Perspectives of Event-Related Potentials Research (EEG Suppl. 44)
Editors: G. Karmos, M. Molnár, V. Csépe, I. Czigler and J. E. Desmedt

ERP changes with intelligence and development in children

P. Robaey[a,b,d], S. Cansino[c] and B. Renault[d]

[a]*Département de Psychiatrie, Hôpital Sainte-Justine, 3100, rue Ellendale, H3S 1W3 Montréal, Québec (Canada);*
[b]*Service de Psychopathologie Infantile, Hôpital Robert Debré, 48 Bd Sérurier, 75019 Paris (France);*
[c]*Facultad de Psichologia, Universitad Nacional Autonoma de Mexico, Av. Universitad 300 Cd. Universitaria, CP04510, Mexico D.F. and Departamento de Neurobiologia de Desarrollo, Instituto Nacional de Perinatologia, Montes Urales 800, Lomas Virreyes, CP 11000, Mexico D.F. (Mexico); and* [d]*CNRS-URA 654, LENA, Paris 6, Hôpital de la Salpêtrière, 47, Bd. de l'Hôpital, 75651 Paris Cedex 13 (France)*

Intelligence theories can be divided into two groups: low- and high-level, respectively. Low-level theories propose that intelligence is determined by biological characteristics of the brain. In contrast, high-level models regard intelligence as determined by culturally and experientially driven characteristics of cognitive functions. Most of the evoked potential (EP) studies on intelligence refer to low-level models. EPs are supposedly knowledge-free and are used as 'pure brain activities' measures to set up correlations with intelligence test scores. Most of these studies were based, either explicitly or not, on Spearman' s (1904) proposal, being that a general factor ('g') permeates all aspects of intelligent behavior. Speed, or brain efficiency, are the factors that would account for differences in g, and neurophysiological variables are expected to provide reliable measures of these functional characteristics.

Low-level models

One of the oldest models of intelligence suggests that the speed of processing could be critical (Galton 1883; Cattell 1890). Ertl and Schafer (1969) proposed that the processing speed could be measured by the latencies of the first early waves of the EP. In a study involving 573 children (aged 8–14 y), significant negative correlations (ranging from –.18 to –.35) between the latencies of the first 4 components of visual EPs and the Wechsler's IQs were obtained. Several subsequent studies have confirmed these findings (Schucard and Horn 1972; Callaway 1973), but others have not (Davis 1971; Engel and Henderson 1973). In addition, the size of these latency-based correlations were comparable to those yielded by other low-level cognitive measures and were thus not very convincing.

However, much more impressive correlations were found by other authors who were examining changes in the form of EPs. By measuring the length of the contour of the waveform during the first 250 msec (as if a piece of string was placed around the trace), correlations as high as .35 were obtained. Furthermore, using highly selected subjects, these correlations were found to be in the order of .7–.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 can be expected to be more spiky because the different epochs that are included in the average have stable peaks and troughs. Therefore, higher IQs should be manifested by spikier EP

Correspondence to: P. Robaey, Département de Psychiatrie, Hôpital Sainte-Justine, 3100 Ellendale, H3S 1W3 Montréal, Québec, Canada.

waveforms. 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 .13 to .50), while more recently Vōgel et al. (1987) failed to observe a consistent relationship between the complexity of visual EPs and intelligence.

Arousal and inhibition were two other low-level parameters of brain functioning tentatively related to intelligence. Using the string measure (taken over 500 msec), Haier et al. (1983) found that the magnitude of the correlation was related systematically to the stimulus intensity, with the maximum correlation (.69) obtained at an intermediate level of light intensity. As the EP measures that relate most clearly to stimulus intensity are also those that relate to intelligence, Haier proposed that higher intelligence is a consequence of greater activation in response to a normal level of stimulation. The arousal level was also of interest to Robinson (1989). He found that IQ differences were systematically related to EP variables that were expected to measure different aspects of thalamo-cortical arousability. On this basis, middling arousability was proposed as 'the neurological determinant of Spearman's g'. Using a counting and a passive condition, Shucard and Horn (1972) observed a consistent pattern of correlations between measures of intelligence and latencies of visual EPs recorded from the fronto-parietal scalp. These correlations generally increased in magnitude when going from the counting to the passive condition. These authors concluded that bright subjects tend to maintain their alertness even during a rather boring passive condition.

Shafer (1985) tested the working hypothesis that inhibition would relate to individual differences in intelligent behavior. The modulation of EPs according to temporal expectation was expected to reflect such inhibition ability. Shafer showed that people who produced smaller EPs to stimuli whose timing they knew, and larger EPs to temporally unexpected stimuli, had higher IQs. In addition, people who showed a larger amplitude decrease to repetitive stimuli also had higher IQs. He therefore concluded (Shafer 1985, p. 241) that 'the brain that inhibits its response to insignificant inputs is also the brain that shows high behavioral intelligence'.

In all these studies supporting low-level models of intelligence, the main assumption is that EPs may be used as direct indicators of neural functioning characteristics. Faithful synapse transmission, for example, was supposedly indexed by the global EP form. However, EPs are clearly complex phenomena, determined by factors as different as interactions between multiple sources, or distortions due to different conductive properties, going from brain generators to the scalp. To predict intelligence test scores by EP measures thus appears difficult until the exact relationships between neural activities and neurophysiological measures are discovered.

High-level models

On the other hand, in high-level models, intelligence is seen as related to a set of different cognitive processes. Consequently, it would make sense to use tasks that specifically address these issues. Event-related potentials (ERPs) recorded during reaction time tasks might give more appropriate measures than early components of EPs recorded in passive condition. In addition, as the relationships between cognitive aspects of the tasks and ERP parameters may be experimentally determined, some predictions can be made about development or intelligence-related changes. In such high-level models, focused on cognitive functions, intelligence has to be divided into different components. Consequently, neurophysiological brain activities have to be related to test results measuring different types of intelligence.

Some authors refer to the distinction proposed by Cattell (1971) between crystallized intelligence (e.g. verbal, vocabulary, reading comprehension, information, mathematical and prior scholastic achievement) and fluid intelligence (e.g. abstract, spatial, figural and nonverbal reasoning). In their previously cited study, Shucard and Horn (1972) obtained significant correlations with fluid abilities (Gf), but not with crystallized ability (Gc). In contrast, Perry et al. (1976) found in 5-year-old children, a correlation between visual ERP variables (e.g. amplitude, latency, complexity, linearity) and the verbal score of the WPPSI, but not with the performance score. Furthermore, by using different tests related either to Gc or to Gf, Federico (1984) found that EPs recorded in the frontal, temporal and parietal regions were primarily indicators of Gc, while those recorded in the occipital regions were primarily indicators of Gf. However, these authors did not use reaction time tasks while recording brain potentials. In the study of Shucard and Horn (1972) only, the subjects were asked to count the number of stimuli; however, only one type of stimulus was used.

Assessing Piagetian intelligence led to a more appropriate use of reaction time tasks. Stauder et al. (1993) recorded ERP in an experimental analogue of a Piagetian liquid conservation task. Nonconservers showed anterior sources at 400 msec poststimulus, a response not found in conservers. The reorganization of behaviour scheme, as proposed by Piaget to account for the acquisition of conservation, would fit with the current functional interpretation (organizing and timing) assigned to the pre-frontal brain.

In their studies, Robaey et al. (in press) investigated how the rank of a subject in a particular intelligence test (assessing verbal, visuo-spatial and Piagetian abilities) would modify information processing in standard oddball tasks. Various cognitive processes are active in these tasks and some of these processes have reliable ERP markers. Correlational methods allowed the investigators to determine which assembly of these processes was related to each form of intelligence. Another issue that was addressed in this study was the difference between development and intelligence. Development refers to the cognitive abilities of a child at a given age. Intelligence is an age-free concept that refers to the relative developmental advance (or delay) of a child as compared with individuals of his (her) age group. ERPs are likely to be modified by both development and intelligence differences. If the correlations yielded by intelligence and development measures are different, these two aspects of cognition may not be viewed as related to the same use of the same process. It is thus possible to determine if a cognitive process (as indexed by an ERP component) is related in the same way to developmental and intelligence measures. The third issue of Robaey et al.'s study referred to the assumption that intelligence is based on the same processes in everyone and anyone. The relevance of this hypothesis is emphasized by the fact that intelligence tests are mainly administrated on developmentally disordered children. In addition, some processes relevant for intelligence were found (Robaey et al. 1992) to be abnormal in children with Attention Deficit Hyperactivity Disorder (DSMII-R 1987). Therefore, the assumption of possible generalization should not be taken for granted. In order to address this issue, correlations yielded by a normal control group and a clinical group diagnosed as ADHD have been compared.

The Wechsler Intelligence Scale for Children-Revised (WISC-R 1981) and the Piagetian Cognitive Development Scale for Children (CDSC 1984) were thus obtained on 30 normal control and 19 hyperactive 6–8 year-old children. Concurrently, amplitudes and latencies of a fronto-central P250 and of the parieto-occipital N250, P350 and P500 (P3b) were measured in 4 oddball tasks. Principal component analyses were performed on the intelligence measures (separately for the verbal, the performance and the Piagetian tests) in order to obtain intelligence group factors. The same procedure was performed on the ERP measures in order to obtain ERP group factors that sorted the subjects according to ERP interindividual differences. Spearman correlations were computed between the intelligence and the ERP factors scores. However, results showed that each type of intelligence was correlated (between .4 and .6) with a specific pattern of ERP amplitude change. In normal controls, verbal intelligence was related to a decrease of P500, performance intelligence to a decrease of both the N250 and the P250, Piagetian intelligence to both a decrease of the P250 and an *increase* of the P500. As P500 amplitude decreases with age, Piagetian intelligence and development are likely to be based on different uses of the process underlied by this ERP component.

In hyperactives, verbal intelligence was also related to a decrease of P500, but a significant negative correlation with the P250 was also found. Performance intelligence was correlated with P250 and N250 amplitude, as in normal control. However, the direction of the the correlations were found to be opposite according to some subtests of the performance scale. N250 was negatively correlated with Block Design scores in normal controls, but positively in hyperactives, and the difference was statistically significant. In Piagetian development, hyperactives showed a strong delay so that they could not be differentiated between themselves on this intelligence scale.

Some conclusions can be drawn from these results. First, each specific form of intelligence modifies specific aspects of information processing in the oddball tasks. This finding supports the idea that these forms of intelligence are really different, although they are usually correlated in normal children. Second, the aspects of information processing related to each type of intelligence are not necessarily the same in normal and clinical samples. Third, intelligence and development may diverge, as in Piagetian tasks.

In order to account for the direction of these correlations, speed or efficiency models are again useful. A first model would suggest that efficiency is related to the speed of information processing. In this regard, ERP peak latencies would be negatively correlated with intelligence measures. Indeed P300 latency was found (Polish et al. 1983) to be negatively correlated with specific memory test scores (Digit Span). In our data set (Robaey et al. in press), Weschler's verbal and performance scaled scores yielded negative patterns of brain waves, as they did with ERP amplitude measures. By contrast, Piagetian intelligence scaled scores did not yield a significant proportion of latency-based correlations. Speed models might fail to account for Piagetian intelligence.

However, efficiency might also be related to ERP amplitude changes. If efficiency is defined as the optimal use of available cognitive structures, it should be related to increasing amplitude of ERP waves. The rationale is that higher intelligence is a result of a better synchronization and stability in timing between multiple sources. A greater selectivity in activating brain generators might also contribute to decreases in the noise. Consequently, ERP waves may be expected to be larger because the different epochs included in the average have stable peaks and troughs. However, until the electrogenesis of ERP components is better understood, the aforementioned assumptions are even stronger than those proposed for Hendrickson's string- measure.

On the other hand, efficiency may be defined in a developmental way that represents a considerable departure from the previous model. In order to handle unexperienced situations, additional activities are required to create new cognitive schemes. However, such additional activities may disappear after the subject creates new cognitive structures. Moreover, as his expertise develops, a greater proportion of processing may be transferred to automatized subroutines. The decreasing amount of neuronal activity may be reflected by the amplitude decrease of certain ERP waves. As a consequence, brain efficiency is negatively correlated with ERP wave amplitude. Such an assumption is supported by converging experimental evidences. For example, brain waves are enhanced by the need to create new concepts or modify old ones when dealing with novel stimuli (Courchesne 1978), or by semantic incongruity (Kutas and Hillyard 1980). These causes are associated with an increase of fronto-central P3 (in adults) and N400, respectively. Developmental data are also in agreement with this model. The frontal activity observed in non-conservers but not in conservers (Stauder et al. 1993) might also fit with the proposal that reorganization of behaviour scheme requires additional activity of the pre-frontal brain. More generally, the fact that ERP waves decrease in amplitude from childhood to adulthood might partly index increasing automatization of cognitive subroutines. However, neural efficiency models are likely to be unable to account for all intelligence differences (Robaey et al. in press). P500 was positively correlated with Piagetian intelligence whereas other intelligence forms were negatively correlated; N250 was positively correlated to Block Design in hyperactives, whereas the correlation was found negative in normal controls.

In conclusion, ERPs seem to provide useful tools for assessing issues of development and intelligence. However, more work is needed, especially using paradigms designed to assess specific abilities in control as well as in defined developmentally disordered children, so that predictions based on sound models can be tested.

References

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. Psychiatry*, 1973, 29: 553–558.

Cattell, J. McK.K. Mental tests and measurements. *Mind*, 1890, 15: 373–380.

Cattell, R. *Abilities: Their Structures, Growth and Action.* Haughton, Boston, Mass., 1971.

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.

Davis, F.B. The measurement of mental capability through evoked potential recordings. *Educ. Res. Res. Bull.*, 1971, 1.

DSM III-R. Diagnostic and statistical manual of mental disorders, 1st edition. American Psychiatric Association, Washington, 1987.

CDSC, Echelle de développement cognitif de l'enfant. In: C. Chevrie-Muller, A.M. Simon and M.T. Lenormand (Eds), *Edition Scientifiques et Psychologiques*, Issy-les-Moulineaux, 1984.

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.

Federico P.A. Event-related-potential (ERP) correlates of cognitive styles, abilities and aptitudes. *Person. Individ. Diff.*, 1984, 5(5): 575–585.

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

Haier, R.J., Robinson, D.L., Braden, W. and Willians, D. Electrical potentials of the cerebral cortex and psychometric intelligence. *Person. Individ. Diff.*, 1983, 4(6): 591–599.

Kutas, M. and Hillyard, S.A. Reading between the lines: event-related potentials during natural sentence processing. *Brain Lang.*, 1980, 11: 354–373.

Perry, N., McCoy, J.G., Cunningham, W.R., Falgout, J.C. and Street, W.J. Multivariate visual evoked responses correlates of intelligence. *Psychophysiology*, 1976, 13(4): 323–329.

Polish, J., Howard, L. and Starr, A. P300 latency correlates with digit span. *Psychophysiology*, 1983, 20(6): 665–669.

Robaey, P., Cansino, S., Dugas, M. and Renault, B. A comparative study of ERP correlates of psychometric and Piagetian intelligence measures in normal and hyperactive children. *Electroenceph. Clin. Neurophysiol.*, in press.

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.

Robinson D.L. The neurophysiological base of high IQ. *Intern. J. Neurosci.*, 46, 209–234, 1989.

Shafer E.W. Neural adaptability: A biological determinant of g factor intelligence. *Behav. Brain Sci.*, 1985, 8(2): 240–241.

Shucard, D.W. and Horn, J.L. Evoked cortical potentials and measurement of human abilities. *J. Comp. Physiol. Psychol.*, 1972, 78(1): 59–68.

Stauder, J.E.A., Molenaar, P.C.M. and van der Molen, M. Scalp topography of event-related potentials and cognitive transition during childhood. *Child Devel.*, 1993, 64: 769–788.

Vetterli, 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.*, 3, 1–3, 1985.

WISC-R. Échelle d'intelligence de Wechsler pour enfants-forme révisée. *Editions du Centre de Psychologie Appliquée*, Paris, 1981.