A comparative study of ERP correlates of psychometric and Piagetian intelligence measures in normal and hyperactive children

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Summary   Verbal and performance scores of the Wechsler Intelligence Scale for Children-Revised (WISC-R 1981) and of a Piagetian battery, the Cognitive Development Scale for Children (EDC 1984), were obtained on 30 normal control and 19 hyperactive 6–8-year-old children. Amplitudes and latencies of a fronto-central P250 and of the parieto-occipital N250, P350 and P500 were measured concurrently in 4 categorization tasks derived from tests of the WISC-R and EDC batteries. Spearman correlations were computed between the intelligence and the ERP factor scores. Results showed that age-related and age-corrected Wechsler's scores were correlated with similar ERP changes (reduced amplitude, decreased latency). With regard to the amplitude changes, each type of intelligence was associated with a specific ERP pattern. The verbal scores were correlated with the P350 and the P500 amplitudes, and the performance scores with the frontal P250 and occipital N250 amplitudes. By contrast, Piagetian development and intelligence scores yielded ERP correlates in the opposite direction: P500 amplitude was negatively correlated with raw EDC scores, but positively with scaled EDC scores. In addition, Piagetian intelligence was not related to the general peak latency decrease with age. In hyperactive children, additional negative correlations were found between P250 amplitude and the subjects' verbal test scores. Correlations with some performance tests that were negative in normal controls, were positive in hyperactive children. In addition, latency-based correlations found in normal controls were lacking in hyperactive children. These findings provide strong evidence that intelligence comprises different components related to different subsets of cognitive processes, as indexed by different ERP waves. They also suggest that the development and intelligence do not always rely on the same changes, and that intelligence forms may not be referred to the same use of the same processes in hyperactive and normal children.

Keywords: Intelligence; Event-related potentials; Cognitive development

1. Introduction

Intelligence models used in psychophysiological research can be divided into 2 groups: low- and high-level, respectively. Low-level models propose that intelligence is determined by biological characteristics of the brain (e.g., processing speed, error rate in the coding and transmission) that influence all cognitive operations. In contrast, in high-level models, different forms of intelligence are distinguished, each being related to specific subsets of cognitive processes. Intelligence differences are then determined by the functional characteristics of these subsets.

Most evoked potential (EP) studies on intelligence refer to low-level models. Evoked potentials were supposedly knowledge-free and provided the "pure brain activity" that represents the "biological basis" of intelligence. EP measures were thus correlated with intelligence test scores. In a study involving 573 children (from 8 to 14 years of age), significant negative correlations (ranging from -0.18 to -0.35) were obtained by Ertl and Schafer (1969) between the latencies of the first 4 peaks of visual EPs and the Wechsler IQs. These authors proposed that the latencies of the first early waves of the EP provide a measure of the brain's processing speed which would be critical for intelligence, an idea that had been already suggested by

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Galton (1883) and Cattell (1890). Several subsequent studies have confirmed these findings (Schucard and Horn 1972; Callaway 1973), while others failed (Davis 1971; Engel and Henderson 1973). In addition, the size of these latency-based correlations was comparable to that yielded by other low-level cognitive measures and thus was not a very convincing "biological basis" of intelligence.

However, much more impressive correlations were found by other investigators who were examining changes in the form of evoked potentials. By measuring the length of the contour of the wave form during the first 250 msec (as if a piece of string was placed around the trace), correlations as high as 0.35 were obtained. Furthermore, in highly selected subjects, these correlations were found to be in the order of 0.7–0.8 (Blinkhorn and Hendrickson 1982). The rationale behind the string measure is that higher intelligence is a result of a low error rate in the coding and transmission of information in the brain. As a consequence of this low error rate, early EP waves were expected to be more complex because the different epochs included in the average had stable peaks and troughs. Therefore, higher IQs should be manifested by more complex EP wave forms. However, contradictory results were obtained by Vetterly and Furedy (1985) when re-evaluating the data of Blinkhorn and Hendrickson (1982). Haier et al. (1983) found smaller correlations (ranging from 0.13 to 0.50), while more recently Vögel et al. (1987) failed to observe a consistent relationship between the complexity of visual EPs and intelligence.

In all these studies supporting low-level models of intelligence, the main assumption is that EPs may be used as direct indicators of various aspects of neural functioning. Faithful synapse transmission, for example, is supposedly indexed by the global form of early EP waves. However, evoked potentials are clearly complex phenomena, determined by factors as different as interactions between multiple sources to distortions due to different conductive properties going from brain generators to the scalp. Therefore the prediction of intelligence test scores by evoked potential measures appears at best speculative until the exact relationships between neural activities and EP measures are better known.

High-level models are just starting to be used in brain studies on intelligence. In such high-level models, each form of intelligence is determined by the functional characteristics of a specific subset of cognitive processes. Event-related potentials (ERP) waves have been used as markers of different cognitive processes. The first aim of the present study was thus to determine the composition of the related subset by identifying the ERP waves that change according to different intelligence measures. This search was restricted to how three different forms of intelligence (verbal,

visuo-spatial, piagetian) modify the use of the cognitive processes elicited in standard oddball tasks. Oddball tasks have been used because the processes underlying the different ERP peaks recorded in theses tasks have been indeed extensively studied. However, one could again object that relating complex aspects of cognition to ERP waves also has its inherent risks until the functional interpretation of these waves can be firmly established. Taking this criticism into account, the first goal of the present study was primarily to compare the subsets of ERP correlates (if any) yielded by different types of intelligence (verbal, performance, Piagetian) batteries. Two different views of intelligence, unitary or componential, can be tested. If different ERP peaks are correlated with different forms of intelligence, the unitary concept of intelligence would be challenged. In contrast, if the different forms of intelligence are found to have the same brain correlates, then the concept of general intelligence may not be questioned on a physiological basis. Moreover, these two models do not have to be mutually exclusive. In a second step, some aspects of functional significance of the ERP correlates could be addressed, but based on a post-hoc interpretation.

The second issue addressed in the present study was to investigate the difference between development and intelligence. "Intelligence" tests provide two types of scores: raw scores that assess development and scaled scores that assess intelligence. Raw scores are yielded by the number of items of a test a child is able to perform, weighted by the response quality and speed. They are strongly related to age. Scaled scores are obtained by comparing each subject's raw score in one test (or in a group of tests for IQ score) exclusively with those obtained by individuals in his(her) own age group. Scaled scores are thus age-free and reflect the relative advance (or delay) of a child as compared with individuals of his(her) age group. Therefore, only scaled scores are usually considered as "intelligence" measures.

ERPs certainly also have a developmental (age-related) component (Courchesne 1978; Kurtzberg et al. 1979; Taylor 1988). Some studies reported age-related changes in ERP wave forms that were interpreted to reflect a change in the processing mode. However, within a relatively short age range, and using oddball-type paradigms, age-related changes represent continuous decreases in latency and amplitude, without any change in wave forms. The basic assumption of this study is that ERPs also have an intelligence (age-free) component. However, for ERP data, we do not have a large reference population that would allow us to compare each subject's scores exclusively with those of his(her) exact age group, as we do have for intelligence data. Nevertheless, even if the exact ERP age corrections are not known, it is possible to determine if a cognitive process (as marked by an ERP peak) is re-

lated in the same way to developmental and to intelligence measures by comparing the correlations yielded by the raw scores with those yielded by the scaled scores. If the two correlations are significantly different, intelligence differences and development differences may not be viewed as being related to the same change of the same process.

The third issue of this study focuses on the assumption that intelligence is based on the same use of cognitive processes for all individuals. This assumption is usually taken for granted: a specific test is assumed to provide a measure of a specific type of processing in any individual. However, processes that could be related to intelligence might be abnormal in children with developmental disorders. For example, in a previous study (Robaey et al. 1992), children with attention deficits (diagnosed as Attention Deficit Hyperactivity Disorder) have been shown to exhibit larger frontal P2 to rare deviants, as compared with normal attentive children. Hyperactive children also showed a smaller increase of occipital N2 amplitudes to words as compared to pictures. In addition, parieto-occipital P3 was smaller in the hyperactive group than in the normal control group (Robaey et al. 1992). If some intelligence forms were found to be specifically related to these ERP waves (P2, N2, P3) that differentiated normal control from hyperactive children, it would be of interest to compare the ERP-intelligence correlations yielded by each group (normal control and ADHD). If these correlations are different in each group, these forms of intelligence may not be viewed as related to

the same use of the same process in any subject. The relevance of this issue is emphasized by the fact that in clinics, intelligence tests are mainly used on children with developmental disabilities whose results are compared with age pairs from a normal reference population.

2. Methods

Subjects

Forty-nine subjects aged 6 years 1 month to 8 years 11 months participated in the experiment. The control group, consisting of 15 girls and 15 boys (mean age: 7 years 7 months; S.D.: 10.6 months), was recruited from public schools by letters sent to their parents. The ADHD group (mean age: 7 years 5 months; S.D.: 9.6 months) consisted of 19 children (17 boys and 2 girls) referred by the Department of Child and Adolescent Psychiatry of the Robert Debré Hospital. Subjects were drug naive before and during selection, during evaluation as well as during all laboratory testing. Diagnosis of ADHD was made by a group of psychiatrists trained to use the DSM III-R (1987) criteria. Scores from the Conners Parent Rating Scale-Revised (CPRS-R; Goyette et al. 1978) and the Conners Teacher Rating Scale (CTRS-R; Goyette et al. 1978) were obtained on all children. Individuals with other disruptive behavior disorders (Conduct Disorder and Oppositional Defiant Disorder) and specific developmental disorders were excluded from the ADHD group. All subjects were
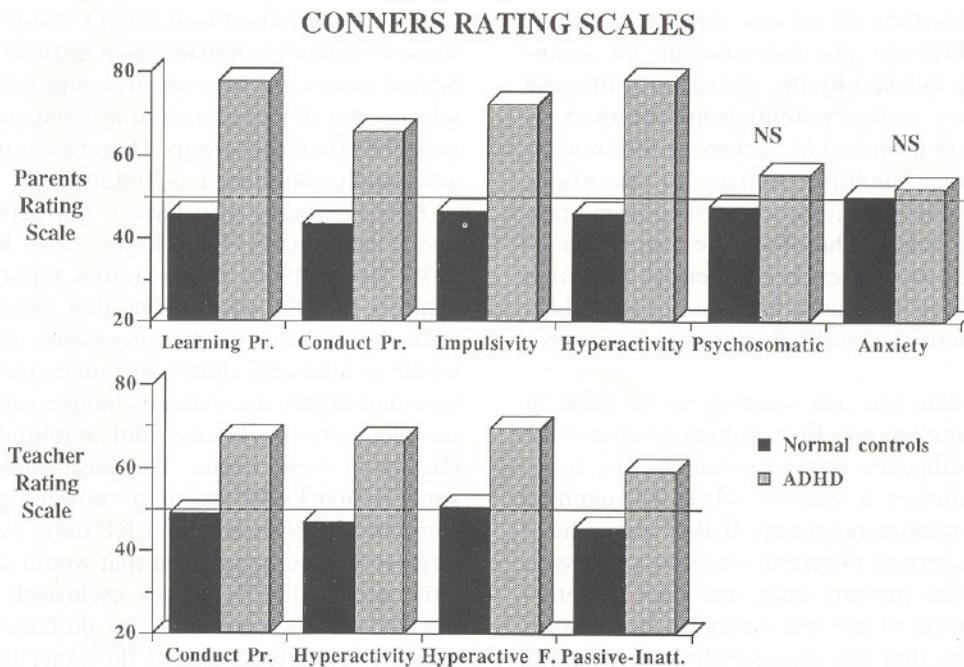
CONNERS RATING SCALES

Fig. 1. Parent's and teacher's rating scaled scores obtained in ADHD and normal control subjects (mean = 50, S.D. = 10). The ADHD children were severely hyperactive.

French-speaking, attending school, and had normal or corrected to normal vision.

Attentive behavior (Fig. 1)

The Conners Rating Scales consist of items (48 items for the parents and 28 items for the teacher's version respectively) enabling them to indicate the degree to which each item of behavior is exhibited. From the items of these scales, factor scores (Hyperactive, Learning problem, Conduct problem, Anxiety, Impulsive, Passive-inattentive, Psychosomatic) could be obtained, with a mean of 50 and an S.D. of 10. According to their teachers and parents, all control subjects exhibited normal attentive behavior, with mean scores around 50 and S.D. below 10 for all factors. In contrast, ADHD children obtained scores above 70 for Learning problems, Hyperactivity and Impulsivity. All factor scores were significantly higher ($P < 0.05$) in the ADHD group than in the control group, except for Psychosomatic (mean: 56) and Anxiety scores (mean: 52) which were in the normal range.

Manual dominance

Manual dominance was evaluated by a test derived from that of Annet (1970). It was considered homogeneous if 10 or more items (in a list of 12) were performed with the same hand. Among the 30 normal control subjects, 26 were right-handed (22 homogeneously) and 4 were homogeneously left-handed. Among the 19 ADHD subjects, 18 were right-handed (15 homogeneously) and 1 was homogeneously left-handed.

Psychometric data (Fig. 2)

The Wechsler Intelligence Scale for Children-Revised (WISC-R 1981) was obtained for all children. The WISC-R consists of 5 verbal tests and 5 performance tests. The French reference population consisted of 1066 subjects divided into 11 age groups of 1 year interval, ranging from 6 to 16 years of age.

A battery of 4 Piagetian tests (Cognitive Development Scale for Children; Chevrie-Muller et al. 1984) were also performed by all children. The EDC assesses operational stages in a Piagetian framework for children ranging from 5 to 8 years of age. The first two tasks are simple conservation tasks. The first task is a token classification task adapted from a task first described by Piaget and Inhelder (1959) and by Inhelder et al. (1974, p. 342–343). The second task is a stick seriation task, very similar to that described by Inhelder et al. (1974, p. 345–346). The last two tasks are complex conservation tasks. The third task is a substance conservation task identical to that proposed by Piaget and Inhelder (1959) and described by Inhelder et al. (1974, p. 336–338). The fourth task is a length conservation task described by Piaget et al. (1949) and
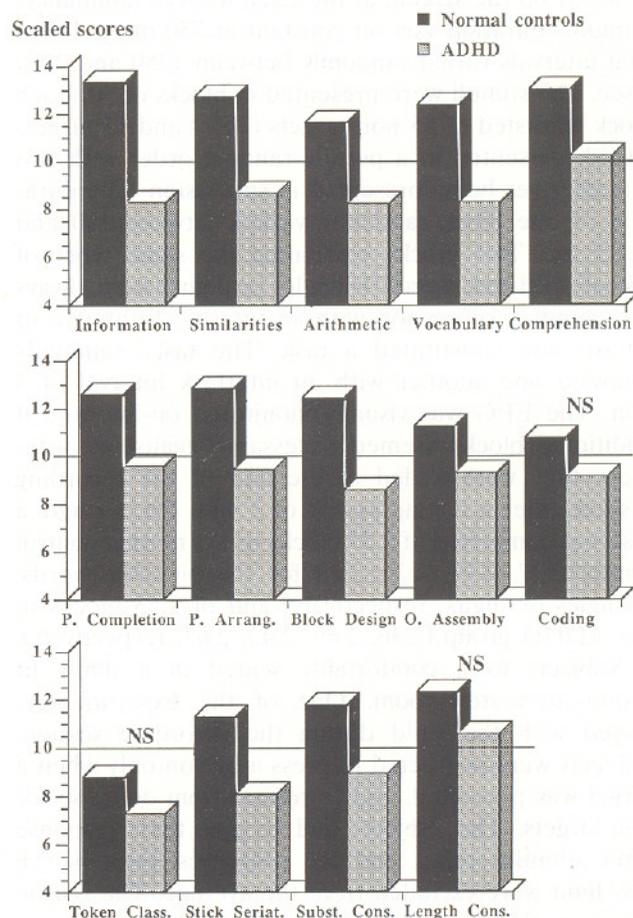
INTELLIGENCE TESTS

Fig. 2. Scaled scores (mean = 10, S.D. = 3) yielded by the ADHD and the normal control children for the 5 verbal and the 5 non-verbal tests of the WISC-R and the 4 conservation tests of the Piagetian battery. Results were significantly lower in the hyperactive group for all tests, except Coding, Token Classification and Length Conservation.

by Inhelder et al. (1974, p. 340–342). The score of each task might be referenced relative to published age norms, in 1 year intervals (Chevrie-Muller et al. 1984).

Each composite scale (verbal, performance, conservation) yields a scaled IQ. By definition, scaled IQs are referenced to published age norms and have a mean value of 100 and an S.D. of 15. In the control group, the mean scaled IQs were about 1 S.D. above the mean (ranging from 111 to 116). In contrast, the ADHD subjects were nearly 1 S.D. below the mean, around 93. Within these composite scales, all subtests scaled scores were significantly lower ($P < 0.05$) in the ADHD group than in the control group, except for those obtained for the Coding (WISC-R), Token Classification (CDE) and Length Conservation (CDE).

Procedure

The child was seated 1.5 m from a viewing screen, so that the angle subtended by the stimulus was 7.5°. All

stimuli were black and white slides that were presented centrally on the screen, at the same level of luminance. Stimulus duration was set constant at 750 msec. Intertrial intervals varied randomly between 1750 and 2250 msec. The stimuli were presented in blocks of 50. Each block consisted of 35 non-targets (70%) and 15 targets (30%), presented in a pseudo-random order with two targets never being presented in succession. The duration of one block randomly varied between 100 and 112.5 sec. Two blocks containing the same types of stimuli (pictures, words, triangles or digits) were always presented in succession with an interblock interval of 30 sec and constituted a task. The tasks randomly followed one another with an intertask interval of 3 min. The EEG was visually monitored on-line and if additional blocks seemed necessary because of artefacts, they were added at the end of the recording session, after a resting period of 3 min. On average, a task was comprised of 2.27 blocks in the normal control group (2.27, 2.17, 2.27, 2.30 for the pictures, words, triangles or digits, respectively) and of 2.53 blocks in the ADHD group (2.36. 2.69, 2.42, 2.63, respectively).

Subjects were comfortably seated in a dimly lit sound-attenuated room. One of the experimenters stayed with the child during the recording session. Subjects were instructed to press a button only when a target was presented, and to refrain from doing so for non-targets. The subjects had to give their response after stimulus offset and the responses given before this limit were excluded from the average. The reason for giving this instruction was to allow sufficient time to process completely the relevant information. Under time pressure, different levels of processing would have been reached by hyperactive and control children, that would have reflected differences in strategic control, but not the processing level that the subject can potentially reach. However, as a consequence, delayed reaction times were not informative about the stimulus processing and were not analyzed.

ERP tasks

Four categorization tasks were performed by each child. Two tasks were classification tasks and two were seriation tasks. In the first classification task, the stimuli were pictures representing 4 different pairs of fruits (apple/cherry, grapes/banana, cherry/grapes, banana/apple) or a fruit and something else (turtle/apple, cherry/fowl). The subjects were asked to press a button whenever "something else than a fruit appeared." In the second classification task, the stimuli were words, printed in capital letters which represented the same items as the pictures. The response instructions were the same as for the pictures. In these classification tasks, the position of the target in the pairs of items was random. In the first seriation task, 3 triangles of different sizes were simultaneously pre-

sented. For the non-targets, the triangles were ordered according to their increasing or decreasing size. For targets, the 3 triangles were randomly ordered (2 targets were used). Subjects were instructed to respond whenever "the triangles were not ordered according to their size." In the second seriation task, 3 regularly increasing digits (2 3 4 or 4 5 6) were simultaneously presented. The subjects were instructed to respond to any change in the series; two targets were used (2 3 6 or 4 5 2). Tasks 1–4 were randomly ordered for each subject.

Recording technique

Fourteen Beckman electrodes were affixed with collodion on the scalp along two longitudinal lines, one on the left hemisphere and one on the right hemisphere. They were placed (F4, C4, P4, O2; F3, C3, P3, O1) according to the 10–20 international system (Jasper 1958), with additional electrodes half-way between these standard locations (Fc4, Cp4, Po2; Fc3, Cp3, Po1). The electro-oculogram (EOG) was recorded by two Beckman electrodes taped to the supra- and infraorbital ridges. All electrodes, including EOG electrodes, were referenced to linked ears. The subject was grounded by a cheek electrode. EOG and EEG were digitized on-line at a rate of 125 Hz by a PDP 11-73 computer over an epoch spanning 200 msec pre- and 750 msec post-stimulus onset. Epochs involving saturation of amplifiers were automatically excluded. Those recordings contaminated by artefacts (eyeblinks, other ocular activities) were excluded from further analysis after off-line visual inspection of the EOG. If a response occurred before stimulus offset (whatever the stimulus), the EEG epoch was also excluded. Skin impedance for all electrodes was below 10 kΩ. The EEG was recorded with a bandpass down 3 dB at 0.08 Hz and 40 Hz and the EOG was recorded with a bandpass of 3.2–40 Hz. For a trial to be taken into account, the subject had to press the button after stimulus offset, and the corresponding EEG epoch had to be free of artefacts.

ERP measurements

For each type of stimulus, separate averages were computed for the correct responses to targets and for the correct responses to non-targets. After artefact rejection, the number of epochs (Appendix I) included in non-target averages and in target averages did not differ significantly according to age and tasks, except for the number of hits in the word classification task that increased with age (F $(2–43) = 4.16$; $P < 0.02$). However, hyperactive childrens' ERPs included significantly fewer ($-26%$) stimuli than those of controls (F $(1–47) = 10.29$; $P < 0.005$). However, this drop in ERP did not differ for targets and non-targets, nor did it vary with age.
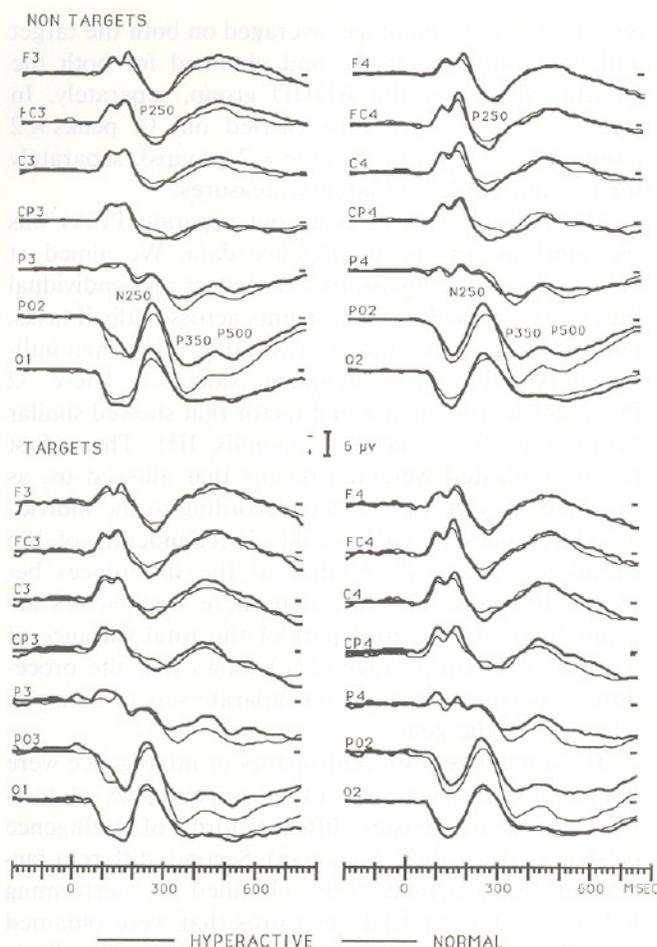
Fig. 3. Grand ERP averages obtained for target and non-target stimuli across the 4 tasks, in the normal control group and in the ADHD group. Usual ERP components were found (P250, N250, P350, P500) and measured.

ERP waves were identified on the basis of each subject's grand averages. Fronto-central ERPs were substantially different in morphology from parieto-occipital ERPs (Fig. 3). For the frontal regions, a positivity peaking at 250 msec (P250) was preceded by an early negative wave at 150 msec and followed by a durable negative wave at 450 msec. For the parieto-occipital regions, a negative wave at 250 msec (N250) was preceded by a positivity at 150 msec and followed by two positive waves, the first at 350 (P350) and the second at 500 (P500). These two positivities were even seen in single trial epochs. In addition, P350 latency was found smaller in hyperactive children, but no difference was found for P500 latency (Robaey et al. 1992). These two peaks are thus likely to index functionally different processes. There are little differences between target and non-target wave forms, although late posterior positivities (P350 and P500) were larger to targets. This is often found in children performing a relatively complex categorization task. Such a task differs from selective attention paradigms in which non-

targets are irrelevant stimuli that have to be neglected. In the oddball tasks we used, non-targets should not be viewed as requiring a different processing, but more likely as demanding less processing capacity than targets. This has already been emphasized by Klorman et al. (1988) in pharmacological studies with ADHD children.

Peak amplitude was first automatically measured relative to the 200 msec prestimulus baseline, and peak latency relative to stimulus onset. P250 amplitude was measured as the maximum voltage from 150 to 400 msec post stimulus among the 3 anterior electrodes, either on the left montage (F3, Fc3, C3) or on the right montage (F4, Fc4, C4). Among the 4 posterior electrodes, either on the left (Cp3, P3, Po1, O1) or on the right montage (Cp4, P4, Po2, O2), N250 was measured as the minimum from 150 to 400 msec post stimulus, P350 as the maximum from 300 to 400 msec, and P500 as the maximum from 400 to 750 msec post stimulus. After the automatic scoring, all measures were verified by visual inspection by two scorers who were blind to the test results in order to correct errors due to ERP variability in children.

Data reduction

In this study, correlations were to be computed between individual intelligence levels and individual differences in the use of the different cognitive processes (as indexed by differences in ERP wave forms). Intelligence is usually measured by combining into one IQ score the subject's results yielded by different tests belonging to the same domain, so that his(her) IQ score can predict the subject's performance in any test of the same domain. In this study, intelligence specific factors (e.g., verbal, visuo-spatial, Piagetian) were similarly obtained by performing separate principal component analyses (PCAs) on each of these 3 sets of tests: the 5 verbal tests of the WISC-R, the 5 performance tests of the WISC-R and the 4 conservation tests of the EDC.

PCAs were used because the first PCA factor usually indicates a weighted mean that represents the largest part of the variance of the variables included in the analyses. The scores of such a general factor reflect only individual differences, regardless of the differences between the variables included. Moreover, this solution is not automatically generated due to the nature of the PCA (Morrison 1983), but is only obtained when a homogeneous part of the variance is accountable by individual differences. In addition, using PCA factor scores has the additional advantage of using the same units for the different sets of data: all PCA scores have a mean of 0 and a standard deviation of 1, regardless of the original units. A correlation matrix was used, and not a covariance matrix, in order to avoid that a higher variance in one test would bias

the construction of the PCA factors, and no rotation was applied in order to keep the maximum variance property (Morrison 1983).

The PCAs were carried out on both the raw (age-related) scores and the scaled (age-free) scores, and in both the control group and the ADHD group, separately. In total, 12 PCAs were thus performed (3 sets of tests × 2 types of scores × 2 groups of subjects). The rationale for carrying out PCAs on separate data sets was to minimize the sources of variance other than those of the individuals. If the PCAs are done on the total sample of the data, additional sources of variance are introduced and the factors reflecting the individual differences account for a smaller part of the total variance. As a consequence, they are less reliable. By contrast, by carrying out PCAs on subsets of data, the first factor was always a general factor, having similar loadings to the tests included in each PCA (Appendix II) and accounting for the greatest part of the total variance. To conclude, these IQ factors are weighted means that capture the common variance of the tests included and rank the subject according to their intelligence level in each domain. When based on age-free (scaled) test scores, they generally appeared uncorrelated and thus domain specific. At the opposite, the different IQ factor scores all capture less specific age-related changes and were thus correlated between them (Table 1).

Individual differences in the use of cognitive processes were based on individual differences in ERP wave forms recorded in oddball tasks. First, ERPs were thus recorded in 4 different oddball tasks. Second, individual measures (amplitude and latency) were obtained for 4 peaks that reflect different stages in information processing: (1) the fronto-central P250, (2) the parieto-occipital N250, (3) the parieto-occipital P350, and (4) the parieto-occipital P500. PCAs were then performed across the 4 tasks, on separate data sets: for each peak (P250, N250, P350, P500), taken on both the

left and the right montage, averaged on both the target and the non-target trials, and obtained for both the control group and the ADHD group, separately. In total, 32 PCAs were thus carried out (4 peaks × 2 montages × 2 types of average × 2 groups), separately for the amplitude and latency measures.

The rationale for carrying out separate PCAs was the same as for the intelligence data. We aimed at obtaining reliable measures that reflect only individual differences in peak measurements across oddball tasks, uncontaminated by sources of variance other than individual (stimulus type, montage, side,...). These 32 PCAs always provided a first factor that showed similar loadings to the 4 tasks (Appendix III). These first factors indicated weighted means that allowed us, as expected, to sort the subjects according to the individual differences in ERP peaks, independently of the variations specifically related to the differences between the tasks. The fact that these first factors accounted for the greatest part of the total variance of each data set (in average 67%) shows that the procedure of performing PCAs on separate sets of data was adequate to the goal.

To summarize, different factors of intelligence were obtained by carrying out PCAs on batteries of tests that supposedly measure different forms of intelligence (verbal, performance, Piagetian). Second, different factors of brain activity were obtained by performing PCAs on different ERP measures that were obtained in oddball tasks, assuming that each ERP peak reflects a specific stage in information processing.

Statistical analyses

The correlations between the 32 general factor scores yielded by ERP measures and the 12 general factor scores yielded by intelligence scores were tested in the ADHD and in the control group, using non-parametric statistics (Spearman rank correlation coefficient). Non-parametric statistics are less sensitive to outliers than the usual Pearson's coefficient. Sign corrections were made so that a positive correlation corresponded to an absolute amplitude increase of an ERP wave, and a negative correlation to an absolute amplitude decrease.

When correlations obtained by ADHD or control subjects (or by raw and scaled scores within a group) were found to be in different directions, the bootstrap method (Beran and Ducharme 1991) was used to test the significance of the difference. This method approximates empirically the behavior of statistical quantities and yields bootstrap p-values. The empirical approximation was obtained by selecting randomly, from the 30^{30} possible resamples of size 30 from the normal control group and the 19^{19} possible resamples of size 19 of the second group, 2000 pairs of so-called bootstrap samples from which we computed, in the manner

TABLE 1

Correlation between IQ scores

	Normal controls		Hyperactives	
Raw IQ factor scores				
Performance	**0.45** **		**0.77** **	
Conservation	**0.64** **	**0.58** **	**0.47** **	−0.01
			Verbal	Performance
Scaled IQ factor scores				
Performance	0.08		0.31	
Conservation	0.17	**0.46** *	0.28	−0.20
			Verbal	Performance

Spearman correlations between the verbal, performance and Piagetian group factor scores, for the raw and the scaled data. Correlations yielded by the control and the ADHD children are presented separately.
* $P < 0.05$ and ** $P < 0.01$.

described by Efron (1982, p. 29 exercise 5.3), the bootstrap distribution of the correlation difference. If the 95% confidence interval of these 2000 differences did not include zero, the hypothesis that the two correlations are equal (and consequently their difference null) was rejected.

3. Results

Target, task, age and hyperactivity effects on ERP wave forms that are observed in these experiments were reported by Robaey et al. (1992) and the reader is referred to this paper for their study. In order to analyze the effects of intelligence, more subjects were recorded for the present study. To avoid repetition, only the results that are specific to the purpose of this article will be presented.

Correlations between intelligence results (Table 1)

Raw IQ scores.. In the control group, all raw scores were significantly intercorrelated. In the ADHD group, the raw verbal score was correlated with the raw performance scores and the raw Piagetian scores, but the latter two IQ scores were uncorrelated.

Scaled IQ scores.. In the control group, only the correlations between the Piagetian scores and the Wechsler's performances scores were significant. In the ADHD group, none of the correlations between the different scaled IQ scores was significant.

Correlation between intelligence and hyperactivity measures (Table 2)

Within each group (ADHD and control), Parents' and Teacher's hyperactivity index were not found to be correlated with any of the intelligence group factors.

TABLE 2

Correlation between intelligence and hyperactivity factor scores

	Normal controls		Hyperactives	
Raw scores				
Verbal	0.19	0.02	0.24	0.28
Performance	0.09	0.20	0.08	0.24
Conservation	0.02	0.11	0.30	0.05
Hyperactivity	Parents	Teacher	Parents	Teacher
Scaled scores				
Verbal	0.11	0.14	0.09	0.10
Performance	0.18	0.16	0.09	0.14
Conservation	0.25	0.08	0.05	0.05
Hyperactivity	Parent's index		Teacher's index	

Spearman correlation between hyperactivity parent's (CPRS-R) or teacher's index (CTRS-R) and the verbal, performance and Piagetian group factor scores for the raw and the scaled data. No significant correlation was found either in the hyperactive group or in the control group.

This lack of correlation was observed for both raw and scaled scores. Within each group, hyperactivity did not confound the question of intelligence.

Correlations between ERP amplitude measures

ERP amplitude-based correlations were weaker in the ADHD group than in the normal control group. In both groups, they can be divided into 4 sets.

Parieto-occipital P350 with P500 amplitudes.. The parieto-occipital P350 and P500 amplitudes were found to be significantly ($P < 0.01$) intercorrelated, with correlations ranging from 0.71 and 0.90 in the control group and from 0.67 to 0.76 in the ADHD group.

Frontal P250 with occipital N250 amplitudes.. The correlations between the amplitude of the frontal P250 and the occipital N250 were significant in the control group but non-significant in the ADHD group. In hyperactives, their magnitudes ranged from 0.32 and 0.29 for the non-target responses on the left and right montages, respectively, in contrast to values of 0.31 ($P < 0.05$) and 0.64 ($P < 0.01$) in normal controls. For ERP to targets these correlations, while low in the ADHD group (0.03 and 0.11 on the left and right montages respectively), were high and significant ($P < 0.01$) in the control group (0.52 and 0.69).

Occipital N250 with P350 and P500 amplitudes.. In the control group, for target ERPs, the occipital N250 was significantly correlated with the following P350 (-0.34; $P < 0.05$) and P500 (-0.39; $P < 0.05$), on the left montage. This correlation was weaker on the right montage, for the P350 (-0.29; NS) and for the P500 (-0.34; $P < 0.05$). For ERPs to non-targets, the correlations were not significant.

In the ADHD group, the correlations between the amplitude of the N250 and the amplitudes of the following positivities (P350 and P500) were always weak and non-significant.

Frontal P250 with parieto-occipital P350 and P500 amplitudes.. In the control group, the amplitude of the frontal P250 was not found to be significantly related to that of the parieto-occipital P350 or P500.

In the ADHD group, the correlations between the amplitude of the frontal P250 and the occipital P350 and P500 also were of low magnitude. Only the correlation between the P250 and the P350 to targets recorded on the right montage reached significance at the 0.05 threshold (0.38).

Correlations between verbal level and ERP amplitudes

Control group.. Significant correlations were obtained between the verbal levels and the amplitudes of late positivities (P350 and P500) recorded in parieto-

occipital regions (Table 3). All these correlations were negative with an increasing level of verbal intelligence being correlated to an amplitude decrease of the P350 and P500 waves in laboratory tasks. Fig. 4 shows that ERPs to targets yielded stronger correlations than the ERPs to non-targets, especially on the right montage, and that the amplitude difference was about 5 μV for a verbal IQ gap of 30 points. These correlations were very similar for both the scaled and the raw scores.

ADHD group..   In hyperactive children, the amplitudes of the P250 to targets and to non-targets were negatively correlated with the verbal scaled scores. Such correlations were non-existent in normal controls. Fig. 5 shows that within hyperactives, a specific P250 amplitude difference of about 5 μV corresponded to an IQ gap of 30 points.

In addition, significant correlations were obtained between the verbal scores and the amplitude of the P500: the higher the verbal level, the smaller the P500 amplitude, this pattern being similar to that already described in control subjects. Fig. 5 shows that as within normal controls, the P500 amplitude difference was about 5 μV for an IQ gap of 30 points. However, two differences were found. In ADHD subjects, these correlations were significant on the right montage only and higher for non-target ERPs than for target ERPs (Table 3).

Correlations between performance level and ERP amplitudes

Control group..   Significant correlations were obtained between the performance scores and the amplitude of the early frontal P250 and parieto-occipital N250 (Table 4). All these correlations were negative, an increasing level of performance intelligence being correlated with an amplitude decrease of the P250 and N250 waves in the laboratory tasks. A 3-dimensional scattergram (Fig. 6) clearly showed that this correlation was not due to a few outliers but reflected a continuous trend.

The same pattern of correlations was found with each performance test, but Picture Arrangement yielded the highest and most significant correlations (Table 5a).

ADHD group..   The only significant correlation obtained was between the N250 recorded to targets on the right montage and the raw performance scores (−0.42). However, the strong relationships observed in normal controls between the scaled performance scores and the amplitude of both P250 and N250 (from −0.33 to −0.56) were lacking in hyperactive subjects.

The lack of correlation in this group, when compared to normal controls, was due to the fact that among the performance tests, some of them (Picture

right montage

Fig. 4. The scattergram between the right P350 or P500 amplitudes and the verbal scores of all normal control subjects is shown on the left side of the figure. Black dots are used for significant correlations and white dots for non-significant correlations. In order to illustrate these correlations, grand average ERPs obtained on the 4 right posterior leads across all tasks are shown. They were averaged across the 7 subjects with the higher (mean verbal IQ = 132.6) verbal scores (thick lines), compared with the ERPs obtained for the 7 subjects with the lower (mean verbal IQ = 102.1) verbal scores (thin lines). The brightest subjects showed smaller P350 and P500 (−5 μV).

Arrangement, Picture Completion) were negatively related to the amplitudes of P250 and N250 (same as in normal controls), whereas others (Block Design, Object Assembly, Code) were positively related to the amplitudes of P250 and N250 (opposite to the normal controls). In ADHD subjects, Picture Arrangement yielded the most significant negative correlations (the higher the test scores, the smaller the P2 and N2 waves). In contrast, Block Design yielded the most significant positive correlations (the higher the scores on this test, the larger the P2 and N2 waves during the laboratory tasks): Table 5b.

The ERP correlates with Block Design were thus opposite in direction when comparing the ADHD and the control groups. Fig. 7 shows that, in normal controls, the subjects who had the higher scores showed

smaller P250s when dealing with the laboratory tasks, whereas the brightest hyperactive children on the same test showed larger P250s. Similarly, the brightest hyperactive children on Block Design had larger N250s, a feature that was not found in the brightest normal controls. These ADHD vs. normal control differences were larger on the left montage than on the right montage.

The differences between the correlations yielded by the control group and the ADHD group were significant, when using a bootstrap method (Beran and Ducharme 1991): Table 6. For the non-target P250 at the left montage, the difference between the correlations yielded by the control and the ADHD groups was −0.96. Bootstrap methods, based on 2000 bootstrap samples of both groups, showed that the simulated
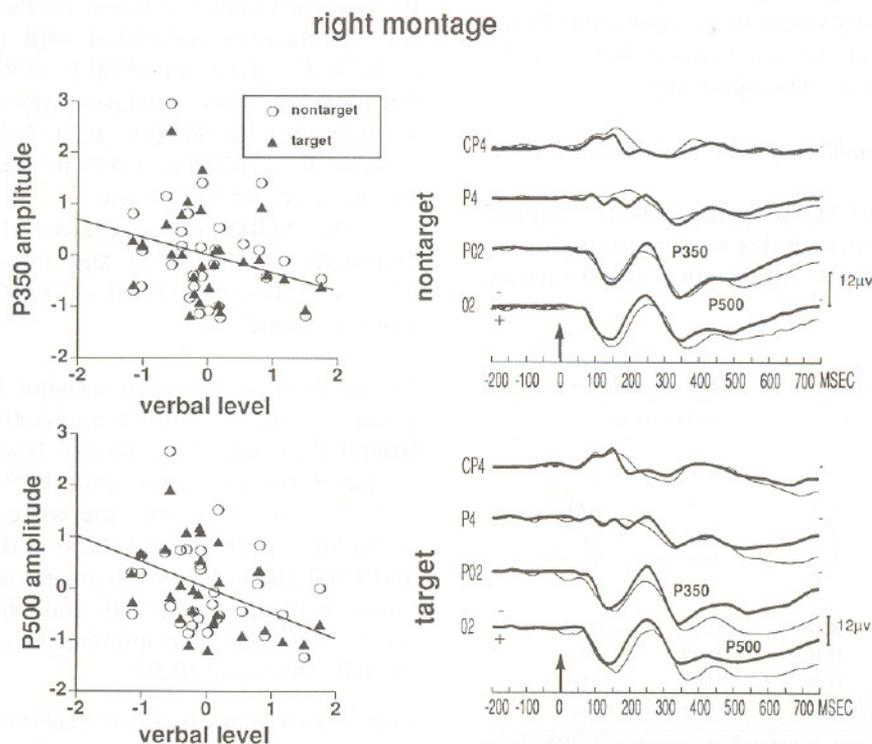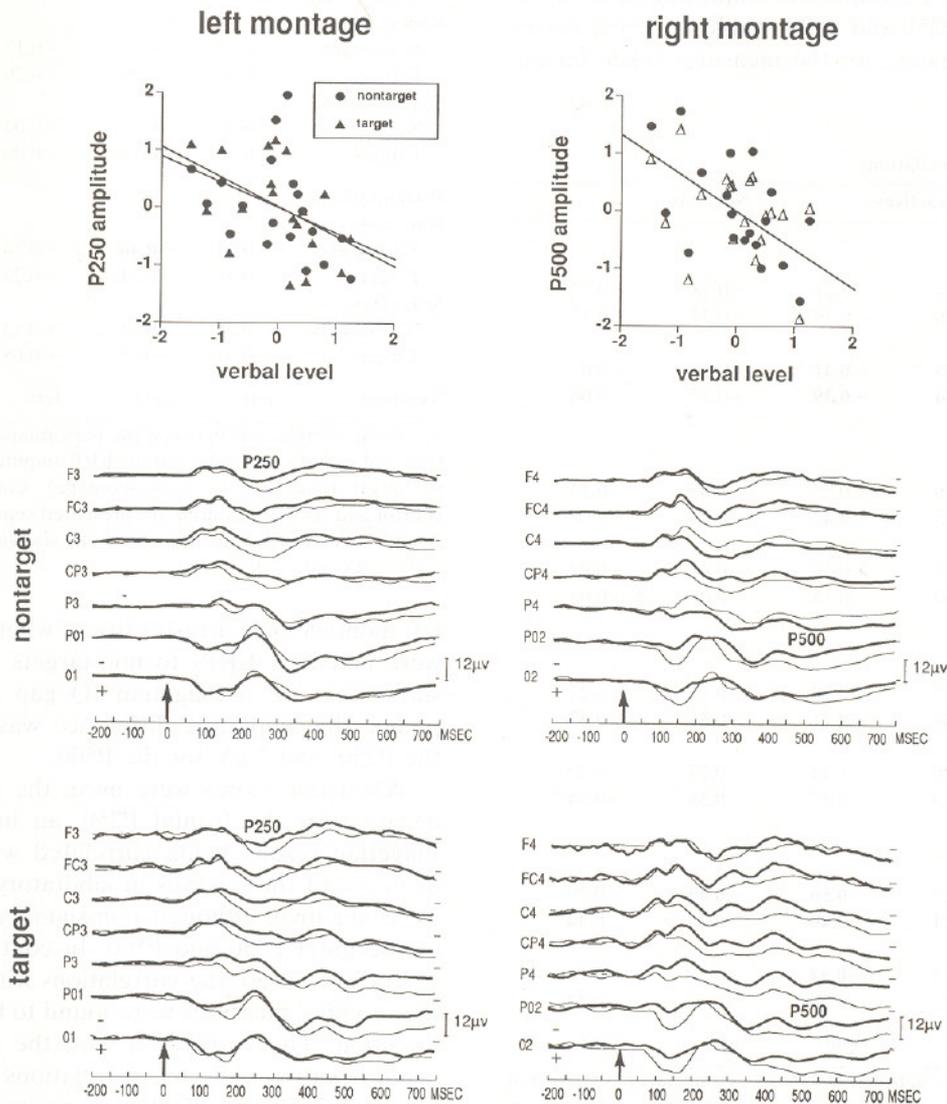

Fig. 5. The scattergram between the P250 or P500 amplitudes and the verbal scores of all ADHD subjects is shown on the left side of the figure. Black dots represent significant correlations and white dots non-significant correlations. In order to illustrate these correlations, grand average ERPs obtained across all tasks are shown. They were averaged across the 5 subjects with the higher (mean verbal IQ = 105.2) verbal scores (thick lines), compared with the ERPs obtained for the 5 subjects with the lower (mean verbal IQ = 75.4) verbal scores (thin lines). The brightest ADHD subjects showed smaller P250 (−5 μV) and smaller P500 (−6 μV).

95% confidence interval of this difference ranged between -1.38 and -0.39. Since this interval does not include zero, the hypothesis that the correlations yielded by the two groups are equal and their difference null $(R1 - R2 = 0)$ might be rejected. For the left N250 to non-targets, the difference was -0.71, with a bootstrap 95% confidence interval ranging between -1.14 and -0.16. The hypothesis that the two correlations are equal and consequently their difference null might thus be rejected.

Correlations between conservation level and ERP amplitudes

Control group.. Significant correlations were obtained between the conservation scores and the amplitude of the frontal P250 and the amplitude of both the parieto-occipital P350 and P500 (Table 7). These correlations were significant for the measures taken on the

TABLE 3

Verbal Spearman's correlations

	Hyperactives		Normals	
P250 amplitude				
Raw scores				
Non-targets	−0.30	−0.21	−0.18	−0.13
Targets	−0.26	−0.19	−0.27	−0.12
Scaled scores				
Non-targets	**−0.53** *	**−0.41** *	−0.11	−0.01
Targets	**−0.54** * *	**−0.39** *	−0.15	−0.06
N250 amplitude				
Raw scores				
Non-targets	−0.36	−0.35	−0.05	−0.13
Targets	−0.25	**−0.42** *	−0.07	−0.08
Scaled scores				
Non-targets	−0.17	−0.17	−0.01	−0.01
Targets	−0.02	−0.15	−0.08	+0.08
P350 amplitude				
Raw scores				
Non-targets	+0.12	−0.10	**−0.41** *	−0.22
Targets	−0.08	−0.11	**−0.51** * *	**−0.43** * *
Scaled scores				
Non-targets	+0.20	−0.14	−0.27	−0.20
Targets	−0.13	−0.37	**−0.38** *	**−0.34** *
P500 amplitude				
Raw scores				
Non-targets	−0.27	**−0.56** * *	**−0.43** *	−0.29
Targets	−0.21	**−0.40** *	**−0.37** *	**−0.40** *
Scaled scores				
Non-targets	−0.15	**−0.54** * *	−0.30	−0.26
Targets	−0.07	−0.36	−0.27	**−0.42** *
Montage	left	right	left	right

Spearman correlations between the verbal group factor scores (raw and scaled separately) and the ERP amplitude factor scores (non-target vs. target ERP, left vs. right montage). Correlations yielded by control and ADHD children are presented separately. Figs. 4 and 5 show scattergrams and ERP wave forms for the most significant correlations (based on P350 and P500 measures).
* $P < 0.05$ and * * $P < 0.01$.

TABLE 4

Performance Spearman's correlations

	Hyperactives		Normals	
P250 amplitude				
Raw scores				
Non-targets	−0.05	−0.04	**−0.55** * *	**−0.49** * *
Targets	−0.06	−0.04	**−0.61** * *	**−0.37** *
Scaled scores				
Non-targets	−0.01	+0.03	**−0.56** * *	**−0.43** *
Targets	−0.10	+0.03	**−0.54** * *	**−0.33** *
N250 amplitude				
Raw scores				
Non-targets	−0.33	−0.24	**−0.41** *	**−0.35** *
Targets	−0.27	**−0.42** *	**−0.34** *	**−0.37** *
Scaled scores				
Non-targets	−0.01	+0.29	**−0.38** *	**−0.33** *
Targets	+0.09	+0.11	**−0.39** *	**−0.34** *
P350 amplitude				
Raw scores				
Non-targets	−0.12	−0.03	−0.17	−0.05
Targets	−0.20	+0.06	−0.29	−0.11
Scaled scores				
Non-targets	−0.16	−0.25	+0.04	+0.00
Targets	−0.28	−0.14	−0.06	+0.06
P500 amplitude				
Raw scores				
Non-targets	−0.34	**−0.46** *	−0.16	−0.02
Targets	−0.35	−0.31	−0.24	−0.09
Scaled scores				
Non-targets	−0.36	−0.31	+0.13	+0.14
Targets	−0.34	−0.15	+0.05	+0.08
Montage	left	right	left	right

Spearman correlations between the performance group factor scores (raw and scaled separately) and the ERP amplitude scores (non-target vs. target ERP, left vs. right montage). Correlations yielded by control and ADHD children are presented separately. Fig. 6 showed 2- and 3-dimensional scattergram of the significant correlations.
* $P < 0.05$ and * * $P < 0.01$.

left montage only, irrespective of whether the measures were taken on ERPs to non-targets or targets. Fig. 8 shows that for a Piagetian IQ gap of more than 30 points, the amplitude difference was about 5 μV for the P250, and 7 μV for the P500.

When raw scores were used, the correlations were negative for the frontal P250, an increasing level of Piagetian results being correlated with an amplitude decrease of these waves in laboratory tasks. They also were negative, although non-significant, for the parieto-occipital P350 and P500. In contrast, when scaled scores were used, the correlations with the frontal and the occipital measures were found to be in the opposite direction. The correlation with the frontal P250 was again negative while the correlations with the parieto-occipital P350 and P500 were positive and significant: an increasing level of Piagetian intelligence was correlated with an amplitude increase of the P350 and P500 waves in laboratory tasks.

The differences between the correlations yielded by

raw and scaled scores were tested by using the bootstrap method. For the P500 to non-targets, the difference between the correlations yielded by raw and scaled Piagetian scores was 0.621. Based on 2000 bootstrap samples, the bootstrap 95% confidence interval of this difference was found to be between 0.297 and 0.897. Thus, the hypothesis that the two correlations are equal might again be rejected. For the P500 to targets, the difference was 0.620, with a bootstrap 95% confidence interval ranging between 0.296 and 0.906. The hypothesis that the two correlations are equal might thus again be rejected (Table 8).

ADHD group.. The distinct pattern of correlations obtained in normal controls (P250 amplitude decrease and P500 amplitude increase on the left montage) was not found in ADHD subjects, even when the correlations were examined for each Piagetian test separately.

Correlations between intelligence level and ERP latencies

Control group.. Correlations were generally negative. For each of the 3 types of intelligence, 16 latency-based

correlations (4 for each peak) were yielded by the raw scores. Out of these 48 correlations, 27 (56%) were significant, ranging between the 0.3 and 0.5 level: 4 yielded by the verbal scores, 7 by the performance scores and 15 by the Piagetian scores. In contrast, with scaled scores, correlations generally dropped to non-significant values: only 8 (16%) were significant, most of them with P250 latency. Among the 12 correlations (4 peaks × 3 intelligence types) yielded by the P250 latencies, 4 were significant with the verbal scores (100%), 2 with the performance scores and 0 with the Piagetian scores. The other two significant correlations were scattered among the measures: one between the verbal scaled scores and the right P500 for targets, and one between the Piagetian scaled scores and the right P350 for targets.

To summarize, for the Piagetian raw scores, 94% of the latency-based correlations were significant, but only 44% for the performance scores and 25% for the verbal scores. In contrast, the scaled scores yielded only 6% of significant correlations for the Piagetian intelligence, but 13% for the performance and 31% for the verbal intelligence.
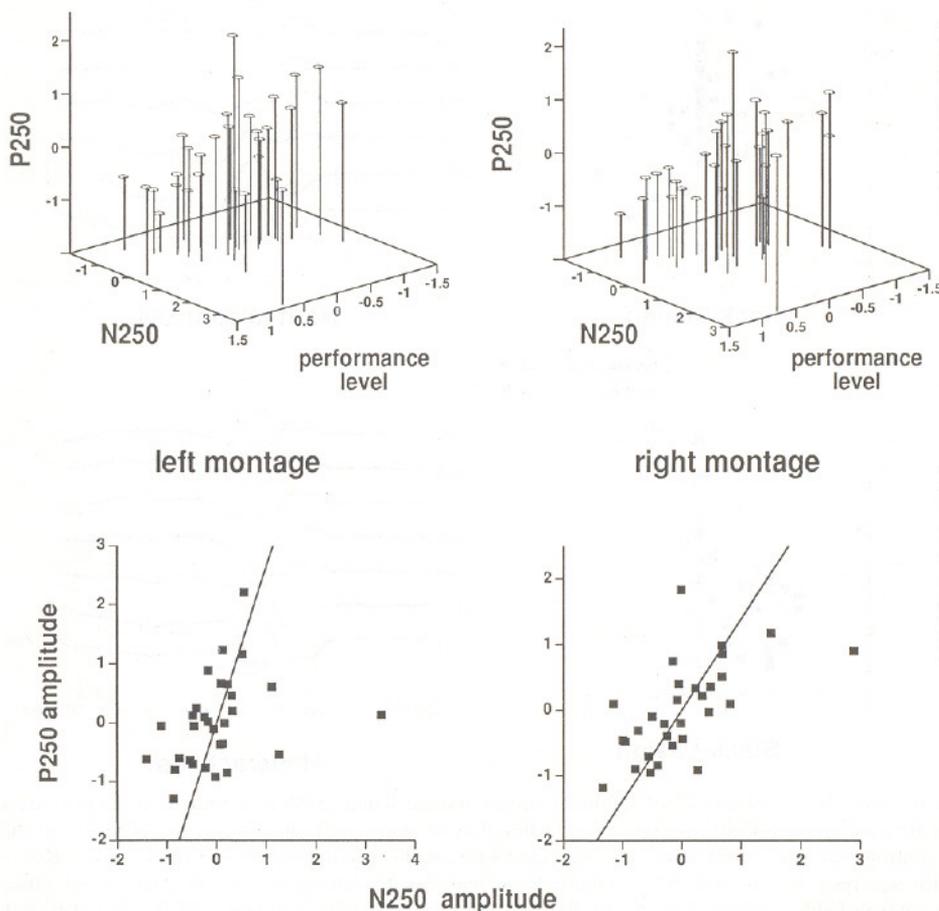

Fig. 6. The correlations between the P250 and the N250 amplitude scores (measured on target ERPs) are shown on the bottom of the figure, for the left and the right montage separately. In the upper part of the figure, 3-dimensional scattergrams showed that both P250 and N250 amplitudes were negatively correlated with the Weschler's performance intelligence scores (scaled data).

ADHD group.. In hyperactives, left P250 latency was correlated with both the verbal raw scores (-0.51 and -0.56, for non-target and target P2, respectively) and the verbal scaled scores (-0.66 and -0.54). No pattern was found for the other forms of intelligence, with only two and one correlations reaching the 0.05 significance level for the performance and the Piagetian scores, respectively.

In total, the numbers of latency-based correlations that were significant in normal controls were thus 9, 9 and 16 for the verbal, performance and Piagetian scores, respectively. In contrast, the respective numbers of significant correlations were 4, 2 and 1 in hyperactive subjects.

4. Discussion

From a psychometric perspective, this study addressed 3 issues: Do different intelligence types yield different subsets of ERP correlates? Do these different ERP correlates differ if the tests scores are corrected for age or not? Do intelligence(s) measures have different ERP correlates depending upon the subjects' clinical characteristics?

Correlations were obtained between ERP amplitude measures obtained in oddball tasks and data from psychometric tests (verbal, performance, Piagetian). In normal controls, 28%, 50% and 25% of the ERP-based correlations were significant for the verbal, performance and Piagetian intelligence, respectively. They were therefore far above the 5% random threshold. In addition, these correlations delineated different and clear-cut intelligence-ERP peak patterns. Moreover, the magnitude of these significant correlations was relatively high, especially if compared with values reported in other studies, as they ranged between 0.31 and 0.66 and accounted for 9–40% of the total variance. The proportion of latency-based correlations which were significant was also above the 5% random
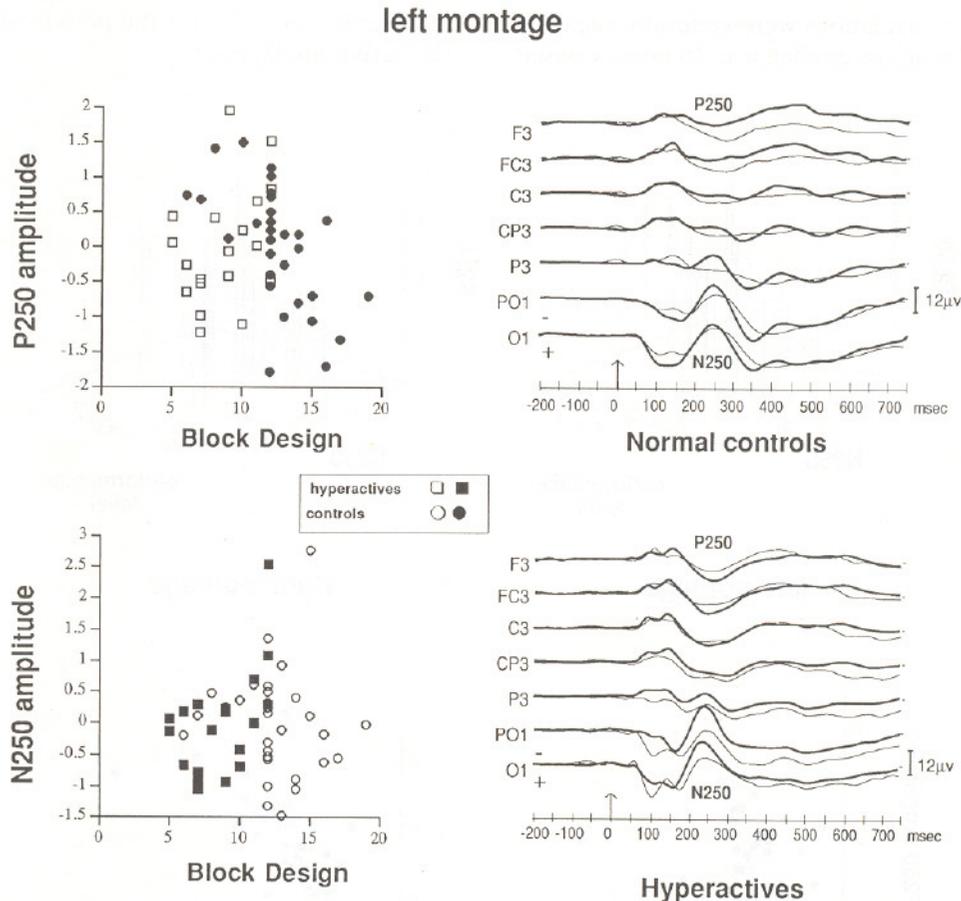

Fig. 7. The scattergrams between the P250 (and N250) amplitude scores and the scores at Block Design of all subjects are shown on the left side of the figure. Black dots are used for significant correlations and white dots for non-significant correlations. Hyperactive children are represented by squares and normal controls by circles. P250 amplitude decreased with intelligence in controls (for black circles, $Rs = -0.64$), but not in the hyperactive group (white squares). In contrast, N250 amplitude increased with intelligence in the hyperactive group (for black squares, $Rs = +0.47$), but not in controls (white circles). In order to illustrate these relationships, non-target ERPs were averaged across the 6 controls (thick lines) with the higher scores at Block Design (16.3) and the 6 controls (thin lines) with the lower scores at Block Design (8.5). At the bottom of the figure are shown the non-target ERPs averaged across the 5 hyperactive subjects (thick lines) with the higher scores (11.6) and the 4 hyperactive subjects (thin lines) with the lower scores at Block Design (5.5). Bright hyperactive children showed larger P250s (and N250s), whereas bright normal controls showed smaller P250s.

threshold, with 28%, 28% and 50% for the verbal, performance and Piagetian intelligence, respectively. The magnitude of these correlations also ranged from −0.3 to −0.5. However, latency-based correlations did not delineate different ERP wave patterns specifically related to different forms of intelligence, as amplitude-based correlations did.

ERP correlates of different types of intelligence

When comparing children ranging from 6 to 8 years of age, ERP traces did not vary on the whole. Rather, two different ERP patterns emerged: the first one grouped the late posterior positivities (P350 and P500) and the other one the frontal P250 and the occipital N250. Moreover, these two ERP subsets were correlated with two different types of intelligence measures. The higher the verbal scores of the WISC-R, the smaller the P350 and the P500 amplitudes. The higher the performance scores of the WISC-R, the smaller the

TABLE 5

	Hyperactives		Normals	
(a) Picture arrangement				
P250 amplitude				
Raw scores				
Non-targets	−0.15	−0.10	−0.43 *	−0.37 *
Targets	−0.36	−0.22	−0.48 *	−0.47 **
Scaled scores				
Non-targets	−0.31	−0.25	−0.34 *	−0.22
Targets	−0.58 **	−0.41 *	−0.31 *	−0.38 *
N250 amplitude				
Raw scores				
Non-targets	−0.19	−0.33	−0.52 **	−0.38 *
Targets	−0.05	−0.39 *	−0.43 **	−0.35 *
Scaled scores				
Non-targets	−0.11	−0.19	−0.38 *	−0.30
Targets	+0.02	−0.19	−0.36 *	−0.27
(b) Block design				
P250 amplitude				
Raw scores				
Non-targets	+0.41 *	+0.27	−0.62 **	−0.53 **
Targets	+0.12	+0.19	−0.61 **	−0.41 *
Scaled scores				
Non-targets	+0.32	+0.15	−0.64 *	−0.47 *
Targets	−0.02	+0.06	−0.58 **	−0.41 *
N250 amplitude				
Raw scores				
Non-targets	+0.33	+0.10	−0.23	−0.30
Targets	+0.26	−0.03	−0.28	−0.31 *
Scaled scores				
Non-targets	+0.47 *	+0.29	−0.17	−0.24
Targets	+0.43 *	+0.21	−0.29	−0.27
Montage	left	right	left	right

Block Design and Picture Arrangement-based correlations with the P250 and N250 amplitude scores (non-target vs. target ERP, left vs. right montage). Correlations yielded by control and ADHD children are presented separately. Fig. 7 shows scattergrams and ERP wave forms for the most significant correlations.
* P < 0.05 and ** P < 0.01.

TABLE 6

Block Design: difference in correlations (bootstrap method)

	Left montage	Right montage
P250 amplitude		
Raw scores		
Non-targets	−1.02 (−1.40, −0.35)	−0.80 (−1.23, −0.17)
Targets	−0.73 (−1.25, −0.08)	−0.61 (1.14, +0.02)
Scaled scores		
Non-targets	−0.96 (−1.40, −0.42)	−0.62 (−1.15, −0.01)
Targets	−0.56 (−1.11, +0.06)	−0.47 (−1.06, +0.15)
N250 amplitude		
Raw scores		
Non-targets	−0.55 (−1.04, +0.09)	−0.40 (−0.96, +0.24)
Targets	−0.54 (−1.08, +0.09)	−0.28 (−0.90, +0.36)
Scaled scores		
Non-targets	−0.64 (−1.09, −0.09)	−0.53 (−1.05, +0.09)
Targets	−0.72 (−1.16, −0.12)	−0.48 (−1.04, +0.18)

Differences (with their 95% confidence interval) between the correlations yielded by the control and the ADHD group (bootstrap method). In the two groups, the correlations were computed between the Block Design scaled scores and the P250 (and N250) ERP amplitude scores. Significant differences imply that the 95% confidence intervals do not include zero.

frontal P250 and occipital N250 amplitudes. In contrast, Piagetian intelligence appeared to be based on uncorrelated and lateralized ERP measures: the children with higher Piagetian levels exhibited smaller frontal P250s and larger occipital P500s, on the left hemiscalp. All these patterns of ERP correlates were very unlikely to be obtained by random (χ^2 (11) = 37.18; P < 0.01).

However, even if different ERP patterns were found correlated with different forms of intelligence, the direction of these correlations was generally negative, i.e., a wave amplitude decrease being related to a test score increase. Courchesne (1978) showed that the ERP waves recorded in an oddball task decrease in amplitude from childhood to adulthood. This trend was also found in this study, between 6 and 8 years of age, as correlations between ERP wave amplitudes and raw (age-related) test scores were generally negative. By definition, intelligence reflects the relative advance of a child in test results as compared with individuals of his(her) age group. As children with higher scaled (age-free) IQs showed smaller ERP waves, they also seem in advance with regard to the age-related ERP trend.

In adults, by using positron emission tomography, Haier et al. (1988) observed that subjects who scored high on a non-verbal test (Standard Progressive Matrix – STM – Raven et al. 1953) used less glucose while performing STM than those with low SPM scores. They referred to an efficiency model to account for this negative relationship: "Smart brains work not harder but better." To test the hypothesis of smaller glucose metabolic rate in more able people, Haier et al. (1992) compared two conditions: the initial trial on a complex

computer game and the very last trial after 4–8 weeks of daily practice. Results indicated that glucose metabolic rate in surface regions of the brain decreased with the improvement in game performance skill, and that the subjects that improved their performance the most showed the largest metabolic decrease. Such data are in agreement with the model of a lower level of brain activity in subjects with higher IQs. In further interpretations, we will refer to an efficiency model of intelligence in which less brain activity is needed by the brightest subjects, as compared with age pairs, in order to reach a given level of performance. If ERP amplitude supposedly reflects this activity level, increasing brain efficiency should be related to a decrease in the amplitude of ERP waves. However, the assumption that in ERP studies a negative correlation supports an efficiency model has to be specifically explored in further studies.

Latency-based correlations were generally negative, for both the raw and the scaled scores. The latency decrease with age is a well documented developmental trend (Courchesne 1978; Kurtzberg et al. 1979; Taylor 1988), which was also found in our data set, despite the relatively small age range. As children with higher scaled (age-free) IQs showed shorter ERP wave latencies, they again seem in advance with regard to the age-related ERP trend. Efficiency models could be extended to processing speed, as the more efficient subjects processed information faster. However, this speed difference with intelligence was not different according to the ERP wave. By contrast, increasing speed was observed for all the peaks of the ERP wave form, whatever the type of intelligence. At first sight, it thus provided a more solid basis for the concept of general intelligence than the amplitude measures did.

ERP correlates of intelligence and development scores

The significant correlations obtained by the Wechsler's verbal scores, regardless of the type of scores (raw or scaled), were yielded by the same ERP measures and were in the same negative direction. It can be concluded that Wechsler's development and intelli-
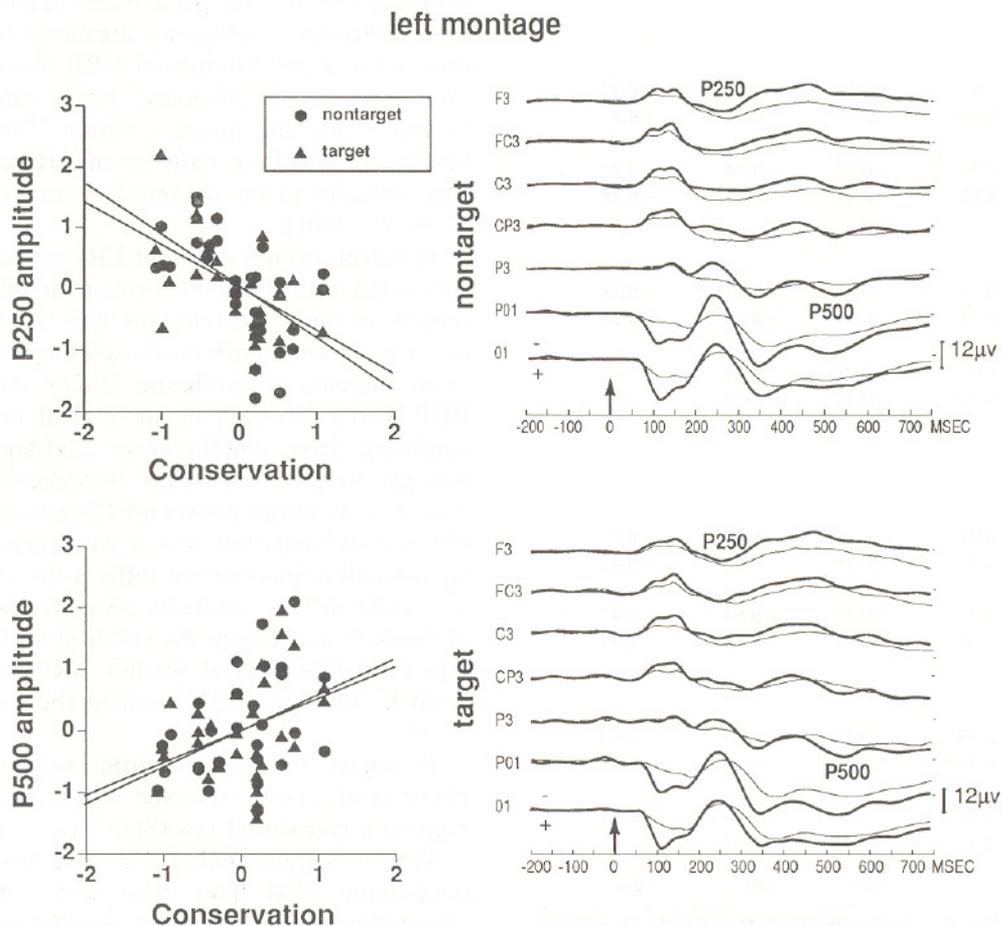
left montage

Fig. 8. The scattergram between the P250 or the P500 amplitude and the Piagetian scores of normal control subjects is shown on the left side of the figure. In order to illustrate this relationship, grand average ERPs obtained across all leads and all tasks are shown. They were averaged across the 7 subjects with the higher (thick lines) Piagetian scores (mean Piagetian IQ = 127.9), compared with the ERPs obtained for the 7 subjects with the lower (thin lines) Piagetian scores (mean Piagetian IQ = 93.5). The brightest subjects had a smaller P250 (mean: −5 μV), but a larger P500 (mean: +7 μV).

TABLE 7

Piagetian Spearman's correlations

	Hyperactives		Normals	
P250 amplitude				
Raw scores				
Non-targets	−0.05	−0.01	−0.51 **	−0.25
Targets	−0.04	+0.10	−0.56 **	−0.25
Scaled scores				
Non-targets	−0.15	−0.20	−0.66 **	−0.21
Targets	−0.25	−0.15	−0.54 **	−0.30
N250 amplitude				
Raw scores				
Non-targets	+0.37	−0.27	+0.03	−0.24
Targets	−0.29	−0.43 *	−0.05	−0.22
Scaled scores				
Non-targets	−0.14	−0.12	+0.05	−0.29
Targets	+0.02	−0.10	−0.20	−0.28
P350 amplitude				
Raw scores				
Non-targets	+0.12	−0.20	−0.20	−0.04
Targets	+0.13	−0.05	−0.34 *	−0.24
Scaled scores				
Non-targets	+0.24	−0.03	+0.37 *	+0.28
Targets	+0.14	−0.11	+0.25	+0.16
P500 amplitude				
Raw scores				
Non-targets	−0.12	−0.30	−0.19	−0.14
Targets	−0.03	−0.30	−0.22	−0.25
Scaled scores				
Non-targets	+0.19	−0.01	+0.43 *	+0.20
Targets	+0.18	+0.01	+0.40 *	+0.05
Montage	left	right	left	right

Spearman correlations between the Piagetian group factor (raw and scaled scores) and the P250, P350 and P500 amplitude scores (non-target vs. target ERP, left vs. right montage). Correlations yielded by control and ADHD children are presented separately. Fig. 8 showed scattergrams and ERP wave forms for the most significant correlations.

* $P < 0.05$ and ** $P < 0.01$.

gence measures (as indexed by raw and scaled scores, respectively) are based on the same cognitive changes. For the Wechsler's performance scores, the same con-

TABLE 8

Difference in correlations between raw and scaled Piagetian scores (bootstrap method)

	Normals
P350 amplitude	
Non-targets	+0.57 (+0.23, +0.86)
Targets	+0.59 (+0.24, +0.87)
P500 amplitude	
Non-targets	+0.62 (+0.30, +0.90)
Targets	+0.62 (+0.30, +0.91)

Difference (with their 95% confidence interval) between the correlations yielded by the Piagetian raw and scaled scores in the normal control group (bootstrap method). The correlations were computed between the Piagetian scores and the P350 (and P500) ERP amplitude scores. Significant differences imply that the 95% confidence intervals do not include zero.

clusions can be drawn: intelligence differences and developmental differences may be viewed as related to the same changes of the same processes.

However, the findings were different for the Piagetian tests. If the Piagetian raw scores yielded negative correlations, the scaled Piagetian scores yielded positive correlations with the P350 and P500 amplitude measures. This change in correlation was significant ($P < 0.05$). The use of conservation implies that the child is able to extract additional information (invariant features) from the stimulus. If this additional cognitive capacity is based on an additional brain activity, a positive correlation might be expected between some ERP waves and Piagetian scores. Nevertheless, as the ERP amplitude generally decreases with age, such a positive correlation could only be observed if the subjects were ranked according to their conservation levels, irrespective of their ages.

This view was supported by the present finding: the more a child was able to extract invariant features from a stimulus as compared with his age peers (as reflected by higher scaled Piagetian scores), the larger were his P500s. Moreover, the fact that raw and age-corrected scores yielded correlations in opposite directions with the left parieto-occipital late positivities (P350 and P500) suggests that this additional activity was relatively restricted to specific cognitive processes. According to the current interpretation of the P300 activity (see Donchin and Coles 1988), the brightest subjects would process more information in updating the cognitive schemas they used to deal with the task situation. Thus, Piagetian intelligence provides the first exception to the efficiency model: an efficiency model generally predicts that the most intelligent people exhibit less brain activity, reflected by smaller ERP waves. However, the more intelligent subjects in Piagetian tests showed larger ERP waves in oddball tasks.

Generally, age-related scores yielded more significant (at the 0.05 level) correlations with ERP latencies than age-free scores, respectively 54% vs. 17%. However, the gap between the proportion of development and intelligence-based correlations decreased going from Piagetian tests (94% vs. 6%), to performance tests (44% vs. 13%), and even reversed for verbal tests (25% vs. 31%). This pattern of opposite trends is very unlikely to be obtained by random (χ^2 (5) = 22.50; $P < 0.01$). Wechsler's verbal and performance scores yielded thus latency-based correlations in the same negative direction, regardless of the type of scores (age-related or age-free). Intelligence and developmental differences may thus be viewed as related to processing speed changes, especially the speed of the frontal P2-indexed process. Wechsler-based correlations are thus also in agreement with an efficiency model, but in term of speed processing: the more efficient the subject, the faster the processing. By con-

trast, Piagetian intelligence again appeared as an exception to the efficiency model. Age-related (raw) Piagetian scores yielded quasi systematically (94%) negative significant correlations with ERP peak latencies. However, almost no significant correlation (6%) was found when the Piagetian scores were age-corrected. If Piagetian development was clearly related to an increasing processing speed, Piagetian intelligence was not linked to speed changes.

To conclude, Wechsler's intelligence was correlated with age-related changes (amplitude and latency decrease), in agreement with an efficiency model. The more efficient the subject, the faster and the smaller the event-related brain activity. In contrast, Piagetian intelligence was not correlated with the processing speed, and showed an positive correlation with amplitude measures, suggesting an increasing brain activity with intelligence. Efficiency models cannot account for Piagetian intelligence.

ERP correlates of intelligence in normal and hyperactive children

In hyperactive children, fewer correlations between ERP amplitudes and intelligence scores were significant, as compared with normal controls (χ^2 (5) = 20.10; $P < 0.01$). This difference was striking (χ^2 (1) = 30; $P < -0.01$) for the performance-based correlations, dropping from an extremely consistent pattern (100% of significant correlations yielded by P2 and N2 amplitudes) to a random level (6.25% of significant correlations). In normal control subjects, the particularly clear-cut subset of significant correlations yielded by the performance scores and the P250 and N250 amplitudes is likely to delineate a functional subset of cognitive processes related to non-verbal intelligence. The first aim of the present study was indeed to determine the composition of the cognitive subsets related to intelligence components by identifying the ERP waves that are correlated to different types of intelligence.

In adults, Ritter et al. (1982, 1983) proposed that the N2c wave was related to semantic discrimination because its topography was occipital and its latency and duration depended on the nature of the categories. In children, an N2 was also found by Taylor (1988) with the same topography. Holcomb et al. (1985) and Robaey et al. (1992) observed that its amplitude was larger for words than for pictures. This N2c might reflect controlled perceptual processing and is clearly different from the anterior N2b that reflects automatic orienting (Renault et al. 1982). N2b is preceded by a positivity (P2). P2 coincides with the change orienting reaction, as the amplitude of this peak was constant over deviant trials and did not decrease in habituation series (Kenemans et al. 1989). The idea that P2 provides a marker of an automatic process is also supported by the fact that P2 did not change in latency (around 250 msec),

amplitude and scalp distribution (anterior), from childhood to adulthood (Courchesne 1978). Although N2 and P2 peaked at the same time, but were opposite in polarity and in location, it is unlikely that they were produced by the same source, as target and reading effects on both P2 and N2 were different, and also differed between groups (Robaey et al. 1992).

According to the previous functional interpretations, N250 and P250 are thus likely to reflect two different modes of cognition: controlled and automatic, respectively. In line with the brain efficiency model, the correlation between the N2 and P2 waves and the performance scores could reflect the fact that children with a larger proportion of automatized subroutines in controlled processing (as indexed by smaller N2) also devoted a smaller amount of automatic processes in detecting changes in the oddball task, as indexed by smaller P2. Smaller N2 and P2 amplitude were indeed found in the brightest subjects.

However, all Weschler's performance tests are not equivalent in terms of degree of familiarity (or inversely, novelty). Picture Arrangement, for example, proposes a familiar-like situation, as the child must arrange a series of pictures in an order that tells a sensible story. In contrast, Block Design appears as a novel situation, since the child has to arrange red/white colored blocks into an abstract design shown on a card. The situation can hardly be referenced to previously experienced situations. As a consequence, the magnitude of the correlations of test scores with N2 and P2 amplitudes should vary according to the relative use of controlled or automatic processes in test situations. The N2 amplitude (relative decrease) should allow us a better prediction of the performance in a familiar, highly automatized situation than in novel, never experienced situations. Inversely, the use of automatic processes (as indexed by the P2 amplitude) should allow us a better prediction in a novel situation (that activates such types of processes) than in a familiar situation. In normal controls, N250 amplitude was correlated ($Rs = -0.38$; $P < 0.05$) with scaled scores at Picture Arrangement, but with Block Design, the correlations with N250 amplitude dropped to a non-significant value ($Rs = -0.17$). Inversely, P2-based correlation showed an opposite trend, being more correlated with a novel test situation, like Block Design (-0.5 to -0.6 level), than with the Picture Arrangement scores (-0.3 level).

Due to their attention deficit, hyperactive children often have learning problems and are likely to automatize fewer controlled subroutines. Hyperactive children are thus likely to deal with familiar-like tests just as normal children deal with novel situations. Correlations between their scores at Picture Arrangement and their N250 amplitude were indeed non-significant. In contrast, and surprisingly, the hyperactive children's

scores in a novel test like Block Design were positively correlated (0.47; $P < 0.05$) with the N250 amplitude. It might be proposed that the ADHD children who were able to adopt an effortful strategy by using more controlled resources in a laboratory situation (as reflected by larger N250), also performed better in a novel test situation. This was not found in normal controls and the correlation difference between the two groups was significant. P2-based correlations also reversed. This suggests that the brightest hyperactive children also devoted more automatic processing in detecting changes in the oddball task than those who obtained lower scores at Block Design.

The hyperactive children yielded fewer significant correlations between ERP latency and intelligence scores than the normal controls (χ^2 (5) = 23.30; $P < 0.01$). The proportion of significant correlations in normal controls were 28%, 28% and 50% for the verbal, performance and Piagetian scores, respectively. In contrast, the proportion of significant correlation was around the random level in hyperactive subjects (12%, 6% and 3%, respectively). Processing speed could not account for developmental or for intelligence differences in hyperactive children, as it frequently does in normal controls.

5. Conclusions

Our results clearly show that ERPs provide appropriate tools to assess the components of intelligence. In a psychometric perspective, the correlation patterns we found provide strong evidence that intelligence comprises different components, each with its own subset of critical cognitive processes. Intelligence correlates were often in the same direction as developmental correlates for either amplitude and latency measures. This conclusion is in agreement with an efficiency model stating that efficiency improves with age, in terms of increasing speed and decreasing demand on brain processes. However, Piagetian intelligence did not meet this efficiency model. Moreover, such an efficiency model also fails to account for the intelligence differences within hyperactive children, in terms of processing speed. On the basis of the positive amplitude-based correlations yielded by Block Design, it could also be proposed, paraphrasing Haier et al. (1988), that if smart brains work better in normal control children, smart brains work harder in hyperactive children. As a consequence, conclusions based on intelligence tests may only be valid within the same subjects' group and for the same test. However, further studies are clearly needed in order to explore the different components of "intelligence," perhaps by using Piaget's or Wechsler's more strictly analogous tasks, and to determine the exact relationships between ERP changes and cognitive efficiency.

Appendix 1

Number of trials	Normal controls		Hyperactives	
Pictures	54.3 (14.1)	24.6 (6.7)	45.7 (16.6)	18.3 (5.8)
Words	56.2 (14.3)	20.5 (9.3)	50.2 (14.3)	14.2 (8.9)
Triangles	54.9 (11.6)	23.9 (6.0)	46.7 (19.0)	21.0 (7.9)
Digits	57.0 (11.7)	22.3 (5.9)	44.4 (15.7)	14.9 (6.7)

Number of trials included in ERP averages (mean and standard deviation) for each type of stimulus, each task and each subjects' group.

Appendix 2

Intelligence measures PCAs: first factor loadings

	Raw data		Scaled data	
	NC	ADHD	NC	ADHD
(a) WISC-R verbal scores				
Information	−0.92	−0.96	−0.84	−0.90
Similarities	−0.83	−0.65	−0.70	−0.50
Arithmetic	−0.90	−0.81	−0.78	−0.49
Vocabulary	−0.83	−0.91	−0.60	−0.85
Comprehension	−0.83	−0.86	−0.65	−0.82
Variance %	74.7	71.0	52.1	53.7
(b) WISC-R performance scores				
Picture completion	−0.86	−0.76	−0.82	−0.63
Picture arrangement	−0.60	−0.73	−0.44	−0.44
Block design	−0.75	−0.30	−0.64	−0.38
Object assembly	−0.82	−0.68	−0.84	−0.64
Coding	+0.30	+0.27	+0.13	−0.24
Variance %	48.5	34.6	39.8	24.0
(c) EDC Piagetian scores				
Token classification	−0.70	−0.76	−0.64	−0.64
Stick seriation	−0.79	−0.82	−0.67	−0.78
Substance conservation	−0.57	−0.35	−0.42	+0.05
Length conservation	−0.30	−0.69	−0.54	−0.68
Variance %	38.3	46.4	33.2	38.5

Factor loadings of the first component provided by principal component analyses carried out on the Wechsler verbal tests, performance tests, and on the Piagetian tests.

Appendix 3

ERP measures PCAs: first factor loadings

	P250 Left	P250 Right	N250 Left	N250 Right	P350 Left	P350 Right	P500 Left	P500 Right
(a) Amplitude to non-targets (normal controls)								
Pictures	−0.79	−0.78	−0.77	−0.72	−0.91	−0.93	−0.79	−0.77
Words	−0.81	−0.83	−0.93	−0.87	−0.95	−0.93	−0.94	−0.91
Triangles	−0.90	−0.84	−0.94	−0.83	−0.91	−0.92	−0.86	−0.86
Digits	−0.89	−0.87	−0.89	−0.89	−0.92	−0.87	−0.79	−0.64
Variance %	71.8	68.7	78.2	69.2	85.3	83.1	71.4	63.8
(b) Amplitude to non-targets (hyperactives)								
Pictures	−0.74	−0.80	−0.83	−0.85	−0.84	−0.82	−0.75	−0.79
Words	−0.86	−0.90	−0.83	−0.87	−0.85	−0.66	−0.59	−0.78
Triangles	−0.89	−0.90	−0.80	−0.80	−0.86	−0.85	−0.84	−0.93
Digits	−0.78	−0.89	−0.84	−0.92	−0.85	−0.85	−0.87	−0.87
Variance %	67.4	75.9	68.2	74.0	72.0	63.7	59.3	71.8
(c) Amplitude to targets (normal controls)								
Pictures	−0.88	−0.87	−0.77	−0.65	−0.88	−0.55	−0.86	−0.76
Words	−0.85	−0.82	−0.92	−0.92	−0.80	−0.73	−0.79	−0.70
Triangles	−0.72	−0.81	−0.85	−0.87	−0.76	−0.78	−0.63	−0.72
Digits	−0.73	−0.76	−0.85	−0.77	−0.71	−0.77	−0.68	−0.79
Variance %	63.8	66.1	72.5	65.4	62.4	50.5	55.7	54.9
(d) Amplitude to targets (hyperactives)								
Pictures	−0.51	−0.63	−0.75	−0.77	−0.75	−0.86	−0.70	−0.72
Words	−0.83	−0.61	−0.88	−0.86	−0.83	−0.82	−0.86	−0.85
Triangles	−0.82	−0.72	−0.90	−0.86	−0.89	−0.82	−0.85	−0.82
Digits	−0.79	−0.84	−0.83	−0.83	−0.85	−0.80	−0.80	−0.77
Variance %	56.0	49.9	70.9	68.9	69.2	68.0	64.7	62.8
(e) Latency to non-targets (normal controls)								
Pictures	−0.88	−0.89	−0.86	−0.77	−0.83	−0.87	−0.74	−0.88
Words	−0.93	−0.84	−0.78	−0.89	−0.91	−0.91	−0.81	−0.77
Triangles	−0.86	−0.89	−0.84	−0.90	−0.88	−0.86	−0.87	−0.87
Digits	−0.87	−0.84	−0.93	−0.84	−0.90	−0.89	−0.49	−0.86
Variance %	78.3	75.2	72.7	72.5	77.3	78.1	54.9	71.6
(f) Latency to non-targets (hyperactives)								
Pictures	−0.89	−0.85	−0.71	−0.91	−0.87	−0.87	−0.49	−0.67
Words	−0.80	−0.88	−0.61	−0.95	−0.96	−0.90	−0.75	−0.81
Triangles	−0.82	−0.81	−0.76	−0.67	−0.59	−0.40	−0.37	−0.54
Digits	−0.69	−0.76	−0.55	−0.82	−0.88	−0.90	−0.83	−0.89
Variance %	64.4	67.8	43.6	71.3	69.9	63.3	41.0	54.3
(g) Latency to targets (normal control)								
Pictures	−0.57	−0.17	−0.83	−0.72	−0.66	−0.58	−0.79	−0.75
Words	−0.82	−0.80	−0.55	−0.61	−0.92	−0.79	−0.77	−0.78
Triangles	−0.79	−0.85	−0.79	−0.61	−0.77	−0.78	−0.73	−0.66
Digits	−0.79	−0.85	−0.72	−0.76	−0.85	−0.84	−0.75	−0.73
Variance %	56.2	53.0	53.4	46.0	64.9	56.6	57.5	53.2
(h) Latency to targets (hyperactives)								
Pictures	−0.85	−0.89	−0.49	−0.74	−0.88	−0.81	−0.45	−0.79
Words	−0.88	−0.85	−0.68	−0.80	−0.72	−0.66	−0.37	−0.23
Triangles	−0.82	−0.81	−0.84	−0.80	−0.72	−0.65	−0.77	−0.77
Digits	−0.67	−0.79	−0.47	−0.64	−0.86	−0.87	−0.89	−0.30
Variance %	65.7	69.5	40.8	55.6	64.0	56.9	43.4	34.1

Factor loadings of the first component provided by principal component analyses carried out on amplitude measures of the P250, N250, P350 and P500 waves (non-target vs. target ERP, left vs. right montage).

References

Annet, M. A classification of hand preference by association analysis. Br. J. Psychol., 1970, 61: 303–321.

Beran, R. and Ducharme, G.R. Asymptotic Theory for Bootstrap Methods in Statistics. Centre de Recherches Mathématiques, Université de Montréal, Montreal, 1991.

Blinkhorn, S. and Hendrickson, D.E. Averaged evoked responses and psychometric intelligence. Nature, 1982, 295: 596–597.

Callaway, E. Correlations between averaged evoked potentials and measures of intelligence. Arch. Gen. Psychiat., 1973, 29: 553–558.

Cattell, R. Abilities: Their Structures, Growth and Action. Haughton, Boston, MA, 1890.

Chevrie-Muller, C., Simon, A.M. and Lenormand, M.T. Echelle de Développement Cognitif de l'Enfant. Editions Scientifiques et Psychologiques, Issy-les-Moulineaux, 1984.

Conners, K. Diagnosis of attention deficit hyperactivity disorder. In: K. Conners and M. Kinsbourne (Eds.), Attention Deficit Hyperactivity Disorder. MMV Medizin Verlag, Munich, 1990: 17–35.

Courchesne, E. Neurophysiological correlates of cognitive development: changes in long-latency event-related potentials from childhood to adulthood. Electroenceph. clin. Neurophysiol., 1978, 45: 468–482.

Courchesne, E. From infancy to adulthood: the neurophysiological correlates of cognition. In: J.E. Desmedt (Ed.), Cognitive Components in Cerebral Event-Related Potentials and Selective Attention. Progress in Clinical Neurophysiology, Vol. 6. Karger, Basel, 1979: 224–242.

Davis, F.B. The measurement of mental capability through evoked potential recording. Educ. Rec. Res. Bull., 1971, 1: 1–171.

Donchin, E. and Coles, M.G.H. Is the P300 component a manifestation of context updating? Behav. Brain Sci., 1988, 11: 357–374.

DSM III-R. Diagnostic and Statistical Manual of Mental Disorders, 1st Edition. American Psychiatric Association, Washington, DC, 1987.

Efron, B. The Jacknife, the Bootstrap and other Resampling Plans. Siam, Philadelphia, PA, 1982.

Engel, R. and Henderson, N.B. Visual evoked responses and IQ scores at school age. Dev. Med. Child Neurol., 1973, 15: 136–145.

Ertl, J. and Schafer, E. Brain response correlates of psychometric intelligence. Nature, 1969, 223: 421–422.

Galton, F. Inquiries into Human Faculty and its Development. McMillan, London, 1883.

Goyette, C.H., Conners, C.K. and Ulrich, R.F. Normative data on Revised Conners Parent and Teacher rating scales. J. Abnorm. Child. Psychol., 1978, 6: 221–236.

Haier, R.J., Robinson, D.L., Braden, W. and Williams, D. Electrical potentials of the cerebral cortex and psychometric intelligence. Pers. Individ. Diff., 1983, 4: 591–599.

Haier, J.H., Siegel, Jr., B.V., Neuchterlein, K.H., Hazlett, E., Wu, J.C., Paek, J., Browning, H.L. and Buchsbaum, M.S. Cortical metabolic rate correlates of abstract reasoning and attention studies with positron emission tomography. Intelligence, 1988, 12: 199–217.

Haier, J.H., Siegel, Jr., B.V., MacLachlan, A., Soderling, E., Lottenberg, S. and Buchsbaum, M.S. Regional glucose metabolic changes after learning a complex visuo-spatial motor task: a positron emission tomography study. Brain Res., 1992, 570: 134–143.

Holcomb, P.J., Ackerman, P.T. and Dykman, R.A. Cognitive event-related potentials in children with attention and reading deficits. Psychophysiology, 1985, 22: 656–667.

Inhelder, B., Sinclair, H. and Bovet, M. Apprentissage et Structures de la Connaissance. Presses Universitaires de France, Paris, 1974.

Jasper, H.H. The 10–20 electrode system of the International Federation. Electroenceph. clin. Neurophysiol., 1958, 10: 371–375.

Kenemans, J.L., Verbaten, M.N., Roelofs, J.-W. and Slangen, J.L. "Initial" and "change orienting reactions": an analysis based on visual single-trial event-related potentials. Biol. Psychol., 1989, 28: 199–226.

Klorman, R., Salzman, L.F. and Borgstedt, A.D. Brain event-related potential in evaluation of cognitive deficits in attention deficit disorder and outcome of stimulant therapy. In: L.W. Bloomingdale (Ed.), Attention Deficit Disorder, Vol. 3. Pergamon Press, Oxford, 1988: 49–80.

Kurtzberg, D., Vaughan, H.G. and Kreutzer, J. Task-related cortical potential in children. In: J.E. Desmedt (Ed.), Cognitive Component in Cerebral Event-Related Potentials and Selective Attention. Progress in Clinical Neurophysiology, Vol. 6. Karger, Basel, 1979: 216–223.

Morisson, D. Applied Linear Statistical Models. Prentice Hall, Englewood Cliffs, NJ, 1983.

Piaget, J. and Inhelder, B. La Genèse des Structures Logiques Elémentaires. Delachaux et Niestlé, Neuchatel, 1959.

Piaget, J., Inhelder, B. and Szeminska, A. La Géométrie Spontanée de l'Enfant. Presses Universitaires de France, Paris, 1949.

Raven, J.C., Court, J.H. and Raven, J. Manual for Raven's Progressive Matrices and Vocabulary Scales. Section 3. Standard Progressive Matrices. Lewis, London, 1953 (1983 edition).

Renault, B., Ragot, R., Lesèvre, N. and Rémond, A. Onset and offset of brain events as indices of mental chronometry. Science, 1982, 215: 1413–1415.

Ritter, W., Simson, R., Vaughan, Jr., H.G. and Macht, M. Manipulation of event-related potential manifestations of information processing stages. Science, 1982, 218: 909–911.

Ritter, W., Simson, R. and Vaughan, Jr., H.G. Event-related potential correlates of two stages of information processing in physical and semantic discrimination tasks. Psychophysiology, 1983, 20: 168–179.

Robaey, P., Laget, P. and Creff, J. ERP study of the development of the holistic and analytic modes of processing between 6 and 8 years. Int. J. Psychophysiol., 1989, 8: 145–153.

Robaey, P., Breton, F., Dugas, M. and Renault, B. An event-related potential study of controlled and automatic processes in 6–8 years boys with attention deficit hyperactivity disorder. Electroenceph. clin. Neurophysiol., 1992, 82: 330–340.

Schucard, D.W. and Horn, J.L. Evoked cortical potentials and measurement of human abilities. J. Comp. Physiol. Psychol., 1972, 78: 59–68.

Spearman, C. General intelligence, objectively determined and measured. Am. J. Psychol., 1904, 15: 201–293.

Stauder, J.E.A., Molenaar, P.C.M. and Van der Molen, M.W. Event-related brain potential analysis of the conservation of liquid quantity. Child Dev., 1993, 64: 769–788.

Sternberg, R.J. Toward a triarchic theory of human intelligence. Behav. Brain Sci., 1984, 7: 269–315.

Taylor, M.J. Developmental changes in ERPs to visual language stimuli. Biol. Psychol., 1988, 26: 321–338.

Vetterly, C.F. and Furedy, J.F. Evoked potential correlates of intelligence: some problems with Hendrickson's string measure of evoked potential complexity and error theory of intelligence. Int. J. Psychophysiol., 1985, 3: 1–3.

Vögel, F., Krüger, J., Schalt, E., Schnobel, R. and Hassling, L. No consistent relationships between oscillations and latencies of visually and auditory evoked EEG potentials and measures of mental performance. Hum. Neurobiol., 1987, 6: 173–182.

WISC-R. Echelle d'Intelligence de Wechsler pour Enfants – Forme Révisée. Editions du Centre de Psychologie Appliquée, Paris, 1981.