the initial normative study were 5.03 (ages 6–11), 3.31 (ages 12–15), and 2.36 (ages 16–20).

Using these critical values, the attention index for each participant was rated as positive or negative for ADHD. Subsequently, this rating was compared with the participant's initial classification, which was based on a behavioral rating scale (ADDES) and a neuropsychological measure of attention (TOVA). The results of this comparison indicated that 90% of the participants originally classified with ADHD scored positive for ADHD on the QEEG-based test

and 94% of the participants from the control group scored negative for ADHD. Overall, the positive predictive power of the QEEG-derived attention index was 98%; the negative predictive power was 76%.

Experiment 2: Criterion-Related Validation Study

Method

Participants. Two hundred eighty-five individuals, ages 6 to 20 (boy:girl ratio = 3:1), participated in this study conducted for the purpose of comparing classification agreement between the computerized power spectral analysis of QEEG (described in Experiment 1) and other commercially available tests that have been developed to assess attentional deficits (e.g., behavioral and CPT measures). Such comparisons are considered useful in examining the validity of any new assessment procedure. All participants were screened at The Family Psychology Institute. Physicians, schools, and mental health professionals located near the institute referred the individuals who participated in this experiment. As noted, none of the participants had been evaluated in either the initial validation study (Monastra et al., 1999) or in Experiment 1 or 3 of this investigation.

The participants in this study had all been diagnosed with ADHD by their pediatricians or primary care physicians based on a clinical interview and review of history. Similarly, all participants were being treated with Ritalin or methylphenidate. None of the participants were being treated with "sustained release" types of stimulant therapy. As in Experiment 1, individuals diagnosed with other medical or psychiatric conditions that could cause attentional deficits were not included in this study. Because of the well-documented report of stimulant treatment on the results of

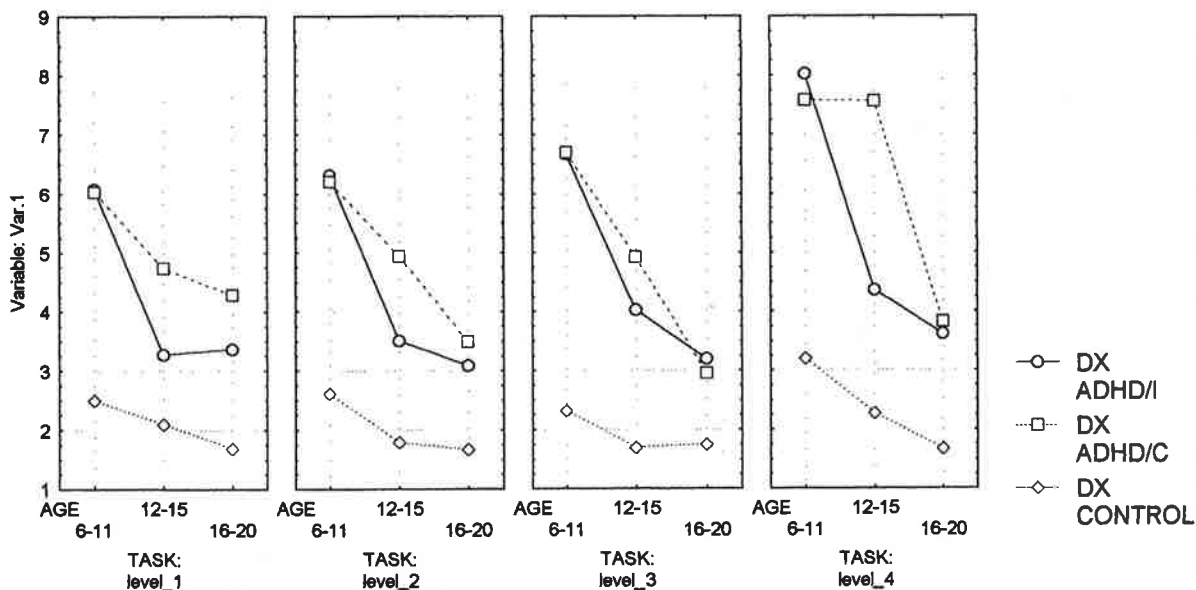


Figure 1. Plot of the mean theta-beta power ratios (unweighted) for the three-way interaction, Age (years) × Diagnosis × Task, during eyes-fixed baseline (Task 1), reading (Task 2), listening (Task 3), and drawing (Task 4) conditions, $F(12, 333) = 0.48$, $p < .9280$. Var. = variable; DX = diagnosis; ADHD/I = attention deficit-hyperactivity disorder, inattentive type; ADHD/C = attention deficit-hyperactivity disorder, hyperactive-combined type.

CPTs (Swanson, McBurnett, Christian, & Wigal, 1995), evaluations were conducted after a medication-free period of at least 24 hr.

Materials. Power spectral analysis was conducted using the Autogenics A-620 EEG and the Assessment Software developed by Autogenics as described in Experiment 1. The ADDES and Conners's (1994) CPT were administered to 100 participants. The ADDES and TOVA were administered to an additional 185 individuals. Classification as ADHD or non-ADHD on each procedure was made based on the recommendations of the test developer for each testing procedure. The computerized interpretation provided after completion of each CPT was used for the two CPTs. As recommended by McCarney (1995), a standard score of 6 or lower on either of the ADDES subscales was considered supportive of a classification of ADHD on the behavioral measure. An attention index indicating a degree of cortical slowing 1.5 standard deviations greater than that of same-age peers on the QEEG procedure (Monastra et al., 1999) served as the basis for classification derived from power spectral analysis. Statistical analysis of the frequency of classification agreement (using a chi-square test) was completed using the Statistica program.

Procedure. Each participant and his or her parents or guardians participated in two testing sessions conducted 1 week apart. Evaluations were conducted between 9 a.m. and 3 p.m. During the first session, parents completed the ADHD Clinic Parent Interview and the ADDES. The participants were tested using either Conners's (1994) CPT or the TOVA. In the second session, all participants were evaluated using a QEEG procedure described in Experiment 1. As noted previously, all participants were evaluated after a medication-free period of 24 hr. Classification of test scores as supportive of a diagnosis of ADHD were made based on guidelines established by each of the respective test developers.

Results

Examination of the degree of classification agreement between the results of the QEEG analysis and behavioral and CPT measures was conducted using a chi-square test. Classification agreement was noted in 83% of the participants evaluated with the QEEG scanning process and the ADDES, $\chi^2(1, N = 285) = 14.70, p < .001$, and in 70% of the participants examined with the QEEG procedure and the TOVA, $\chi^2(1, N = 285) = 5.81, p < .01$. These findings provided evidence of what is considered criterion-related validation as the QEEG scanning procedure yielded test results that were consistent with those obtained from other procedures used in assessing patients with attentional deficits.

Such classification consistency was not obtained when QEEG results were compared with those derived from Conners's (1994) CPT (agreement in only 48%), $\chi^2(1, N = 100) = 0.50, p < .48$. However, because a similar low degree of agreement was noted in comparisons between the diagnostic decisions derived from the ADDES and Conners's CPT (percentage agreement = 44%), $\chi^2(1, N = 100) = 0.28, p < .60$, current findings appear consistent with previous research questioning the validity of certain of the CPTs in the assessment process for ADHD (summarized by Barkley, 1990), as well as Golden's (1996) report of a 57% predictive accuracy rating using the Conners's CPT.

Because all of the participants in this experiment had been diagnosed with ADHD, issues of test sensitivity and specificity could only be partially addressed. However, the classification accuracy of each procedure (i.e., the rate of agreement between each assessment instrument and the initial physician diagnosis) was examined. The test sensitivity of the various procedures was as follows: Conners's CPT = 49%, TOVA = 72%, ADDES = 78%, and QEEG scan = 80%. Conversely, the false-negative error rate of each of these procedures was as follows: Conners's CPT = 51%, TOVA = 28%, ADDES = 22%, and QEEG scan = 20%. Although the absence of a "gold standard" for diagnosing ADHD makes it difficult to adequately address issues of test sensitivity and specificity, the findings of this experiment indicate that the results of the QEEG scan were consistent with those derived from two instruments commonly used in the assessment of patients with attentional deficits.

Experiment 3: Test Reliability Study

Method

Participants. Fifty-five individuals, ages 6 to 20 (50 boys and 5 girls), were evaluated in this study. All evaluations were conducted at The Family Psychology Institute. As in Experiment 1, participants were referred for screening for ADHD by their pediatrician or primary care physician. None of the participants had been diagnosed with any other medical condition known to cause impaired attention. At the time of the test sessions, none of the participants were being treated with any pharmaceutical product known to influence attentional functions.

All of the individuals participating in this study were classified with either ADHD, inattentive type ($n = 20$), or ADHD, combined type ($n = 35$), using the procedure described in Experiment 1. Essentially, the process requires a clinical history consistent with a diagnosis of ADHD, as well as scores more than 1.5 standard deviations above those of same-age peers on a behavioral rating scale (the ADDES), on a CPT (the TOVA), and on a QEEG scanning process (Monastra et al., 1999). Only participants classified with ADHD were included because the purpose of the third study was to determine if the attention index derived from the QEEG was a reliable electrophysiological measure of cortical slowing in patients diagnosed with ADHD.

Materials. Barkley's ADHD Clinic Parent Interview and McCarney's ADDES were completed by parents or guardians. The TOVA was administered as a neuropsychological measure for attentional deficit. An Autogenics A-620 EEG with associated Assessment Software was used to obtain and analyze EEG recordings. The Statistica software program was used for data analysis.

Procedure. Participants were evaluated during three sessions. At the first session, parents or guardians completed the ADDES and were interviewed using the Barkley ADHD Clinic Parent Interview. The TOVA was administered to all participants. If the results of both the ADDES and the TOVA were positive for ADHD (using criteria established by the test developers), and patient history was consistent with a diagnosis of ADHD, then the participant was evaluated using the QEEG process described in Experiment 1 during a second session conducted 1 week later. Each participant was then retested using the QEEG process during

a third session conducted 1 month after the initial QEEG evaluation. All evaluations were conducted between 9 a.m. and 3 p.m. without use of any medications.

Results

Statistical analysis of the test-retest reliability of the QEEG-derived attention index was conducted. As noted previously, the attention index was calculated as follows. First, a power spectral analysis was conducted on EEG data obtained via a monopolar montage (ear reference) at the vertex. Next, the electrophysiological power (in picowatts) recorded in the theta band (4–8 Hz) was divided by the power recorded in the beta band (13–21 Hz). This analysis was conducted on EEG recordings obtained during four conditions (eyes fixed–baseline, silent reading, listening, and drawing). The average theta–beta ratio over these four tasks constituted the attention index. The test-retest correlation coefficient, based on an analysis of QEEG data obtained from individuals with ADHD tested on two occasions, 30 days apart, was .96 ($p < .05$). These findings provide an initial indication that the QEEG scanning procedure used in this study yields consistent results in patients diagnosed with ADHD.

Discussion

An examination of the simplified QEEG scanning process for use in the assessment of patients with ADHD (Monastra et al., 1999) was conducted using research procedures developed to examine test validity and reliability. The principal findings were as follows. First, groups of participants with either inattentive or combined types of ADHD could be differentiated from nonclinical control groups on the basis of the attention index derived from a spectral analysis of power in the theta and beta bands. Second, application of the critical values derived from Monastra et al.'s (1999) original study could be used to classify individual participants into ADHD or non-ADHD groups with a high degree of test sensitivity and specificity. Third, comparison of classification as ADHD or non-ADHD on the basis of history and clinical interview, behavioral rating scale (ADDES), neuropsychological test (TOVA), and an electrophysiological (QEEG) screening process revealed significant levels of consistency among the four procedures. Finally, analysis of the test-retest reliability of the attention index indicated that the results of the QEEG scan are stable across time.

The results of the current investigation constitute a replication of the Monastra et al. (1999) study and show a pattern of electrophysiological slowing in ADHD patients that is consistent with prior QEEG (Chabot & Serfontein, 1996; Mann et al., 1992) and neuroimaging studies (Amen et al., 1993; Casey et al., 1997). However, it is important to stress that our examination of the QEEG scanning process developed by Monastra et al. was a well-controlled research application. Our studies were designed to examine electrophysiological characteristics of patients with ADHD while

minimizing the potential confounding influences of physical or psychiatric conditions that could cause symptoms of inattention, impulsivity, or hyperactivity.

Examination of our research design reveals that in order to reduce initial classification errors based on interview data alone, participants in Experiments 1 and 3 were classified as ADHD or non-ADHD on the basis of a screening process that required not only physician diagnosis (based on history and clinical interview) but also impaired performance on a CPT and evidence of a significantly high frequency of ADHD behaviors on a behavioral rating scale. Conversely, participants in the control groups did not display evidence of impairment on any of the psychometric measures nor did they meet *DSM-IV* criteria for ADHD. Furthermore, to reduce confounding due to other psychiatric disorders, none of our participants exhibited a sufficient number of symptoms to meet criteria for any other *DSM-IV* disorder. Although such experimental control was considered necessary in order to complete this stage of our research program, additional research is needed in order to assess the application of our findings in clinical settings.

Because ADHD occurs comorbidly with other psychiatric conditions (Biederman et al., 1991; Milberger, Biederman, Faraone, Murphy, & Tsuang, 1995), examination of the sensitivity and specificity of the QEEG scan in studies involving patients with ADHD and comorbid conditions, as well as patients with psychiatric disorders other than ADHD, is needed. At a minimum, validation of the QEEG scanning process will require multiple clinical settings in which individuals with a variety of psychiatric disorders (including ADHD) are evaluated. To minimize experimenter bias, analysis of the recorded QEEG data should be conducted by investigators who are naive to the patient's diagnosis. Such a study seems required prior to acceptance of this procedure as a laboratory test for ADHD.

In addition to constituting a replication of Monastra et al.'s (1999) study, the QEEG data obtained in our three studies provide an electrophysiological perspective relevant for examining issues of subtype. Spectral analysis of QEEG findings indicated that two of the primary types of ADHD (i.e., inattentive and combined types) are predominately characterized by electrophysiological indicators of cortical slowing. However, differentiation of subtype was not evident in the QEEG scanning process used in this study. Because the *DSM-IV* criteria for ADHD, inattentive type and ADHD, combined type require the presence of inattention in both of these subtypes, the presence of cortical slowing at the vertex in both groups was consistent with expectations. However, clear differences exist in the degree of behavioral inhibition exhibited by these two subgroups, which were not reflected in the type of QEEG analysis conducted in this study. Consequently, systematic QEEG examination of cortical regions associated with motor control (e.g., investigations of the sensorimotor rhythm recorded over the motor cortex at C3, Cz, or C4) may assist in developing a neurophysiological perspective on the factors that differentiate these subtypes.

Finally, in the present study approximately 10% of the participants diagnosed with ADHD by their physicians failed to demonstrate evidence of cortical slowing at the vertex. This finding is similar to the results of Monastra et al.'s (1999) initial study and is consistent with Chabot and Serfontein's (1996) report of electrophysiological "subtypes" of ADHD. Essentially, the results of our current investigation, as well as the findings of Monastra et al. and Chabot and Serfontein, suggest that although evidence of cortical slowing at the vertex and over frontal cortical sites is commonly noted during QEEG examination of patients with ADHD, it is not found in all patients with ADHD. A pattern of "hyperarousal" in the frontal region has been suggested as a secondary neurological subtype found in patients with ADHD (Chabot & Serfontein, 1996). Because a significant percentage of patients with ADHD (ranging from 20% to 50%) do not respond positively to cortical stimulants (Barkley, 1998), we question whether "nonresponders" will exhibit a pattern of cortical slowing. Consequently, additional QEEG studies examining the relationship between cortical slowing and stimulant responsivity are planned.

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