EVENT RELATED POTENTIALS AND COGNITIVE DEVELOPMENTAL BEHAVIOR

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 1994

EVENT RELATED POTENTIALS AND

COGNITIVE DEVELOPMENTAL

BEHAVIOR

Thesis Approved:

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ACKNOWLEDGMENTS

I which to express sincere appreciation to Dr. David Thomas for his support and advice throughout my struggle with the dissertation process. Many thanks also go to Dr. Robert Weber, Dr. Fromme and Dr. Joe Weber for serving on my dissertation committee. Their suggestions and support were very helpful throughout the study.

Matchless thanks goes to Robin who gave me endless encouragement and support. Without her belief in me I would not have been able to complete the project.

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Abstract

This study investigated the relationship of cognitive developmental changes and physiological changes. Once cognitive developmental levels were assessed of 36 males, twelve each at the ages of 10, 11, and 12 years of age, event-related potentials (ERPs) were recorded during a visual "oddball" task. Cognitive developmental levels were assessed using Fischer's (1980) skill hierarchy as to their ability to derive a single abstract concept from the comparison of two concrete instances of that concept. Results showed that the amplitude of P300 was significantly greater for boys in Level 7 compared to Level 6($p < .05$). P300 latency was significantly different as a function of age, but the change was not linear. Trial-to-trial variability of the ERP was found to decrease from Level 6 to 7 with marginal significance ($p = .056$).

Visual Event Related Potentials and Cognitive Developmental Behavior

Many developmental scientists will argue that cognitive changes seen in humans from infancy to adulthood are related to corresponding brain changes (Fischer, 1987). Yet when attempting to establish specific relationships between brain and behavior development, linkages have been difficult to validate. Although this line of research has great potential, it is still in its infancy. A problem that plagues this research area is that factors that generally change with age will usually be highly correlated with other factors that change with age, yet have no direct linkage to each other. For example, as an individual physically matures, his/her shoe size will increase, as well as a later time in his/her bedtime. Yet, there is no causal relationship between the two. The correlation between shoe size and bedtime is due to a third causal link--age. When investigating the relationship between brain and behavior in cognitive development, there is, in addition to age, a second potential source of spurious correlational links: namely intelligence. Both of these factors will be addressed in the design of the study.

In designing and investigating a developmental study that looks for a robust relationship between brain and cognitive development, two primary issues need to be addressed. First, what, if any, are the stages or levels of discrete cognitive developmental change and how does one measure them? Second, what, if any, are the neural changes that might relate to significant cognitive developments in human beings?

Behavioral Manifestations of Cognitive Development

The first issue of whether there are discrete levels of cognitive change is one that has been repeatedly debated within the field of developmental psychology. How to define the systematic change in cognitive behavior of children over time has been of critical concern. In general, there tends to be two opposing positions: (a) development is a long-term accumulation of learned behaviors or rules (Klahr & Wallace, 1976; Skinner, 1969) resulting in a smooth continuous progression in cognitive development; or (b) developmental processes are mainly organismic, involving genetic factors, properties of the person's mind, and other types of endogenous influences (Piaget, 1952, 1970) manifested in stage-like spurts. Basically, this debate can be reduced to this question: Does cognitive development progress continuously throughout childhood, or are there developmental spurts, i.e., large, rapid advances in many behaviors?

Hundreds of studies have been designed to either (a) demonstrate stages, with little or no attempt to assess individual differences or environmental effects, or (b) to demonstrate environmental effects or to examine individual differences without any assessment of stages (Fischer & Silvern, 1985). Fischer (1984) asserts that the result of this volume of research is that both positions are valid: Cognitive development is both continuous and discontinuous. The evidence reveals that cognitive development is stage-like and consistent across domains, as well as involving environmental and individual differences (Flavell, 1982; Fischer et al., 1985). Therefore, several developmental scientists are channeling their efforts into theoretical frameworks that combine stages with individual differences (Fischer, 1980).

Recently, Fischer (1980) has proposed a theoretical framework called 'skill theory' that explains cognitive development by conjoining the two processes of organismic and environmental influences. Skill theory is based on two concepts: optimal level and skill acquisition. Optimal level is the upper limit of a person's performance that can be induced by supportive environmental factors. Over relatively long age spans, the individual's optimal level increases, producing a series of hierarchically organized developmental levels. Skill-acquisition processes determine how the skills are actually constructed--how the person moves from a particular skill in a given context to a more complex or general skill.

This theory proposes that children may learn new behaviors and develop new capacities almost every day; however, the emergence of a new optimal level will be manifested by a large, rapid advance in many behaviors. Accordingly, individuals are limited by the complexity of the skills they can construct as defined by the developmental level they are in. When individuals are functioning at their optimal level in many skills, i.e. at the upper limit of a developmental stage, a developmental spurt will be seen in a relatively short period of time. When they are not performing at their optimal level in many skills, change occurs gradually over a longer period of time (Fischer et al., 1984).

Fischer and Silvern (1985) propose that human beings move through at least eight developmental levels between birth and 18 years of age, and yet the behavior of a child within any domain will vary as a result of environmental support and arousal state. Competence does not seem to be a point but a range or zone on a developmental scale, with both environmental and organismic influences affecting movement within that zone (Fischer et al., 1985). Strong support for the hypothesis of optimal levels is seen in infant development. If spurts in developmental change are used to index emergence of a level, the ages for the levels seem to be 3 to 4 months, 7 to 8 months, 11 to 13 months, and 20 to 24 months--the age for Levels 1 to 4 in skill theory (Corrigan, 1983; Fischer, 1982; Kagan, 1982; McCall, 1983; Zelazo & Leonard, 1983). The emergence of later levels appear during childhood at approximately 4, 7 and 11 years; in adolescence and adulthood, they appear at 15, 19 and perhaps 25 years (e.g., Biggs & Collis, 1982; Epstein, 1974, 1980; Fischer, Hand & Russell, 1983; Jaques, Gibson & Isaac, 1978; Kenny, 1983; Kitchener, 1983; Peters & Zaidel, 1981; Tabor et al., 1981).

Complex conceptual skills have been described by Jean Piaget (Inhelder & Piaget, 1958; Piaget, 1970, 1952) as the stage of formal operations. This change occurs at 10-12 years and marks the start of the development of abstract thinking (Fischer, 1980). According to skill theory an individual gradually moves from being limited to the concrete toward an ability to organize concrete experiences into abstract categories and relations. Between the ages of 10 and 18, skill theory proposes there are two levels of abstraction: Level 7, single abstractions, and Level 8, abstract mappings.

The important conceptual skill that is acquired at Level 7 is the ability to compare two concrete instances of concepts (Fischer et al., 1984). For example, an individual entering this level of development would be able to generate a general definition of arithmetic concepts for addition and subtraction. Other single abstractions include personality descriptions such as conformity or hypocrisy and sociomoral concepts such as law, society, or justice. With this new ability, preadolescents can start to understand abstract concepts as they are used by adults (Fischer et al., 1984).

According to skill theory, the two conceptual processes (optimal level and skill acquisition) in normal development should manifest themselves in the same age period despite individual differences in intelligence and limitations on memory (Fischer et. al., 1984). This theory proposes that regardless of the IQ level of a child, progression through the developmental levels will occur in approximately the same age range under environmental conditions that produce optimal performance. At a given age, people do not vary widely in optimal level; most individuals develop each optimal level at about the same age. On the other hand, skill-acquisition processes demonstrate large individual differences (Flavell, 1982). In children, performance on standard intelligence tests varies as a function of both factors, but skill-acquisition processes account for much more of what psychologists traditionally assess on such tests (Fischer et al., 1984).

Many theories of cognitive development are based on the information-processing approach which suggests that one of the fundamental bases of large-scale developmental changes is improvement in short-term or working memory. Skill theory proposes a contrasting explanation for the improvement in short-term or working memory in cognitive development. As previously described, optimal level is the limit on the type of skill structure the person can construct and control. The within-level acquisition process (skill acquisition) is limited by the number of components that can be combined into a single skill. The emergence of a new optimal level provides the capacity to reorganize skills in a more efficient way (Fischer et al., 1984). The resulting efficiency is not due to an increase in the number of items that can be held in working memory but from a change in the type of structure that can be controlled. Because optimal level limits the reorganization of a skill, the within-level rules are used to create more complex skill structures at a given level. These more complex skill structures require more memory resources than do the simpler structures of that level placing greater demands on processing (Fischer & Pipp, 1984). For example, children who are in Level 6 will progressively increase in their ability to utilize their memory capacity. When the child advances into Level 7, the cognitive change results in a qualitatively different skill structure rather than a memory capacity increase. The memory capacity is constant and only appears to increase within the level at which the child is operating cognitively.

Fischer and Pipp (1984) designed a study to test skill theory using a method of multiple tasks. Subjects were middle-class Anglo students in Denver: four males and four females for every year of age from 9 to 20 (Fischer et al., 1984). A set of tasks was devised for each developmental level and subjects performed them under four environmental conditions varying in the degree to which optimal performance was promoted. The condition providing the least support for optimal performance, called the 'spontaneous' condition, was similar to the typical testing conditions in most cognitive-developmental research. Students were simply given several arithmetic problems for each level, without any opportunity for practice or any help from the experimenter. The condition providing the most support for optimal performance was called the 'practice and support' condition. After students had completed the problems in the spontaneous condition, they were shown an example of a good answer for each problem and they were encouraged to practice the problems on their own during the interim before the next testing session. Two weeks later they were again shown a good answer to each problem, the answer was taken away, and they were asked to provide the answer in their own words. The criterion for correct responses involved a general or abstract definition without need to refer to a concrete example. The subject could not merely state the definition in disconnected pieces or use the same prototypic definition provided by the examiner. Thus correct responses had been aided by practicing the problems for two weeks and the support of seeing a good answer to the problem.

The results revealed a markedly different pattern for the practice-and-support condition. Performance on the Level 7 task spurted at 11-12 years to over 60% correct while the spontaneous condition revealed a 10% correct rate (Fischer, Pipp & Bullock, 1984); whereas the practice-and-support condition showed several such spurts, the spontaneous condition resulted in a slow, gradual increase over a period of many years. At age 9 the performance on the Level 7 task with practice-and-support was less than 10% correct (see Figure 1). This study has also been replicated by Bullock and Pipp et al. (1990) with similar results.

Insert Figure 1 about here

The Fischer study provides a method for detecting developmental spurts by integrating two of the most potent environmental influences: practice and instruction, which typically produce dramatic improvement in performance (Fischer et al., 1984). The emphasis in Fischer's study highlights the environmental influence of cognitive development, as well as support for the conclusion that developmental spurts do occur.

Physiological Correlates of Cognitive Development

The other issue of concern involves what, if any, central nervous system changes occur which may accompany the developmental spurts seen in infants and children. During the nineteenth century one of the chief debates in physiological psychology had to do with how the brain actually controls behavior; i.e., are there specific areas that control specific behavior events--known as the specific-localization thesis--or whether the brain operates more or less as a whole in its control of behavior (Schneider & Tarshis, 1986). Research in physiological psychology has revealed that although our understanding of how the brain affects our behavior is still in an exploratory stage, there is support that there is a combination of the antilocalization and localization view of how the brain operates to control behavior. There are areas of the brain that are more involved in the control of specific behavior than other areas, as localizationist would argue, but no one area is involved in the exclusive control of a specific behavior, as antilocalizationists would argue (Schneider & Tarshis, 1986).

The frontal lobes of the cerebral cortex are traditionally considered to be the seat of the 'highest' mental functions, and the center of those activities which make us characteristically human (Beaumont, 1983). This is largely because in evolutionary terms the frontal cortex has been the most recent to evolve, and humans possess large frontal lobes that account for up to about half of the cerebral cortex (Beaumont, 1983). The frontal lobes have been associated with intelligent abilities. However since the frontal lobes are large, they may subserve many functions and as a result affect 'intelligent' behavior more than other lobes of the brain. The change in the quality of thinking most commonly linked with the frontal lobes is intelligence and abstract thought.

A review of the research in physiological psychology suggests that the emergence of developmental levels may be accompanied by major biological changes in children, including changes in brain size and brain electrical activity (Emde, Gaensbauer, & Harmon, 1976; Epstein, 1974, 1980; Kagan, 1982; White, 1970). Head circumference, which seems to relate to certain cognitive levels in infancy, does not produce clear findings in children (Epstein, 1974; McCall, Meyers, Martman & Roche, 1983; McQueen, 1982).

Neuroanatomical research in human cerebral development has been relatively scarce. In the measurement of human cortical cytoarchitecture the number of neurons at birth reaches a maximum at the age of approximately 2 months in the posterior cortex (Goldman-Rakic, 1987; Huttonlocher, 1984; Rabinowicz, 1979) and approximately 2 years in frontal cortex, after which there is an exponential slow decline to approximately the age of 6 years (Goldman-Rakic, 1987; Rakic, 1988). Research in cortical volume (Blinkov & Glezer, 1968; Schade & Groeningen, 1961) measures cerebral development. Blinkov and Glezer (1968) reported that there are critical stages in the postnatal growth and development of neocortical pyramidal cells that occur at the age of about three months postnatal, at about two to three years and about six to seven years. Another consistent feature of Blinkov and Glezer's data and Conel's (1955, 1959, 1963, 1967) data is that the frontal lobes tend to exhibit slower frequencies of oscillation over the lifespan than the more posterior cortical regions. The frontal lobes also tend to show growth spurts both early (e.g., within the first year) and late (e.g. over 17 years) over the early adulthood life span.

Electroencephalograms (EEGs) have been used in developmental research because they offer a rather direct access to the functioning of the human brain. EEGs record fluctuations in the electrical fields of the brain, and can reveal the temporal patterning of neuronal population activity associated with sensory information processing. Therefore, EEGs may reflect changes in brain functioning.

By convention, the EEG is divided into four frequency bands--delta (1.5-3.5 Hz), theta (3.5-7.5 Hz), alpha (7.5-12.5 Hz), and beta (12.5-25 Hz). Alpha waves in adults predominate during quiet, alert mental activity, especially when their eyes are closed or there is no sudden visual stimulus. The EEG of newborns is undifferentiated, irregular, and shows little evidence of any sustained rhythmic activity. A precursor of alpha waves first appears reliably at 3 to 4 months of age. Alpha waves continue to show systematic developmental changes throughout the rest of childhood, and some relationships with developmental levels have been noted (Epstein, 1980; Survillo, 1971).

Matousek and Peterson (1973) collected EEG data on 1- to 21-year old Swedish subjects measured in a quiet, awake state. A number of different measures were taken, involving different areas of the scalp and different components of the EEG. They used absolute and relative powers in 6 frequency bands. In general the results revealed that there were changes that differed across ages and scalp location.

Although Matousek and Peterson did not test for relationships with developmental level, Fischer (1987) recently reanalyzed the data and found relative energy in alpha waves in the occipital-parietal area which related consistently with age of onset of developmental levels proposed by Piaget (1970). Relative energy in the EEG is a global measure of brain-wave change. Relative energy for any particular frequency band, such as alpha, includes information from all frequency bands; it is calculated by dividing the amount of energy in alpha by the total energy at all wave frequencies. Discontinuities occurred in the alpha growth curve during the age periods for all the later developmental levels-- with spurts at approximately 4, 8, 12, and 15 years (Fischer et al., 1984). Fischer (1987) suggests that these spurts correspond to the same estimated age range proposed in skill theory for the emergence of Levels 5 through 8. Although developmental patterns were strongest in the occipital-parietal area, they were also present in weaker form in other brain areas, including the frontal

(Fischer, 1987). These findings suggest that there are basic changes in brain functioning as measured by EEGs that coincide with several of the developmental levels proposed by Piaget (1970) and more recently by Fischer (1980).

There is increasing interest in relating changes in Event Related Potential (ERP) components to changes in brain structure and function associated with cognitive development (Courchesne, 1983). ERPs represent neural activity (i.e., changes in the electrical activity of the nervous system) having a definite relationship to the occurrence of a specific physical stimulus or psychological event and the associated response (Loveless, 1983; Picton & Hink, 1974). A sensory stimulus normally triggers a sequence of relative negative and positive voltage deflections in the scalp-recorded EEG that have characteristic time delays. These electrical responses may be synchronized with time-locked external events; hence they are known as event-related potentials (ERPs) (Hillyard, 1985).

ERPs are popular clinical and research tools because they are non-invasive (Young, 1981). Except for amplitude attenuation, scalp recordings correspond reasonably well to intracranial ERP activity (Wood & Allison, 1981).

The stimulus may be of any modality (e.g., visual or auditory) and intensity depending on the investigators' requirements, but it must be abrupt in onset since slowly changing stimuli elicit poorly time-locked responses (Picton et al., 1974). The ERP must be distinguished from other irrelevant neurophysiological activity; therefore, signal averaging is typically used to examine the ERP (Young, 1981). The stimulus must be exactly controlled and reproducible since the averaging process requires consistent repetition (Picton et al., 1974).

In signal averaging, the stimulus is repeated a number of times, and on each occasion an epoch of EEG is recorded. Each epoch has the same temporal relationship with the stimulus. The EEGs are then averaged by a computer. Potentials having a consistent time-relationship with the stimulus will summate, while the spontaneous activity, which is not time locked, will tend to average to zero. Signal averaging thus improves the signal-to-noise ratio; this improvement is approximately proportional to the square root of the number of trials averaged (Loveless, 1983; Young, 1981).

Averaging produces a complex waveform consisting of a sequence of components, potentials generated by groups of cells in different parts of the brain which become active at different times after stimulus presentation (Loveless, 1983). The latencies of these components will vary with changes in the stimulus parameters (i.e., the sensory modality and type of stimulus) or with the subjective state of the subject (Loveless, 1983). The waveform will also vary according to the nature of the cognitive and perceptual processes that are being engaged (Hillyard, 1985).

In the auditory modality, the early components, waves I-IV, have a latency of 1-18 ms post-stimulus and originate from the auditory pathways and nuclei of the brainstem. The middle latency components, waves No-Nb, have a latency of 18-45 ms post-stimulus and may derive from a deep structure such as the thalamus. The late components (greater than 45 ms), P1, N1, P2, N2, and P3, of the auditory and visual ERP have been extensively investigated. They are of relatively large amplitude and probably originate in the cortex (Loveless, 1983).

In general, the ERP components with latencies less than 60-80 ms represent evoked activity that is relatively independent of the psychological state of the subject. These exogenous or evoked components are highly sensitive to both the physical parameters of the eliciting stimulus and the integrity of the mediating neural structures. The exogenous components are useful for the diagnosis of neurological diseases that affect the sensory pathways. The later components, the waves occurring after 80 ms, do vary according to the state of the subject and the type and degree of higher stimulus processing.

Two variables of the wave component are typically of interest: the latency of the wave component from stimulus onset and the amplitude of the wave component. There are three related problems regarding the ERP. The first is that during signal averaging, wave activity that is not time-locked will tend to average out to zero. Therefore, the variability of the onset of each wave component (i.e., the temporal variability) will affect the amplitude of the ERP. Finding that one ERP is larger in amplitude than another ERP does not necessarily indicate a larger amplitude neural response. Unless the onset of each wave component is 'lined up' before the amplitude averaging is performed, the amplitude of the wave in the ERP may appear artificially lower than the true average of the individual trials. Therefore, the second problem occurs; that is, the average is not representative of the single trials. The average amplitude may not represent the amplitude in the single trials due to the latency variability across the single trials. The third problem is that although the investigator has a mean waveform, there is no measure of the variance of the amplitude and latency across the single trials (Thomas, Neer & Price, 1989).

Due to the limitations in the signal averaging procedure, several investigators have begun analyzing ERP data at the level of single trials. These techniques give information about the amplitude and the temporal variability of the ERP components in the individual trials. Since, theoretically, the amplitude of the average ERP is directly related to the single trial amplitudes and is inversely related to the amount of temporal variability in the single trials, single trial analysis allows the investigator to estimate the contribution of each of these factors to ERP amplitude (Thomas et al., 1989).

One method of single trial analysis that is of interest here is the template-matching procedure, based on the Woody adaptive filter (Woody, 1967) and reported by Michalewisk, Prasher, and Starr (1986) and Thomas et al. (1989). In this method a template is created from the average ERP for each individual wave component of interest. A given time window is then searched in each single trial to find the point of maximum correlation with the template. This point of maximum correlation identifies the component within the single trial, allowing both the amplitude and latency to be calculated. In addition, one is able to assess the relative contribution of the amplitude and latency variability to the ERP. In other words, the template-matching procedure helps to answer the question of whether an increase in the amplitude of the ERP is due to increases in amplitude of individual trials or is due to a decrease in the temporal variability of the single trials. Another advantage of this procedure is that it enables the computer to 'line up' the peaks of interest across all the individual trials. This gives a better measure of the average amplitude of that peak since it removes the confounding factor of difference in time of onset of that peak (Woody, 1967).

A review of the research relating ERP changes to cognitive development reveals there are three measures of brain activity that are potentially associated with developmental change. The first involves a developmental change in the P300 wave of the ERP, specifically changes in the latency and amplitude. The second potential measure involves the underlying network of brain neural activity. It appears that the underlying network increases and becomes more discrete with development. The last potential measure involves the efficiency of ERPs; i.e., that information that is coded and transmitted in the brain becomes less error prone as an individual develops cognitively. These three measures are reviewed below.

P300 wave changes. The P300 wave of the ERP is often studied because it is so large in some circumstances that it is rather difficult to overlook. P300 is a broad, positive component, peaking at about 300-600 ms after stimulus onset, with maximal amplitudes at parietal and central midline recording sites of the scalp (measured as potential differences, against the ears or the nose) (Verleger, 1988). The P300 wave has become to be seen as an "endogenous" component of the ERP since it appears to be relatively insensitive to the physical attributes of the stimuli presented (Donchin & Coles, 1988). The P300 is often viewed as a surface manifestion of an internal information-processing operation (Donchin, et al., 1988). Consequently there have been numerous research studies attempting to link psychological and cognitive attributes to this wave. Although the specific intracranial sources that generate the potentials are generally unknown, the P300 wave appears to be involved in memory and decision making (Hillyard, 1985).

Despite the potential value of ERPs in the study of cognitive development, only a few studies have attempted to investigate the developmental trends of the P300 in both young children and adults. Kurtzberg et al. (1979) conducted a longitudinal study of cognitive components. They recorded visual ERPs in a simple visual discrimination task using 5- to 8- year-olds. Each subject was tested three times at one year intervals. A P300 wave component was found over the central, parietal and temporal scalp sites in response to target events but not to non-target events. Across the three recording sessions, P300 mean latency changed from 400 ms to 325 ms and its amplitude became more prominent over right parietal sites. Mean reaction time (RT) to target events changed in a similar fashion decreasing from 340 ms to 280 ms. Kurtzburg et al. (1979) suggested that the ERP and RT changes reflect developmental changes of parietal association areas involved in non-verbal information processing. The RT-ERP changes suggest that changes in the speed of processing may be attributable, in part, to functional alterations in some neural areas active in processing (Courchesne, 1983).

In 1979 Courchesne conducted a study that attempted to investigate the developmental changes in late ERP waves in 6- to 36-year olds (Courchesne, 1979). Courchesne attempted to collect information that would facilitate an understanding of the development of cognitive processes and neural systems underlying them (Courchesne, 1979). ERPs to tachistoscopically flashed slides were recorded from parietal, central and frontal lateral scalp sites (Pz, Cz, and Fz). Subjects received two different types of stimulus events: those which were explicitly categorized for the subject (i.e., targets and backgrounds), and those which were not (i.e., dims and novels), thereby leaving the subject to categorize the event according to his/her own internal rules (Courchesne, 1979).

The findings revealed that the most dramatic age-related change was in P300 latency for the explicitly categorized event (i.e. targets and backgrounds), which was nearly 300 msec longer in children (ca. 700 msec) than in adults (ca. 410 msec). Adult latencies were not reached until midteens or later (Courchesne, 1979).

Courchesne retested the majority of children and pre-adolescents who participated in a previous study of visual ERP changes associated with development

(Courchesne, 1983). The original 6-8 year olds were now 10-13 years old and the original 10-13 year olds were now 14-18 years old. The results of this longitudinal study confirmed many of the original findings in the initial cross-sectional study. Of interest to this study, the parietal P300 to targets decreased in latency with age (Courchesne, 1983).

Courchesne et al. (1987) conducted a series of studies investigating changes in auditory and visual ERPs associated with development from childhood to adulthood (Courchesne, 1977, 1978, 1979). The following age groups were studied: 4-5, 6-8, 10-13, 14-18, and 23-44 years. Analogous auditory and visual paradigms were used. Each paradigm incorporated two general types of events: (a) bizarre, 'unrecognizable' or 'novel' events not seen or heard before by the subject and (b) precisely specified events. ERPs were recorded from electrodes below the right eye, above the right eye, at the outer canthus of the left eye, at Fz, Cz and Pz.

Courchesne et al. (1987) presented the results of this study and a previous visual study already published in a combined data analysis. Results revealed the following findings with regard to the target ERPs: (a) in visual and auditory modalities in each age group, the P300 component was maximal in amplitude at the parietal electrode, and (b) in both modalities, P300 decreased in latency with age in concert with response time and reached adult values by adolescence.

Friedman, Sutton and Putnam (1987) conducted a cross-sectional sampling of subjects between 6 and 39 years, grouped into 7 age categories (6-7, 8-9, 10-11, 12-13, 14-15, 16-17, and adult 20-39) to investigate child/adult differences in cognitive ERPs elicited by pictorial stimuli. Subjects were instructed to respond 'same' or 'different' by pressing one of two choice keys to a two-alike pictorial slide sequence. The results revealed (a) P300 was seen in all age groups, at about 700 msec in children and 500 msec in adolescents and adults; (b) P300 latency decreased with age; (c) P300 latency increased with complexity of the instruction condition (Friedman et al., 1987). There was a marked discontinuity in P300 latency between the 10-11 and the 12-13 year old age groups, as well as across all ages, with a faster P300 latency to the 'same' matches than to 'different' matches (Friedman et al., 1987).

Due to the developmental changes observed in the P300, a study by Howard and Polich (1985) attempted to compare P300 latency and memory span development for children and adults. Subjects included 24 children ranging in age from 5 to 14 years and 24 adults ranging in age from 20 to 40 years. Auditory P300 recordings were made using an 'odd-ball' stimulus detection paradigm. The results indicated that as memory span increased (as measured by the Digit Span on the Wechsler Adult Intelligence Scale), P300 peak latency decreased dramatically for the younger subjects relative to the adults (Howard & Polich, 1985). P300 latency became shorter for the children (r = -.46) and somewhat longer for the adults (r = .21) as age increased. Partialing out the effects of age on component latency, the coefficient between P300 latency and memory score for the children remained substantial: r = -.43 (Howard et al., 1985).

A study by Ladish and Polich (1989) investigated P300 amplitude and latency in three groups of 12 children each, ages 5-9, 10-14, and 15-19 years. The study was designed to provide data on the relationship between P300 and cognitive development using short-term memory changes as a component in P300 amplitude and latency changes. They found that the middle and older subjects tended to produce larger central and parietal P300 amplitudes as compared to the younger subjects.

Also there were age group differences such that the older subjects produced shorter P300 latencies than the younger subjects ($F(2,30) = 8.6$, $p < .10$).

A summary of the salient features that are relevant to the issue under consideration is as follows: (a) ERP components associated with cognitive processes are different in children and adults; (b) these differences are both quantitative and qualitative; (c) the transition from childhood ERP waveforms to adulthood waveforms is gradual; however, this does not mean that the rate of change is necessarily constant; (d) components reach 'maturity' at different ages (for example, P300 reaches maturity during pre-adolescence and adolescence); and (e) the P300 component may have very similar characteristics in both visual and auditory modalities but that developmental changes occur within visual and auditory evoked potentials at differing scalp locations (Courchesne, 1983). Therefore, the P300 wave component has relatively strong endogenous developmental changes that relate to cognitive processing. Thus, there is strong support that the endogenous P300 wave changes developmentally in both its latency and amplitude and it has been shown to be related to cognitive processing, but thus far, research has not looked for specific discontinuities in its developmental changes. Prior research has investigated only general trends. Despite the lack of focus on this issue, a study by Friedman et al. (1987) found a marked discontinuity in the P300 latency between the 10-11 and the 12-13 year old age groups.

It is not surprising that endogenous discontinuities have not been noted since the problem that plagues the research in cognitive development as measured behaviorally will also be a problem within this area. To detect a real discontinuity, the qualitative change must be substantial enough to be measured. Therefore, in order to detect significant brain wave changes that reflect endogenous changes and are possibly related to cognitive levels, individuals within a group need to be clearly operating within the same cognitive level. As previously discussed, a group of 10 year olds may be in different levels of cognitive development. It is for this reason that this study has investigated the changes in the latency and amplitude of the P300 wave in children that are measured to be in one of the two levels (Level 6 or Level 7) of cognitive development as proposed by Fischer (1980).

Underlying network change. A second potential measure of developmental change involves investigating the underlying network of brain neural activity. A recent study attempted to use EEG coherence and phase network analyses to investigate cerebral hemispheric development in a large cross-sectional study of normal children ranging in age from 2 months to early adulthood (Thatcher, Walker & Giudice, 1987). Coherence is equivalent to the absolute value of the cross-correlation function in the frequency domain and reflects the number and strength of connections between spatially distant generators (Otnes & Enochson, 1972). For example, increased coherence is due to either an increase in the number and/or strength of connections between assemblies of neurons (Thatcher, 1992, in press). Measures of phase provide estimates of lead and lag times between spatially separate but connected systems of generators as well as measures of frequency dispersion and conduction velocity (Thatcher, Krause & Hrybyk, 1986; Nunez, 1981).

The advantages of EEG coherence and phase are that they reflect cortico-cortical connectivity properties of both short- and long-distance axonal systems and are relatively insensitive to volume conduction, especially at scalp distances greater than 7 cm (Thatcher et al., 1986; Nunez, 1981). In other words, measures of phase and coherence provide information about the interconnected relationship between distant electrode sites.

The significant finding from Thatcher et al. (1987) revealed certain consistent and stable patterns of EEG development. In general, there were five dominant growth periods in intrahemispheric cortico-cortical coupling from birth to adulthood (Thatcher et al., 1987). The timing of the EEG changes overlapped with the timing for the Piagetian stages of human cognitive development: 0-3 years; 4-6 years; 8-10 years; 11-14 years and from 15 to adulthood (Thatcher et al., 1987). One of the conclusions of the Thatcher (1987) study was that most if not all of the growth spurts in EEG coherence and phase involved frontal lobe connections. For example, the frontal-central, frontal-temporal, frontal-parietal, frontal-occiptal, and local frontal connections developed at different rates in the left and right hemisphere until approximately puberty (e.g., 11 to 14 years), after which there were nearly synchronous bilateral frontal lobe growth spurts. Thatcher (1991) proposes that the unfolding and elaboration of connections with the different zones of the frontal lobes seems to be a dominant feature of human cerebral development and this process appears to occur in stages or as a discontinuous function of age (Blinkov & Glezer, 1968; Hudspeth & Pribram, 1990; Schade & Groeningen, 1961; Thatcher et al., 1987).

A study designed by Karrar and Johnson (1986) using ERP changes instead of EEG changes investigated a hypothesis similar to the one generated by the Thatcher et al. study. They proposed that the underlying network of brain neural activity and the strength of the coupling between spatially separate but connected systems of generators should increase with development. Karrar et al. studied the underlying network and coupling pattern of slow event-related potentials by computing the intercorrelations between electrodes in 3 different tasks. One task was a simple non-warned reaction time (RT) to a light flash; the second task entailed the same response emitted by the subject rather than elicited by a 'go' signal; and the third task involved a tone followed 1.5 sec later by a letter. Subjects were instructed to memorize sets of 1, 3, or 5 letters prior to performance. These letters were presented on half the trials, while new letters were given on the other half. ERPs were recorded from one group of retarded young adults and 3 groups of normals: young children, pre-adolescents, and young adults. Electrodes were placed at frontal, central, occipital, C3 and C4 (lateral-central). The areas under the curves were separately determined for both positive and negative activity on each trial. Regional coupling was determined by computing Pearson correlations for each subject across trials of the area measured between each lead combination (10 combinations). These within- subject correlations were the data for analyses of changes in brain organization with age and with levels of IQ, response time, and memory performance (Karrar & Johnson, 1986). The strength of the coupling between lead combinations was measured by the degree to which the leads correlated. In other words, Karrar et al. inferred that the higher the correlation measure, the stronger the coupling.

In general, the results revealed: (a) an increase in the extent of coupling with age, especially for measures of positivity; (b) significant similarity of coupling pattern for individuals within each group as well as across groups; (c) central coupling was strongest, frontal coupling was next, and occipital weakest; and (d) there were group differences in the relative strength of the coupling, i.e., adults had higher central and frontal coupling values than did the children or retarded (Karrar et al., 1986). Karrar et al. concluded that coupling probably reflects maturation and differentiation of processes underlying task performance at several levels offering a correlational method for indexing the changing organization of neural activity across development and task requirements.

The proposed study will investigate the organization of neural activity of children measured to be in one of two levels of cognitive development (Level 6 and Level 7) as proposed by Fischer's skill theory (1980). It is hypothesized that the children in the higher level of cognitive development will have a significantly higher central and frontal coupling values than the lower developmental level suggesting a quantitative change in the organization of neural networking.

Consistency of the ERP. A third potential measure of developmental change involves the consistency of ERPs. A. E. Hendrickson (1982) has proposed that higher intelligence is a function of low error rates in the way in which information is coded and transmitted in the brain. Intelligence would be inversely related to errors in the coding and transmission. Since the average ERP waveform is defined by averaging the EEG from several single-trial waveforms, a low error rate could be characterized by consistency, that is low trial-to-trial variability in the positive and negative components of the waveforms. Therefore according to Hendrickson's theory each EEG waveform would be similar in the number of peaks, the size of the peaks and the trial-to-trial latency variability of the peaks. If this is true then there should be larger but fewer peaks in the average ERP when low error rates are present. Hendrickson then proposed that to indirectly measure error rates, a string could be laid over the wave and the length of the string measured. If Hendrickson is correct in his error hypothesis, then a reduction of errors in the CNS would decrease the variability of the single trials, resulting in larger peaks in the average ERP and a longer string. In contrast, an increase in errors would increase the single trial variability, resulting in a smaller ERP and a short string. Hendrickson utilized this technique to study the data generated by Ertl and Schafer (1969). Ten high IQ and 10 low IQ subjects were selected as a sample and the string measure yielded a correlation of +0.77 with IQ.

Another study by D. E. Hendrickson (1982) yielded similar results. Using a sample of 219 school children, correlations of +0.72 were found between IQ (as measured by the WISC) and the string measure. A further study by Blinkhorn and Hendrickson (1982) utilizing 33 adults subjects (18-36 years) with a mean IQ of approximately 129 revealed correlations of approximately +0.53.

The large difference in the resulting correlations between the two studies cited may be attributed to the underlying premise that the string measure is a measure of intelligence. The string measure may be a measure of a different cognitive process such as cognitive developmental stages. In these studies, the subjects were significantly different in their age and mean IQ. It could be that the subjects were within differing cognitive developmental stages.

The proposed study, therefore, will investigate the correlation of the consistency of ERPs to cognitive developmental levels using the template-matching procedure previously outlined. It is theorized that as individuals move from one cognitive level to another, the errors in the coding and transmission of information in the brain is qualitatively reduced.

<u>Hypotheses</u>

This study will investigate the relationship between three distinct measures of brain activity and cognitive development as proposed by Fischer (1980). Therefore, the following research questions will be investigated in this study:

1. Due to the strong developmental changes of the endogenous P300 wave of auditorialy and visually evoked potentials, it is hypothesized that there are significant differences in the amplitude and latency of the P300 in relation to the cognitive developmental level that individuals are operating. It is hypothesized that as individuals progress from Level 6 to Level 7 of Fischer's (1980) theory of cognitive development, the latency of P300 will significantly decrease and the amplitude will significantly increase.

2. This study will also investigate the theory proposed by Karrar et al. (1986) that the neural activity of different areas of the brain should increase in synchronization and become more discrete with development. By computing the intercorrelations between the electrodes at differing scalp locations, it is proposed that there will be a significant increase in coupling (i.e., intercorrelation across trials) for individuals in Level 7 as compared with individuals operating within Level 6 of Fischer's (1980) cognitive developmental theory. It is also proposed that the relative strength of the coupling for individuals

operating within the higher level will have greater correlations for central and frontal areas, than for parietal and occipital suggesting higher linkages between these discrete areas of the brain.

3. The last theory to be investigated in this study involves the error theory proposed by A. E. Hendrickson (1982). The present study proposes that the level of cognitive development at which an individual is operating, rather than their intelligence, is a function of error rates in the CNS. Therefore, using the template matching procedure previously described, a measure of amplitude and trial-to-trial latency variability will give information as to whether cognitive levels are a function of fewer errors in neural responding. It is hypothesized that as individuals progress from Level 6 to Level 7 of Fischer's (1980) theory of cognitive development, the amplitude variability and latency variability will significantly decrease.

In general, this study is investigating the relationship between brain and cognitive development. Despite the intrinsic logic of the potential relationship, research studies have not been designed specifically to address this issue. Therefore, this study will attempt to increase our knowledge of how the brain functions as it relates to cognitive development.

Method

Subjects

The subjects were 36 male preadolescents from a small midwestern city ranging in age from 10 to 12 years of age. The subjects were divided into six groups of six each on the basis of age and cognitive developmental level. The age range and mean for each group is presented in Table 1. The subjects were given a payment of five dollars upon completion of the study. One criterion for subject selection was that there were no known visual or neurological deficits (based on parental report).

Insert Table 1 about here

Initially subjects were recruited from the local schools and various extra-curricular activity organizations such as boy scouts, soccer teams, etc. within the surrounding areas. The local school system would not allow any subjects to be recruited from their schools due to concerns of possible (regardless of how minimal) psychological and/or phyisical harm that may occur. Approximately ten of the subjects were recruited from the boy scouts and local park and recreation baseball teams. The remaining subjects were recruited by asking each subject that participated in the study to recommend friends of theirs that might also be interested in participating in the study. Because of the strict requirements of the study approximately sixty potential subjects were involved in the initial stages of the study.

Subjects were selected so that there were twelve males in each age category with six of the subjects in Level 6 and six subjects in Level 7 of Fischer's skill theory of cognitive development (1980) based on the single abstraction arithmetic test (Fischer, 1980). Each subject was also administered Piaget's colored tokens test. The colored tokens test is a formal operations task that measures abstract, hypothetico-deductive thinking (Inhelder & Piaget, 1958). Subjects who were able to successfully complete both tasks were identified as operating within Level 7 of Fischer's skill theory. Likewise, subjects who were unable to complete both tasks were identified as operating within Level 6. There were five 10-year- olds, four 11-year-olds and eleven 12-year-olds who did not complete the study because (a) they passed only one test, or (b) they met the criteria but for a design cell already filled.

Materials

Screening. The initial screening interview with parents included a checklist of potential deficits in the child's background that would indicate a high-risk for possible neurological impairment or for confirmation of visual and/or neurological difficulties.

Slosson Intelligence Test-Revised. The Slosson Intelligence Test-Revised (SIT-R) provided a measure of intellectual level. The SIT-R was designed to be a screening test measuring verbal intelligence. All questions were presented verbally and required spoken responses. There were no time limits. The test required between ten and thirty minutes to administer and scoring was objective. Test-retest and split-half reliabilities are in the .90s (Slosson, 1990). Correlations with the full scale of the Wechsler Intelligence Scale for Children-Revised and Wechsler Intelligence Scale for Adults-Revised are in the .80s (Slosson, 1990).

Colored Tokens Test. The colored tokens test provided one of two behavioral tasks used to assess cognitive level. Performance on this task classified subjects into either concrete operations or formal operations according to Piaget (1958). Piaget (1958) indicated that the formal operational person initially thinks of all the possibilities that might be present in a situation and then proceeds systematically to test out all of the possibilities before determining the relevant variables to the situation. The colored tokens test is one of several formal operations tasks designed by Inhelder and Piaget (1958) that elicit formal operational thinking. A study by Martorano (1977) investigated the developmental changes in level or performance on this developmental task. Subjects' performance on the colored tokens test revealed that 60% of 12-13 year olds were able to successfully complete the task, suggesting that formal operations thinking begins to emerge around the age of 12.

The test consisted of six groups of colored blocks: Red, green, yellow, blue, orange, and purple. Each color group contained 10 blocks. The experimenter placed on the table a group of red and green blocks. The subject was instructed that he could make one of two combinations using red and green blocks, either green/red or red/green. It was explained that the order did not matter, i.e. red/green or green/red would be considered the same. The subject was then given a third color group and asked to make all pair combinations using red, green and yellow. Once the subject successfully completed the task, he was given a fourth color group and told that there would be two rules to the task. First, he was to make all possible pairs using two of the colors without same-color pairs (e.g., the pair red/red did not count). Secondly, he was not to repeat any of the pairs, i.e., using red/green and green/red.

Once the subject made all the correct pairs on the practice using four colors he was given two more groups of colored blocks and asked to make as many pairs as he could using all six colors. He was also instructed to see if he could find a trick or a system that made it easy for him to make the pair combinations. This procedure is based on Goodnow's (1962) adaptation of the procedure designed by Inhelder and Piaget (1958).

Subjects' performance on the task was assigned a score of 1 for concrete operations or 2 for formal operations based on the following criteria.

1. Concrete Operations. The subject's actions on the token task was random and haphazard. He was unable to generate all possible combinations correctly, or if all combinations were found, explanations to questions were contradictory or limited to describing what he saw

and was unable to classify the tokens in terms of a systematic rule.

2. Formal Operations. The subject was able to generate all possible token combinations correctly, and was able to give an explanation to the experimenter of the correct rule that was needed to form all possible pairs systematically.

Fischer's Single Abstraction Arithmetic Test. The Single Abstraction Arithmetic Test (SAAT) was developed by Fischer (1980) to provide a measure of the cognitive developmental level of an individual. SAAT is based on the concepts proposed in skill theory (Fischer, 1980) and was used as the second task to determine the cognitive level of the subjects. Tasks representative of Level 7 in skill theory were presented in each of three operations (addition, subtraction, and multiplication) to the subjects. Subjects were asked to provide a general definition of addition, subtraction and multiplication. There were then required to demonstrate how addition, subtraction and multiplication operate on a number line. Responses for each item were scored as either a pass (+) or a fail (-) according to the following general criteria for passing responses:

1. Subject was able to give a general or abstract definition for each operation. An abstract definition is defined as one that did not use only specific numbers or concrete examples but referred instead to numbers in general.

2. Subject had to give a satisfactory, complete definition. He could not merely state different, disconnected pieces of the definition. He could not use the word for the operation itself in his definition.

General Criteria for Failing Responses.

1. Subject was unable to explain the operation in complete form.

2. Subject was unable to think of a word other than 'add', 'subtract' or 'multiply' for those operations, respectively.

3. The subject was only able to explain the operation in terms of concrete examples, not in more general terms. He was unable to focus on the abstract aspect of an operation; could not get away from concrete examples. Each item was scored independently and charted. (See Appendix A for instructional manual).

Stimuli. The stimuli in all ERP conditions consisted of visual stimuli of equal intensity. The stimuli were presented on a computer monitor screen while the subject was seated in a sound attenuated and electrically shielded room. The visual stimulus was presented on the screen for 80 ms at regular intervals of 1250 ms. The letter I was designated as the "target" and was presented at a visual angle of 0.5 degrees at its widest part. The letter F was designated as "background." The F was composed of the same number of pixels as the I and thus had the same luminance; visual angle subtended was also 0.5 degrees at the widest part. The computer monitor was situated 65 cm from the subject. The presentation of target events ($p = 0.20$) was randomly interposed in sequences of background events ($p = 0.80$). The subject was given a response button that he held in his dominant hand. He was asked to press the button when the target letter I is presented.

EEG Data. Silver-silver chloride electrodes were used to collect the EEG data. The electrodes were placed at Oz, Pz, Cz, Fz, A1 and A2 according to the International 10-20 System (Jasper, 1958). Oz, Pz, Cz, and Fz overlie the midline of the cerebral cortex from occipital (Oz) through parietal (Pz) and central (Cz) to frontal (Fz) areas. A1 and A2 are the left and right earlobes. The Oz, Pz, Cz and Fz electrodes were referenced to linked ear lobes, A1 and A2. Eye movement (EOG) artifact was monitored by two additional electrodes, one placed super-orbitally and one over the outer canthus of the left eye. Electrode impedances were kept below 5 kohms and were checked at the time of placement and after each condition. The EEG and EOG were amplified by five channels of a Grass Instruments Co. Model 79 polygraph with band passes of 0.1 to 100 Hz with 60 Hz notch filters utilized. Outputs from the two amplifiers were digitized by a metraBYTE DASH 16 analog to digital (A/D) conversion board and stored on a fixed disk. An IBM PC-XT was used to control the presentation of the stimuli and to collect the electrophysiological data. For each stimulus, EEG data were stored 100 ms prior to the onset of the stimulus, and for 1200 ms after stimulus onset for a total EP window of 1300 ms (stimulus duration = 80 ms). Within the EP window, each channel of EEG was sampled every 12 ms.

Procedure

The parent(s) of the subjects who volunteered to participate in the study were contacted by telephone for an initial screening to determine (a) preliminary consent for their child to participate in the study and (b) possible neurological and/or visual deficits of the subject. The parents and subject were instructed as to the purpose of the study and the procedure involved. At the initial appointment, the parent(s) and subject were required to sign a consent form which included the purpose and procedures involved in the study and stated that scores on the tests would not be released to them.

Subjects were administered the SIT-R to obtain their IQ level. Subjects were then administered Fischer's SAAT. After the administration of the SAAT, subjects were instructed that they would be tested again on the same items in two weeks. They were encouraged to think about the arithmetic relations in the interim.

Two weeks later, the SAAT was administered again. Subjects who obtained a score of correct answers equalling 60% or greater were classified as operating within Level 7 of Fischer's cognitive developmental skill theory (1980). Subjects scoring below 60% were classified as operating within Level 6.

Subjects were also administered the colored tokens test at this time. Subjects were classified as operating either in Level 7 if they scored in the formal operations level and in Level 6 if they scored in the concrete operations level.

Subjects who scored within Level 7 on both cognitive behavioral tasks were retained for the study.

Likewise, subjects who scored within Level 6 on both cognitive behavioral tasks were also retained. Subjects who scored within Level 7 on one of the tasks and Level 6 on the other task, were dismissed from the study. Subjects were tested and classified until there were 12 subjects in each age category with an equal number of subjects in Level 6 and 7.

Subjects' answers for the SAAT and the colored tokens test were audiotaped. A second rater, who was trained to score the responses as outlined above, also scored the subjects' responses to provide a reliability index. The two raters were in complete agreement on 80% of the subjects and differed on only one of the cognitive tasks on the remaining subjects. The reliability index may have been greater if the second rater had been able to visually assess how the subjects were performing on the Colored Tokens Test. Subjects were required to organize the colored tokens correctly into all pair combinations as well as verbally explain the system or rule that he used. The second rater scored some subjects as passing the Colored Tokens Task solely on the verbal response and was not able to view how the subject organized the tokens. Therefore, the second rater scored a few of the subjects as passing the Colored Tokens Test based on the audiotaped response without realizing that the subject was either disorganized or inaccurate in organizing the colored tokens.

The subjects who met the above requirement were then ushered into a sound attenuated room and seated in a reclining chair. The experimenter read them a brief description of the purpose of the study and then attached the electrodes.

The electrodes were affixed with Grass Instrument EC2 paste with a small piece of cotton placed over the electrode. Clip electrodes were used on the earlobes. Impedances were checked at the time of placement and after each condition. Electrodes with impedances greater than 5 kohms were reset. After the electrodes were affixed, the experimenter read the instructions to the subject. To familiarize the subjects with the discrimination task, five target and five background presentations were given, alternating target and background. The subjects were instructed to push a response key when they saw a target. The experiment proper consisted of 200 artifact-free trials (40 targets, 160 background). Single ERPs containing excessive eye movements were rejected online and replaced. Subjects fixated their eyes on a dot at the center of the viewing screen during the presentations.

Data Reduction

P300 Amplitude and Latency. Four average ERPs were calculated for each subject, one from each of the electrode sites (Oz, Pz, Cz and Fz), for target events. From the average ERPs, the mean amplitude and latency of the P300 peak were calculated. P300 was defined as the largest positive peak in the 200-1200 ms range past the P200 peak. P200 is the most prominent peak of the visual ERP and occurs between 150 and 250 ms. If two points within this time window were within 5 microvolts of each other, the mean of the two amplitudes and latencies were used. Both of the peak points had to be on the same slower wave (See Figure 2). P300 latency

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Insert Figure 2 about here

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was calculated from stimulus onset. P300 amplitude was calculated from baseline, i.e., the mean of 100 ms of EEG prior to stimulus onset.

Latency Variability. The template procedure (Michalewski et al., 1985; Thomas et al., 1989) was employed to calculate the latency variability of P300 in the single trial waveforms. A computer program carried out the following steps: After P300 was identified in the average ERP of an individual subject, a template of that peak was constructed consisting of 16 data points on either side of the peak point. This process created a 33 point template that covered a 384 ms time window. This template was then moved across an 800 ms window (216 - 1016 ms post-stimulus) of the individual trial on a point by point basis. As the template moved, a correlation coefficient was calculated between the template and each successive group of 33 points in the window. The point at which the maximum positive correlation was found between the template and the individual trial waveform was determined to be the latency of the P300 for that particular trial. This latency was then taken for every trial and the standard deviation derived, which served as the estimate of latency variability for P300 for each subject.

Amplitude variability. Amplitude variability was calculated using the standard deviation of the amplitude of each of the 100 post-stimulus data points derived from the digitized ERP. Amplitude variability was calculated for each subject across the entire time window following stimulus onset rather than for each peak as in latency variability. A two dimensional array of the amplitude values was formed, with the columns representing each of the 100 points in time and the rows representing each of the 40 individual trial waveforms for the target condition. The standard deviation of each of the 100 columns was then calculated. Amplitude variability for each subject was the mean of these 100 standard deviations.

Coupling. Coupling was estimated by measuring the relationship between pairs of electrodes (Callaway & Harris, 1973). To measure coupling between two electrodes the average ERP waveform of each electrode were analyzed in the following way. Each successive data point was classified as to its polarity (either positive (+) or negative (-)), and whether the voltage was greater (>) or smaller (<) than the preceding point. Therefore, each data point could be classified into one of the following four groups: + >, + <, - >, - <. The degree of coupling between the two waveforms was computed from the contingency table using a coefficient of information transmission which had values from 0 to 100; 100 meant that each point of the waveform from one electrode was perfectly predictable (100% coupled) from the other electrode; 0 meant no predictability (0% coupled) (see Appendix B).

Results

The present study was designed to investigate the relationship between three distinct measures of brain activity and cognitive development. The results pertaining to each research question in the study are reported below. Included as well is a section investigating the relationship of IQ with each dependent variable.

The data were examined utilizing a repeated measures multivariate analysis of variance (MANOVA) procedure using electrode site, age, and cognitive level as independent variables (age X cognitive level X electrode site). The electrode sites, Oz, Pz and Cz were analyzed for P300 amplitude and latency and amplitude and latency variability. P300 at Fz was not sufficiently predominate to be measured for amplitude and latency. All multivariate F's were converted from Wilks' criterion. All MANOVA F's that were significant at $p < .05$ were then examined utilizing a Tukey's *post hoc* test comparing means using their specific error terms from the multivariate analysis of variance. Also, significant findings were analyzed using a MANCOVA with IQ as the covariate. The F values listed are from the multivariate analysis of variance. Means and standard deviations for each of the independent variables and interactions that are significant are presented in Table 2. Means and standard deviation for all independent variables and interaction are presented in Appendix C.

Insert Table 2 about here

An analysis of variance (ANOVA) using intellectual level (IQ) as the dependent variable and age and cognitive level as independent variables (age X cognitive level) was also performed since IQ was an important correlate of a number of the independent variables. Also, all of the dependent variables were compared to IQ utilizing correlation procedures.

P300 wave changes

Research question #1: Are there significant (a) increases in the amplitude and (b) decreases in the latency of the P300 wave of visual ERPs for individuals functioning in Level 7 as compared to Level 6 of cognitive development as proposed by Fischer (1980)?

Amplitude. There was a significant interaction between cognitive level and electrode site ($F(2, 29) = 4.06$, $p < .05$). A Tukey's post hoc test revealed that there was a significantly smaller P300 amplitude at level 6 than at level 7 at Cz (see Figure 3). Even though the significance of the interaction between

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Insert Figure 3 about here

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cognitive level and electrode site was weakened ($F(2, 29) = 3.03$, $p = .06$) when IQ was statistically removed from the analysis in the MANCOVA, the results suggest that the amplitude of P300 is significantly smaller for individuals functioning in level 6 when compared to level 7. There were no significant differences in the P300 amplitude between cognitive level or age at Oz and Pz.

There was a significant main effect for electrode site ($F(2, 29) = 47.67$, $p < .05$). Tukey's *post hoc* test indicated that the amplitude at Cz was significantly smaller than the amplitude at Oz and Pz, and the amplitude at Oz was significantly smaller than at Pz. However, when IQ was statistically removed from the analysis in the MANCOVA, the main effect for electrode site was removed ($F(2,29) = 0.20$, $p = 0.81$). There were no significant main effects for cognitive level or age for the P300 amplitude.

Latency. There was no significant main effect in the P300 latency for cognitive level, nor were there any significant interactions. There was, however, a significant main effect for age ($F(2, 29) = 4.11$, p <

.05). The P300 latencies were significantly longer at age 10 than at age 11 (see Figure 4). The P300 latency at age 12 was not significantly different from either age 10 or age 11.

Insert Figure 4 about here

There was also a main effect for electrode site ($F(2, 29) = 4.71$, $p < .05$). The P300 latency at Cz was significantly longer than at Oz and Pz. However, the P300 latency was not significantly different between the two posterior electrodes, Oz and Pz.

When the data were analyzed statistically removing IQ from the analysis in the MANCOVA, age was the only effect that remained significant ($F(2, 29) = 3.89$, $p < .05$). The P300 latency for age 10 remained significantly longer than at age 11 regardless of intellectual level.

Underlying Network Change

Research question #2: Are the measures of coupling between electrode sites significantly greater for individuals in Level 7 as compared with individuals operating within Level 6 of Fischer's (1980) cognitive developmental theory? Additionally, are the relative strengths of the coupling for individuals operating within the higher developmental level primarily central and frontal couplings?

The results of this analysis describe the degree to which the activity of any two electrodes was synchronized. The results showed that there were no coupling differences due to cognitive level or age, nor were there any significant interactions. However, there were significant differences among the six couplings ($F(5, 26) = 52.68$, $p < .05$; see Figure 5). The OzPz and PzCz couplings depicted in Figure 5 show

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Insert Figure 5 about here

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that these adjacent pairs of electrodes were the most highly synchronized. These two couplings were significantly different from the remaining four couplings, three of which represent non-adjacent pairs. Similarly, the two pairs of electrode sites, OzFz and PzFz, that are positioned furthest apart were significantly different from all the other couplings.

Consistency of ERPs

Research question #3: Are there significant differences in the P300 latency and amplitude variability for individuals functioning in Level 6 as compared to Level 7 of Fischer's (1980) cognitive development?

Latency Variability. This analysis attempted to assess the degree to which the P300 latency varied from trial to trial. It was predicted that an individual operating in a higher cognitive level would produce less latency variability from trial to trial. This would suggest that an individual in a higher cognitive level is more efficient in processing and coding information than an individual in a lower cognitive level. The results indicated that there were no significant main effects or interactions, which indicates that latency variability is not sensitive to cognitive level changes as hypothesized.

Amplitude Variability. This dependent variable measured the amplitude variability from trial to trial. It was also predicted, as with the latency variability, that the less the waveform amplitude varied, the higher an individual is functioning cognitively. A marginally significant effect for cognitive level ($F(1, 30) = 3.86$, $p = 0.06$ was revealed for amplitude variability. When IQ was statistically removed from the analysis, cognitive level remained marginally significant ($F(1, 33) = 3.69$, $p = .06$).

The multivariate analysis revealed that electrode location also showed a significant effect ($F(2, 29) = 13.9$, $p < .05$,). Cz had a significantly smaller amplitude variability than Oz and Pz (see Figure 6). Amplitude variability was not significantly different between Oz and Pz. There were no significant differences in age nor were any interactions significant.

Insert Figure 6 about here

These results indicate that amplitude variability does decrease somewhat as a result of cognitive level changes.

Intellectual Quotient

The finding that in two of the above analyses using IQ as a covariate weakened effects involving cognitive level suggests that the two measures are related. This was substantiated by the age x level analysis of variance (ANOVA) which used IQ as a dependent measure. This ANOVA revealed that there were significant differences in IQ as a function of cognitive level ($F(1, 30) = 13.29$, $p < .05$ see Table 3). The average IQ for subjects in Level 7 was

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Insert Table 3 about here

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significantly higher than for subjects in Level 6. The mean IQs were 102.2 and 88.7 for subjects in Level 7 and Level 6 respectively. There were no significant age or age X cognitive level effects for intellectual level.

P300 Amplitude. The Pearson correlation coefficients revealed there were also significant relationships between IQ and P300 amplitude at both Pz ($r = .40$, $p < .05$) and Cz ($r = .60$, $p < .05$). There was no significant relationship between IQ and P300 amplitude at Oz.

P300 Latency. There were no significant relationships between the P300 latency at Oz, Pz, and Cz and IQ suggesting P300 latency is not related to intellectual level.

Underlying Network Change. The Pearson correlation analysis revealed there were significant relationships between IQ and OzCz ($r = .33$, $p < .05$) and PzFz ($r = -.343$, $p < .05$), two of the nonadjacent couplings. Interestingly, the coupling OzCz is positively correlated with IQ, while the coupling PzFz is negatively correlated with IQ.

Consistency of ERPs (Latency Variability/Amplitude Variability). The correlation coefficient analysis revealed there were no significant relationships between the latency variability at Oz, Pz and Cz and intellectual level nor between amplitude variability at each electrode site and intellectual level. This finding suggests that neither latency variability nor amplitude variability is related to intellectual level.

Summary of findings

Results pertaining to research question #1 revealed that the amplitude of P300 was significantly larger for individuals functioning in Level 7 of Fischer's cognitive development when compared to individuals in Level 6 at the electrode site Cz. This finding supports the study's proposed hypothesis that the amplitude of P300 is sensitive to cognitive developmental changes and was only slightly weakened when IQ was statistically removed from the analysis.

In contrast, results of latency changes of P300 revealed significant age and electrode site differences. P300 latency was significantly longer at age 10 than at age 11 and remained significant even when IQ was statistically removed. This finding suggests that P300 latency is sensitive to age changes rather than cognitive developmental changes.

Results pertaining to research question #2 and #3 revealed that the measure of coupling between two electrode sites and P300 latency variability from trial to trial was not successful in measuring cognitive developmental changes. However, trial-to-trial amplitude variability was marginally successful in measuring cognitive developmental changes. Amplitude variability was significantly less for individuals functioning within Level 7 of Fischer's (1980) cognitive development when compared to individuals at Level 6. This latter finding is consistent with the proposed hypothesis of the study. Also, there were scalp distribution differences for amplitude variability.

The findings revealed that there were significant differences among the coupling measures. Two of the adjacent pairs of electrode sites were highly synchronized, while two pairs of electrode sites that are positioned furthest apart were least synchronized.

When the relationship of intellectual level (IQ) to each of the dependent measures was analyzed, the results revealed that there were significant relationships at P300 amplitude at electrode sites Pz and Cz. This finding suggests that P300 amplitude is related to intellectual level.

There were also significant relationships between intellectual level and two of the nonadjacent coupling measures: OzCz and PzFz. OzCz was positively correlated with IQ, while PzFz was negatively correlated with IQ. This finding suggests that the degree of synchronicity between the two nonadjacent electrodes situated posteriorly is related to intellectual level. In contrast, the degree of synchronicity between the two anteriorly positioned electrodes is inversely related to intellectual level.

The results also revealed that there is a significant difference in cognitive level when using IQ as the dependent variable. This finding is not surprising given the effect IQ had on each of the dependent variables when IQ was statistically removed from the analysis in the covariance analyses. The results indicated that the significant differences found for cognitive level in P300 amplitude and amplitude variability were weakened when IQ was statistically removed.

Discussion

The purpose of this study was to investigate relationships among three distinct measures of brain activity and cognitive developmental change. Each of these brain activity measures will be discussed separately, as will the relationship of IQ to each of the dependent measures.

P300 wave changes

Amplitude. The hypothesis that there would be a significant change in the P300 amplitude for children operating at Level 7 when compared to Level 6 of Fischer's skill hierarchy of cognitive development was supported for the Cz electrode site. Thus, the centrally located late positive wave, P300, appears to be sensitive to cognitive developmental changes in children aged 10-12. This finding, however, was weakened somewhat when the effect of IQ was statistically removed by the covariance analysis. This analysis revealed that the effect of cognitive level did not remain at the .05 level of significance but was reduced to a .06 significance level, suggesting that IQ is highly related to cognitive developmental levels. Further analysis provided support that there is a significant relationship between IQ and cognitive level in that the mean IQ was different between the two levels.

The significant relationship between IQ and cognitive level is not surprising since Fischer et al. (1984) reports that children's performance on standard intelligence tests varies as a function of both factors that he proposed in his theory of cognitive development--optimal level and skill acquisition. As previously defined, optimal level is the concept that describes the upper limit to which an individual's performance may be induced and supported by environmental factors (Fischer et al., 1984). Skill acquisition, on the other hand, is defined as the process of acquiring competence in skills in many domains within the optimal level. When an individual develops a new optimal level, they have the capacity to construct skills at the new level, but they do not actually have any competencies at that level until those skills are built. Therefore, using this two-process model, it is possible that exceptionally bright children and children of normal intelligence may attain an optimal level at about the same age. However, once the new level has emerged, bright children will quickly be able to master a wide range of skills at that level; in contrast, children of normal intelligence will take a longer time to acquire mastery in the same range of skills. These skill acquisition processes are what is generally measured on intelligence tests suggesting that cognitive level and intellectual level are highly correlated.

Although Fischer proposes that exceptionally bright children and children of normal intelligence may reach an optimal level at about the same time, the ability to apply the skills of that stage may take longer for less intelligent children to develop. This study measured two cognitive developmental behaviors: Fischer's single abstraction arithmetic test and Piaget's colored tokens test. Since the children in this study were required to successfully complete both tasks to be classified in Level 7, brighter children were more likely to have already mastered a broader range of skills. Therefore, the observed strong relationship between cognitive level and IQ may be a result of the requirements of this study.

Is the P300 effect due to cognitive developmental changes? The present study investigated one cognitive developmental change, i.e., concrete operational thinking vs. abstract thinking. If developmental change is primarily responsible for the significant increase in the P300 amplitude at Cz, then at each cognitive developmental level, there would be a significantly larger amplitude for P300 at Cz. Therefore, persons who are functioning within Level 8 would be predicted to have a larger P300 amplitude at Cz than those operating at Level 7 and so forth.

Fischer (1984) has described 10 cognitive developmental levels; the last of which emerges at 24-26 years of age. If P300 amplitude at Cz becomes larger at each developmental stage, then this peak will maximize its amplitude in early adulthood. A study by Ladish and Polich (1989) indicates that the amplitude of P300 appears to increase at the frontal, central and parietal electrode sites as children progress into late adolescence suggesting that further research is needed to clarify the extent that the P300 amplitude at Cz is sensitive to developmental changes beyond Level 7. Courschene et al. (1975, 1977, 1978) have also found that the P300 amplitude at Fz increases in size dramatically during adolescence and early adulthood. Therefore, it is possible that there may be a shift to a frontal P300 amplitude change as an indicator of later developmental stages.

Although the significance of cognitive level was weakened when the effect of IQ was removed, it certainly did not eliminate cognitive level as a predominant factor in the amplitude change at Cz. Also, since the amplitude variability from trial to trial was significantly smaller for the Level 7 children, as predicted, it suggests that the mechanism which controls P300 amplitude changes are affected by cognitive level, independent of IQ.

Is the developmental change due to IQ? If IQ is most responsible for the P300 effect, then it would be expected that brighter children will always have a larger P300 amplitude regardless of cognitive developmental level. Therefore, it would be predicted that smarter children at Level 7 and Level 8 will have the same amplitude size at P300. Likewise, less bright children at Level 7 and Level 8 would have a consistently smaller P300 amplitude.

Further research can more clearly define the degree to which the changes revealed in this study are a result of cognitive level changes or intellectual level. Specifically, the following questions need to be addressed:

1. Is the P300 at Cz effect only found from Level 6 to Level 7?

2. Is the change in P300 amplitude at Cz a result of cognitive level change or intellectual level?

3. If the P300 amplitude change at Cz is a result of cognitive developmental level, are all P300 amplitudes at Cz at higher cognitive levels larger than previous levels?

4. If the P300 amplitude change is a result of intellectual level, are P300 amplitudes consistently larger for brighter children regardless of cognitive level?

Another interesting finding from this measure is the difference in the scalp distribution. There were significant amplitude differences among Oz, Pz, and Cz. The amplitude at Pz was significantly larger than at Oz and Cz. This finding is consistent with previous research findings by Courchesne (1983) that visual ERPs to target stimuli are largest at electrode sites located over the parietal cortex (Pz) for subjects between 6 and 36 years of age when compared to Cz and Fz.

These differences in the scalp distribution, however, were removed when IQ was statistically removed from the analysis. Therefore, although P300 amplitude appears to be sensitive to scalp location, intellectual level can account for most of the significant changes seen in the amplitude changes at Pz. In fact, upon further analysis, P300 amplitude at Pz is significantly related to intellectual level (r = .40), as well as P300 amplitude at Cz (r = .60). Therefore, it appears that the larger parietal P300 amplitude is significantly related to intellectual level suggesting that scalp distribution differences are contributed to by intelligence.

There were no P300 amplitude differences that were age-related. This finding is also consistent with Courchesne's (1975, 1977, 1978) previous research in which he found no age-related changes in P300 amplitude.

Latency. Contrary to prediction, there were no significant differences in the P300 latency for children functioning in different cognitive levels. Similarly, there were no significant relationships between P300 latency at any of the electrode sites measured and intellectual level. These findings suggest that P300 latency is not a sensitive measure for cognitive level changes or IQ.

Interestingly, there were significant age effects on the P300 latency. The P300 latency for 10 year olds was significantly longer than at age 11. This finding is also consistent with previous research by Courchesne (1978) that P300 latency decreases with age. This finding, however, did not reveal that the latency for 12 year olds was significantly shorter than for 10 or 11 year olds as would be expected. In fact, if the mean latency for each age group is compared, the latency for 12 year olds is longer at each electrode site when compared to the 11 year olds, although the difference was not statistically significant (see Table 3). One possible reason for what appears to be an inconsistency in this finding may be due to the age span comparisons in much of Courchesne's research. Although Courchesne (1978) reports that the P300 latency decreases with age, his age groups were as follows: 6-8 year olds; 10-13 year olds; 14-17 year olds; and adults. The present study used a more fine analysis when it compared 10, 11 and 12 year olds. This suggests that there may not be a precise correlation between age and P300 latency but rather when comparing 3-year age spans, the mean latency for P300 decreases. Therefore, although the P300 latency for 12 year olds did not significantly decrease when compared with 11 year olds, the mean latency for all subjects in this study are consistent with the mean latency for P300 in Courchesne's (1978) research.

Although Courchesne's research has revealed developmental changes in P300 latency, other studies have not found latency changes across ages in P300. Friedman et al. (1981) conducted a study with 70 subjects between 12 and 17 years of age using auditory stimuli. They found no latency changes in P300 related to age changes. Friedman et al. (1981) also conducted a study using a visual stimuli paradigm and there, too, found no effect of age on P300 latency.

Therefore, although it appears there is an inconsistency in the research regarding P300 latency decreasing with age, Courchesne (1983) proposes that although the "transition from childhood ERP waveforms to adulthood waveforms is gradual...it does not mean that the rate of change is necessarily constant (p. 340)." The results of the current research demonstrated significant changes in P300 latency from age 10 to age 11 but not from age 10/11 to age 12. This finding suggests that P300 latency is sensitive to age; however, the change may not be linear and constant. Another possibility is that there are other variables which may be contributing to the age developmental changes that were not examined in this study.

The significant age difference in P300 latency is robust even when IQ was statistically removed from the analysis. This result further supports that P300 latency is related to age changes and is not significantly related to intellectual level.

There were also significant differences in the scalp distribution of P300 latency. The latency at Cz was significantly longer than at Oz and Pz while there were no significant differences between Oz and Pz. Other investigators who have studied P300 latency changes have not presented information on scalp distribution changes in the P300 latency. This finding may indicate that the mode of processing easily identified information and the neural substrate for such processing is slower centrally and faster posteriorly.

Summary of P300 amplitude and latency changes. Overall, the results of the P300 amplitude and latency changes suggest that they each may be a potential indicator of developmental change. The results suggest that P300 amplitude at Cz significantly increases when an individual is operating at a higher cognitive developmental stage and would, therefore, be a potentially sensitive indicator of cognitive developmental change. Since it appears that cognitive level and intellectual level are highly similar in what they measure, it is not surprising that P300 amplitude at Cz is also significantly related to IQ.

Pineda et al. (1986) and Courchesne et al. (1987) have speculated on the possible neural generator(s) of P300. They have suggested that P300 is generated in the cortex by the action of the noradrenergic locus coeruleus neurons (LCA). Basically, the functional aspect of LCA is:

(a) facilitation of processing of novel or affectively important information by enhancing the signal-to-noise conditions of cortical neurons (Segal, 1980; Aghajanian & Rogawski, 1983), and

(b) aspects of recognition memory when they are triggered by novel, interesting or important information from any sensory modality (Pritchard, 1981).

Processing of information and memory recognition are both components of cognitive level and/or intellectual level. Therefore, an individual who is functioning higher cognitively and/or intellectually may have a greater quantity of synapses available to process information. This greater synaptic quantity may reflect amplitude changes in P300 at Cz. Huttenlocher et al. (1979, 1982) and Rakic et al. (1986) have shown that by the end of the first decade of life there are roughly half as many synapses in all cortical and limbic areas as there were during late infancy and early childhood. Although this suggests that P300 amplitude changes are related to age changes, individuals who are in a higher level cognitively may lose synapses at a significantly slower rate or the synapses they do have function more efficiently.

Of the three ERP measures taken in this study, the electrode placement of Cz is the one nearest the frontal lobe. Although the specific intracranial sources that generate evoked potentials are generally unknown (Donchin & Coles, 1988), it is most likely that the neuronal mechanism that generates a specific evoked potential will generally be in the area of the electrode placement. As previously discussed since the frontal lobes are traditionally considered to be associated with intelligence and abstract thinking, it may be inferred that the increased amplitude at Cz is an indicator of frontal lobe involvement for the Level 7 individuals. Possibly as individuals progress through higher cognitive developmental levels, P300 amplitudes at Cz and Fz will become larger due to the frontal lobe involvement. Since the P300 amplitude at Fz was not predominate enough to be analyzed in this study, the P300 amplitude at Cz may be the sensitive indicator of initial stages of abstract thinking. This may further support the hypothesize that as an individual progresses through higher levels of cognitive development a more frontal P300 amplitude will become dominant. It is necessary, however, to be a little cautious about what functions can be ascribed to the frontal lobe region. In this study the subjects were classified into two different cognitive developmental tasks that were differentiated by how they behave on complex tasks, while ERP's are a reflection of a signal detection task.

That P300 latency significantly decreased with age and not with cognitive developmental changes suggests that P300 latency may be a better measure of age changes (i.e., physiological maturation). Courchesne (1987) proposed that latency changes may reflect the gradual process of myelination. Myelination of cortical association areas and parts of the reticular formation are not complete until after the first decade of life (Yakovlev & Lecours, 1967). Therefore, P300 latency changes as they relate to age changes would be highly related to the maturation level of the subjects. Although age and maturation are highly correlated they are not equivalent. Since it is very difficult to control for maturation in children, inconsistencies in age-related research may be confounded with maturation issues. This may also account for what appears to be the inconsistent findings in this study on the P300 latency changes.

Underlying Network Change

This research question asked whether the underlying network of brain neural activity would increase in synchronicity (coupling) when individuals are functioning within a higher level of cognitive development. However, the findings revealed there were no significant differences in coupling among Oz, Pz, Cz and Fz between children operating in Level 6 as compared to Level 7 of Fischer's (1980) cognitive developmental theory, suggesting that this brain activity measure is not a sensitive measure for cognitive developmental changes.

There were differences between the level of synchronicity among all pair combinations. Two of the adjacent pairs of electrodes, OzPz and PzCz, were significantly synchronized when compared to the remaining four pairings. All but one of these remaining four pairings were nonadjacent electrode pairs suggesting that the pattern of the P300 wave of visual ERPs is significantly similar to P300 waves that are closest in electrode position on the scalp. Likewise, the two electrode pairs that were positioned furthest apart in distance were significantly less synchronized than the remaining four adjacent pairs of electrodes. This organization of the underlying network of brain neural activity is not related to the levels of cognitive development measured in this study, but it does suggest this measure of neural activity may provide an index of changing organization across other developmental or task requirements not measured in this study.

Although there was no relationship between cognitive level and the synchronicity of different electrode sites, there was a significant positive correlation (r = +.33) between intelligence and the electrode pair OzCz and a significant negative correlation (r = -.34) for the electrode pair PzFz. PzFz is inversely related to intelligence, i.e., the higher one's intelligence, the less synchronicity there is for the pair PzFz. This suggests that in a visual task, there is a posterior nonadjacent coupling that is related to intelligence, while there is a decoupling for an anterior nonadjacent pair.

The OzCz coupling was not significantly synchronized when compared to the other couplings, however, it appears to be significantly correlated with intelligence suggesting that the neuronal connections between these ERP measurements may be involved in levels of intelligence. The studies of Thatcher et al. (1987) suggest that human cerebral development involves a sequential differentiation and elaboration of corticocortical connections between posterior, central, and temporal cortical regions with different zones of the frontal lobes. In fact Thatcher et al. (1987) studies that most of the growth spurts in EEG coherence and phase involved frontal lobe connections. Although this study did not find the significant synchronicity between the posterior-to-frontal connections as suggested by Thatcher et al. (1987) study, the central-occipital coupling may indicate that this connection is a dominant feature of IQ. Since Thatcher (1991) suggests that the various sections of the nonfrontal cortex become sequentially connection with the frontal lobes at different ages until adulthood, the lack of significant synchronicity between the occipital, parietal and central zones with the frontal area may be associated with the levels of cognitive development measured in this study.

Although Karrar's et al. (1986) study found age changes in the coupling measures, his research differed from the present study in two significant areas. First, his study involved additional electrode placements and his experimental groups involved large age spans within the groups of children and adults. Therefore, his results found age changes between children and adults and not between different ages of children. The present study was designed to detect more discrete changes within a specific age span of children only. This would account for the lack of significant differences between couplings related to age changes as found in Karrar's study (1986).

Consistency of ERP

The last research question to be investigated in this study involved the variability of the latency and amplitude of P300 from trial to trial. It was predicted that the measure of individual trial variability of the P300 latency and amplitude will give information as to whether an individual is operating within a higher cognitive level. The results indicated that P300 latency variability did not significantly decrease as a function of cognitive level. There were, in fact, no significant effects for latency variability in any of the independent variables or interactions. This finding points to the inability of this brain activity measure to differentiate between cognitive developmental levels of children aged 10 to 12 years of age.

There were, however, marginally significant differences in cognitive level for amplitude variability. This significant finding remained relatively the same even when IQ was statistically removed from the analysis. Further analysis also revealed that IQ was not significantly related to amplitude variability. Therefore, it appears that amplitude variability may be an independent indicator of cognitive level changes. Individuals functioning in a higher level have a significantly smaller trial-to-trial amplitude variability when compared to lower cognitive levels.

Hendrickson (1982) had proposed that the efficiency of ERPs may be a measure of intelligence. Since his studies had a wide variation in their correlations, i.e., .72 and .53, this study proposed that if IQ and age were controlled, then the efficiency of ERPs may be a measure of cognitive developmental stages. The results of this study support the premise that the efficiency of ERPs when using a trial-to-trial amplitude variability measure is sensitive to cognitive level changes. In fact the trial-to-trial amplitude variability in this study revealed no significant correlation between IQ and this measure which is in contrast to what Hendrickson (1982) had proposed. Therefore, individuals who are in a higher cognitive developmental level are able to code and transmit information in their brain with less error.

As previously discussed, P300 amplitude also appears to be sensitive to cognitive level changes. Although P300 amplitude changes may be effected by IQ, trial-to-trial amplitude variability appears to not be sensitive to IQ differences. Therefore, as individuals progress through cognitive developmental levels, their trial-to-trial amplitude variability will consistently decrease resulting in the P300 amplitudes becoming larger.

There were also significant differences in scalp distribution for amplitude variability. Cz had a significantly smaller P300 amplitude variability than at Oz and Pz. As previously discussed, the P300 amplitude at Cz was significantly smaller than at Oz and Pz. These findings revealed that when comparing Oz, Pz and Cz, the amplitude and amplitude variability from trial to trial for males aged 10-12 were significantly decreased from Oz and Pz. The significantly smaller amplitude variability at Cz may be due to the smaller P300 amplitude at Cz.

Summary

This study was designed to investigate three distinct measures of brain activity as they relate to cognitive development. Of the three hypotheses proposed, the P300 amplitude of visual ERPs and amplitude variability from trial-to-trial at the electrode site Cz were the measures that significantly changed for cognitive level. Although the P300 amplitude significance was somewhat weakened when IQ was statistically removed, this finding is not surprising since IQ and cognitive level are highly correlated. The degree to which cognitive level or IQ contributes to P300 amplitude increases and to decreased amplitude variability from trial-to-trail can be more clearly defined in further research.

The significantly large P300 amplitude at the centrally located electrode suggests that the neuronal mechanisms in the prefrontal area of the cerebral cortex may be involved in an individual's ability to operate in the first stage of abstract thinking as defined by Fischer (1980). As previously discussed this needs to be further researched as to what exactly is being measured. Specifically, is this a measure of cognitive level, intellectual level or possibly a decision making ability of the subject?

Although there were not any significant findings as they relate to cognitive development using the hypothesis that the underlying neuronal network becomes more synchronized, there were suggestions that the connections between nonfrontal areas are related to intellectual level. Since the connection between the occiptal and central electrodes were significantly correlated with IQ and that the P300 amplitude at Cz appears to be influenced by IQ and/or cognitive developmental level, further research might investigate the relationship with the centrally located electrode with other areas of the cerebral cortex and IQ/cognitive developmental levels. Since Thatcher et al. (1987) studies did find significant developmental connections between frontal areas and nonfrontal areas, future research is needed to investigate ERP connections in cognitive developmental stages beyond Level 7 of Fischer's (1980) cognitive developmental theory.

The last hypothesis investigated in this study predicted that an individual operating within a higher cognitive level would be able to code and transmit information in their brain with less error. This theory was supported when using trial-to-trial amplitude variability. The marginally significant results suggest this is a good indicator of cognitive level changes and not intellectual level. Future research is needed to investigate this brain activity measure using other cognitive level stages.

Future research might also consider comparing groups of children that are in other stages of cognitive development as well as including females in the comparison groups so that generalizability can be strengthened. Since visual ERPs were used in this study, it might be beneficial to replicate the study using auditory ERPs to distinguish if there are any discretionary changes in the results based on the stimulus input.

Implications

This study was designed to investigate what potential brain activity changes may be occurring that could be related to the cognitive developmental changes seen in humans. Although each of the brain activity measures were previously researched using developmental and/or cognitive changes, no one had specifically attempted to investigate a relationship between the brain activity measures and cognitive developmental changes. The results of this study have established that the use of evoked response potentials are potential measures of cognitive developmental stages. Clearly more research is needed before comprehensive and integrated theories can be made from the research. However, there appears to be significant results that would suggest that this is an area of research that has potential of facilitating our understanding of what may be occurring in the brain that accounts for what is seen in cognitive developmental stages and/or intellectual level.

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Appendix A

Addition

Addition is putting one number together with another number to get a sum or total. When you add, you combine single numbers so the answer increases or get larger. The following equation shows how addition works:

$$5 + 3 = 8 \qquad 4 + 9 = 13$$

In both equations you take the first number and put it together with the second number to get the sum.

On the number line, addition moves to the right. You start at 0 and move to the first number and then move to the right the number of spaces in the second number. The number you land on is the answer. In these equations:

$$5 + 3 = 8 \qquad 4 + 9 = 13$$

you move right from 0 to the first number and then move right again by the number of spaces in the second number. The space you land on is the answer.

Subtraction

Subtraction is taking one number away from another number to find the difference or the answer. When you subtract, you decrease single numbers so the answer gets smaller than the number start with. The following equations show how substraction works:

12 - 7 = 5   7 - 4 = 3

In both equations you take the second number away from the first number in order to find the difference between the two numbers.

On the number line, subtraction moves to the left. You start at the largest number and then move to the left the number of spaces in the smaller number. The number you land on is the answer. In these equations:

12 - 7 = 5   7 - 4 = 3

you start at the first number and move to the left as many spaces as are in the second number. where you land is the answer.

Multiplication

Multiplication is putting one number together over and over a certain number of times to get a product. When you multiply, you take one number and repeat it by another number. The first number tells the size of the groups and the other number tells how many times to repeat that group. The following equations show how multiplication works:

5 X 4 = 20   4 X 3 = 12

In both equations you take the first number and put it together as many times as the second number says to get the answer. In other words you add the first number to itself the number of times as the second number says to get the product.

On the number line multiplication moves to the right by equal groups or jumps of numbers. The first number tells the size of the groups and the second number tells how many times to move that group to the right. These equations

$$5 \times 4 = 20 \quad 4 \times 3 = 12$$

both move to the right. You move to the first number and then keep moving that number as many times as the second number says. The number you land on is the answer.

Appendix B

The following formula (Shannon & Weaver, 1949) was used to estimate coupling. If Pi is the probability of an event in the ith of N categories, uncertainty (H) is:

$$H = - \sum_{i=1}^{N} Pi \text{ Log } Pi$$

For a given EEG channel, N = 4 and Pi is estimated from the relative frequency of EEG samples classified into each of the four categories. If uncertainty in channels x and y are H1 and H2 and that in the contingency matrix is Hx,y, the coefficient of information transmission is

$$100(Hx + Hy - Hx,y)/$$
$$(\text{minimum } Hx, Hy)$$

Appendix C

Means and Standard Deviations of Independent Variables and Interactions

Research Question #1:

P300 Amplitude

Variable	Mean	SD
By Electrode Site		
Oz	19.1	9.7
Pz	22.9	8.7
Cz	13.8	7.4
By Cognitive Level		
	Coglv 6	
Oz	19.9	9.3
Pz	22.3	9.3
Cz	10.5	5.2
	Coglv 7	
Oz	18.4	10.3
Pz	23.4	8.3
Cz	17.0	8.0
By Age		
	10	
Oz	17.9	8.9

Pz	21.7	9.1
Cz	13.0	7.4
	11	
Oz	19.7	9.5
Pz	24.0	7.5
Cz	12.5	7.8
	12	
Oz	19.7	11.3
Pz	23.0	9.8
Cz	15.9	7.1
By Age X Coglvl		
	Age 10 Coglvl 6	
Oz	21.5	6.7
Pz	22.6	10.3
Cz	10.7	7.4
	Age 10 Coglvl 7	
Oz	14.3	9.9
Pz	20.7	8.7
Cz	15.2	7.5
	Age 11 Coglvl 6	
Oz	17.9	12.0
Pz	22.5	9.0
Cz	10.1	4.9
	Age 11 Coglvl 7	
Oz	21.6	6.8

Pz	25.4	6.3
Cz	14.9	9.7
	Age 12 Coglvl 6	
Oz	20.3	9.8
Pz	21.9	10.2
Cz	10.8	3.4
	Age 12 Coglvl 7	
Oz	19.2	13.6
Pz	24.1	10.1
Cz	21.0	6.0
P300 Latency		
By Electrode Site		
Oz	362.1	76.9
Pz	378.7	67.0
Cz	407.3	110.1
By Cognitive Level		
	Coglv 6	
Oz	376.9	83.8
Pz	387.7	75.4
Cz	414.7	115.1
	Coglv 7	
Oz	347.3	68.4
Pz	369.7	58.1
Cz	400.0	107.8

By Age

	10	
Oz	381.8	101.2
Pz	419.0	70.1
Cz	475.5	119.8
	11	
Oz	344.0	67.6
Pz	339.0	53.1
Cz	342.5	61.9
	12	
Oz	360.5	56.7
Pz	378.0	55.3
Cz	404.0	103.6

By Age X Coglvl

	Age 10 Coglvl 6	
Oz	407.7	114.6
Pz	439.0	88.8
Cz	497.0	136.4
	Age 10 Coglvl 7	
Oz	356.0	88.3
Pz	399.0	44.2
Cz	454.0	109.0
	Age 11 Coglvl 6	
Oz	358.0	89.0

Pz	345.0	67.4
Cz	355.0	82.2
	Age 11 Coglvl 7	
Oz	330.0	40.7
Pz	333.0	39.8
Cz	330.0	36.0
	Age 12 Coglvl 6	
Oz	365.0	33.2
Pz	379.0	38.4
Cz	392.0	81.6
	Age 12 Coglvl 7	
Oz	356.0	76.9
Pz	377.0	72.4
Cz	416.0	128.9

Research Question #2:

By Coupling

OzPz	36.8	15.1
OzCz	21.9	13.5
OzFz	14.0	7.1
PzCz	38.0	12.5
PzFz	16.0	7.2
CzFz	22.9	9.7

By Cognitive Level

	Coglv 6	
OzPz	39.1	13.9

OzCz	20.0	14.3
OzFz	12.0	6.4
PzCz	37.3	13.5
PzFz	17.2	8.7
CzFz	22.2	8.1
	Coglv 7	
OzPz	34.5	16.2
OzCz	23.8	12.9
OzFz	16.1	7.3
PzCz	38.7	11.9
PzFz	14.7	5.1
CzFz	23.6	11.3
By Age		
	10	
OzPz	36.5	12.6
OzCz	18.7	10.4
OzFz	12.1	6.5
PzCz	35.4	13.4
PzFz	14.7	6.5
CzFz	20.6	6.8
	11	
OzPz	37.1	16.9
OzCz	26.2	14.5
OzFz	15.4	5.5
PzCz	41.2	13.7

PzFz	17.4	9.2
CzFz	27.0	12.9
	12	
OzPz	36.8	16.6
OzCz	20.7	15.3
OzFz	14.4	9.1
PzCz	37.6	10.7
PzFz	15.7	5.8
CzFz	21.0	7.7
By Age X Coglvl		
	Age 10 Coglvl 6	
OzPz	37.0	10.3
OzCz	15.1	9.8
OzFz	8.8	6.3
PzCz	31.3	13.4
PzFz	13.7	5.7
CzFz	21.0	4.2
	Age 10 Coglvl 7	
OzPz	36.0	15.6
OzCz	22.3	10.5
OzFz	15.7	4.9
PzCz	39.4	13.4
PzFz	15.7	7.5
CzFz	20.3	9.1

	Age 11 Coglvl 6	
OzPz	42.3	19.2
OzCz	28.7	19.1
OzFz	15.7	4.4
PzCz	47.5	14.2
PzFz	21.4	11.8
CzFz	27.3	10.9
	Age 11 Coglvl 7	
OzPz	31.9	14.0
OzCz	23.8	9.0
OzFz	15.2	6.9
PzCz	34.8	10.7
PzFz	13.5	2.9
CzFz	26.7	15.7
	Age 12 Coglvl 6	
OzPz	38.0	12.7
OzCz	16.1	9.5
OzFz	11.5	7.3
PzCz	33.2	7.0
PzFz	16.6	7.1
CzFz	18.2	5.9
	Age 12 Coglvl 7	
OzPz	35.6	21.1
OzCz	25.4	19.3
OzFz	17.3	10.4

PzCz	42.0	12.5
PzFz	14.9	4.5
CzFz	23.8	8.8

<u>Research Question #3</u>:

<u>Amplitude Variability</u>

By Electrode Site		
Oz	20.8	4.9
Pz	21.1	3.9
Cz	19.4	2.6
By Cognitive Level		
	Coglv 6	
Oz	22.2	5.2
Pz	22.2	4.1
Cz	20.1	3.3
	Coglv 7	
Oz	19.4	4.4
Pz	20.0	3.4
Cz	18.7	1.8
By Age		
	10	
Oz	22.6	3.9
Pz	23.7	3.0
Cz	20.6	2.3

	11	
Oz	19.3	4.2
Pz	19.4	3.0
Cz	18.7	2.5
	12	
Oz	20.7	6.2
Pz	20.2	4.3
Cz	18.9	2.9
By Age X Coglvl		
	Age 10 Coglvl 6	
Oz	24.4	2.9
Pz	25.3	2.8
Cz	21.7	2.4
	Age 10 Coglvl 7	
Oz	20.7	4.1
Pz	22.0	2.1
Cz	19.5	1.7
	Age 11 Coglvl 6	
Oz	19.7	5.3
Pz	20.1	3.7
Cz	18.9	3.3
	Age 11 Coglvl 7	
Oz	18.8	3.3
Pz	18.8	2.2
Cz	18.5	1.7

	Age 12 Coglvl 6	
Oz	22.5	6.3
Pz	21.0	4.3
Cz	19.7	3.8
	Age 12 Coglvl 7	
Oz	18.8	5.9
Pz	19.4	4.7
Cz	18.2	1.9

Latency Variability

By Electrode Site

Oz	197.7	35.8
Pz	198.8	31.3
Cz	204.7	36.4

By Cognitive Level

	Coglv 6	
Oz	189.9	40.6
Pz	201.9	27.1
Cz	207.5	35.8
	Coglv 7	
Oz	205.5	29.2
Pz	195.7	35.5
Cz	201.9	37.6

By Age

	10	
Oz	208.7	40.9
Pz	199.1	22.7
Cz	201.4	24.4
	11	
Oz	191.6	38.4
Pz	215.7	33.5
Cz	220.2	37.2
	12	
Oz	192.8	26.9
Pz	181.6	29.1
Cz	192.5	42.5

By Age X Coglvl

	Age 10 Coglvl 6	
Oz	197.6	42.7
Pz	199.7	18.8
Cz	199.4	23.9
	Age 10 Coglvl 7	
Oz	219.9	39.6
Pz	198.5	28.0
Cz	203.4	26.9
	Age 11 Coglvl 6	
Oz	188.1	51.7

Pz	215.6	28.2
Cz	216.4	45.2
	Age 11 Coglvl 7	
Oz	195.1	23.3
Pz	215.8	41.0
Cz	223.9	31.0
	Age 12 Coglvl 6	
Oz	184.1	31.7
Pz	190.4	31.0
Cz	206.7	39.4
	Age 12 Coglvl 7	
Oz	201.5	20.0
Pz	172.9	26.7
Cz	178.3	44.0

Table 1

Mean age in years for each experimental group (age X cognitive level)

Age	Cognitive Level	Age
10	6	10-5
10	7	10-5
11	6	11-7
11	7	11-9
12	6	12-3
12	7	12-6

Table 2

Means and Standard Deviations for Significant Independent Variables and Interactions

Research Question #1:

P300 Amplitude

Variable	Mean	SD
By Cognitive Level X Age		
	Coglv 6/All ages	
Cz	10.5	5.2
	Coglv 7/All ages	
Cz	17.0	8.0
By Electrode Site		
Oz	19.1	9.7
Pz	22.9	8.7
Cz	13.8	7.4

P300 Latency

By Age		
10	425.4	97.0
11	341.7	60.9
12	380.8	71.9

(table continues)

Research Question #1:

P300 Latency

Variable	Mean	SD
By Electrode Site		
Oz	362.1	76.1
Pz	378.7	66.8
Cz	407.4	111.5

Research Question #2:

Coupling

By Coupling		
OzPz	36.8	15.1
OzCz	21.9	13.5
OzFz	14.0	7.1
PzCz	38.0	12.5
PzFz	16.0	7.2
CzFz	22.9	9.7

(table continues)

Research Question #3:

Amplitude Variability

Variable	Mean	SD
By Cognitive Level		
Level 6	21.5	4.2
Level 7	19.4	3.2
By Electrode Site		
Oz	20.8	4.9
Pz	21.1	3.9
Cz	19.4	2.6

Table 3

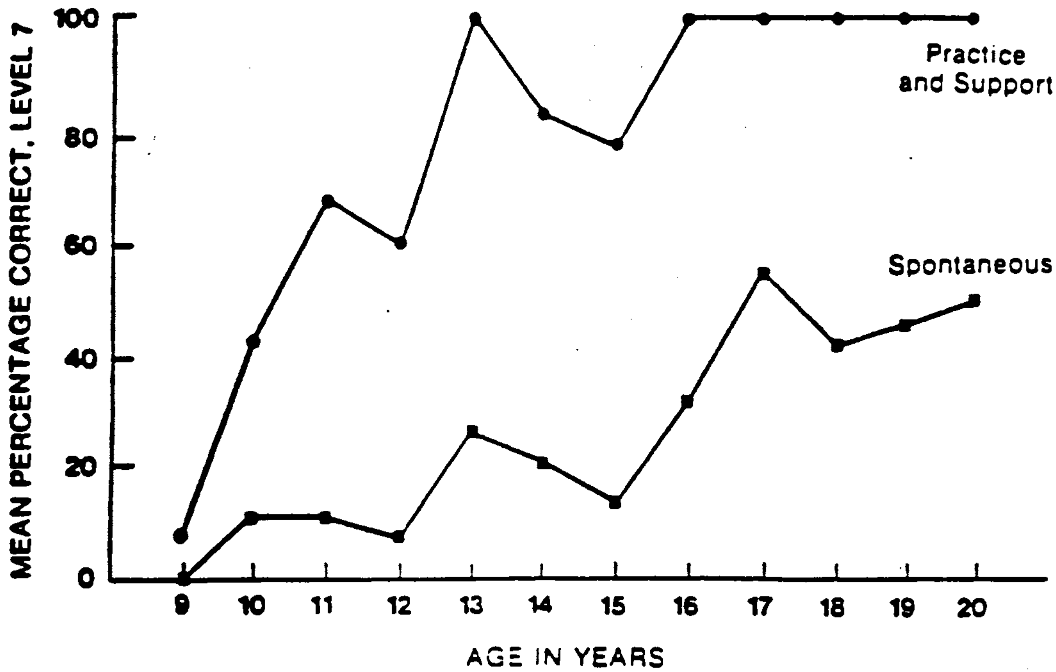
Mean IQ for each experimental group (age X cognitive level)

Age	Cognitive Level	IQ
10	6	89.1
10	7	101.1
11	6	91.1
11	7	103.5
12	6	85.8
12	7	101.8

Figure Caption

Figure 1. Fischer's study (1984) shows changes in the percentage of Level 7 arithmetic problems solved under two conditions according to age. Eight subjects, four of each sex, were tested at each age. The same subjects performed arithmetic tasks under two conditions: with and without practice-and-support.

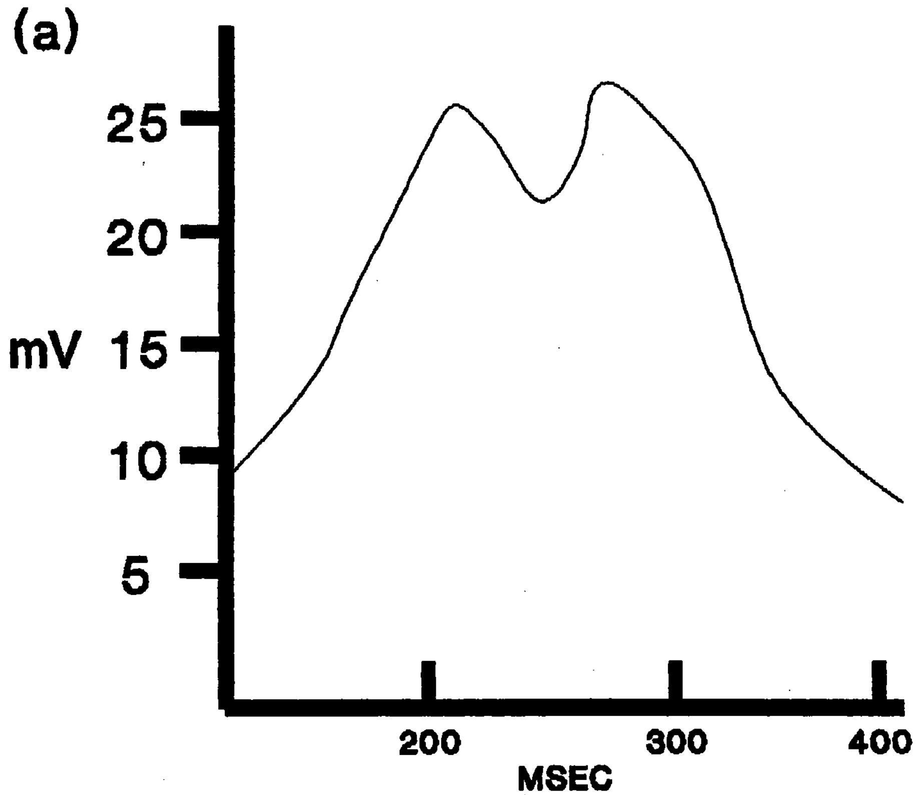
Note. From The development of abstractions in adolescence and adulthood by K.W. Fischer, H.H. Hand, A.S. Russell, 1984. In M.L. Commons, F. A. Richards, & C. Armon (Eds), Beyond Formal Operations: Late Adolescent and Adult Cognitive Development, (pp. 43-73). New York: Praeger.



MEAN PERCENTAGE CORRECT, LEVEL 7
100
80
60
40
20
0
9
10
11
12
13
14
15
16
17
18
19
20
AGE IN YEARS
Practice
and Support
Spontaneous

Figure Caption

Figure 2. P300 amplitude and latency was defined as the largest positive peak in the 200-1200 ms range past the P200 peak. If two points within this time window were within five microvolts of each other as shown in Figure 2(a), the mean of their latency and amplitude were taken. Both of the waves had to be on the same slower wave.


(a)
25
20
mV 15
10
5
200
300
400
MSEC

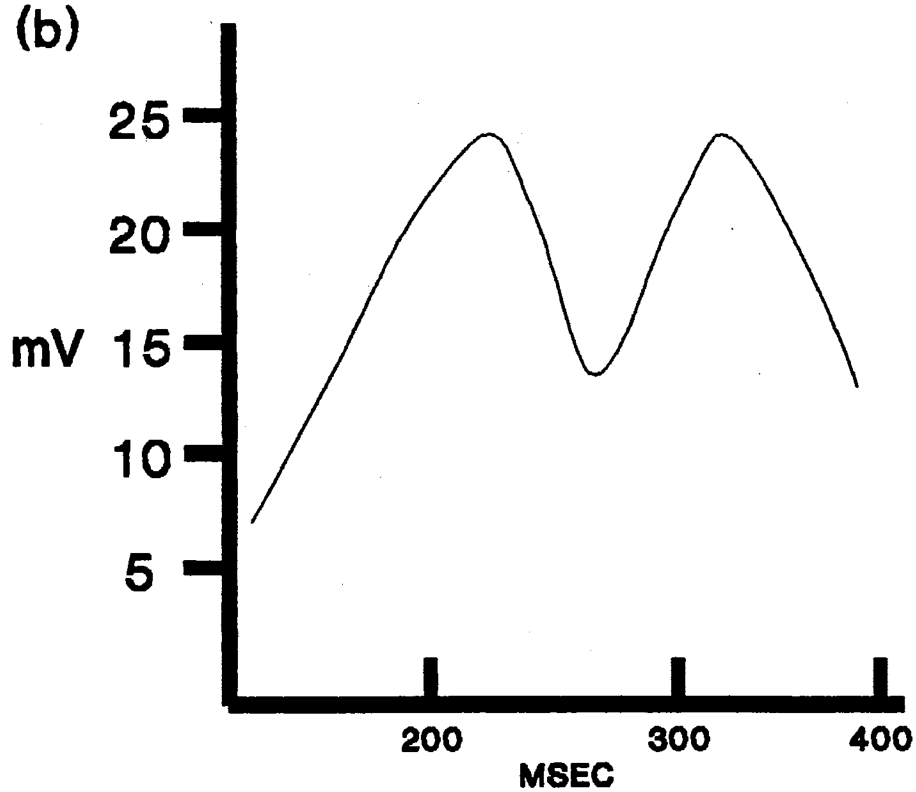

(b)
25
20
mV 15
10
5
200
300
400
MSEC

Figure Caption

Figure 3. When the grand average ERPs are taken for all subjects, this figure shows the significant difference between the P300 amplitude at the Cz electrode for Level 6 and Level 7 subjects supporting one of the hypotheses in this study.

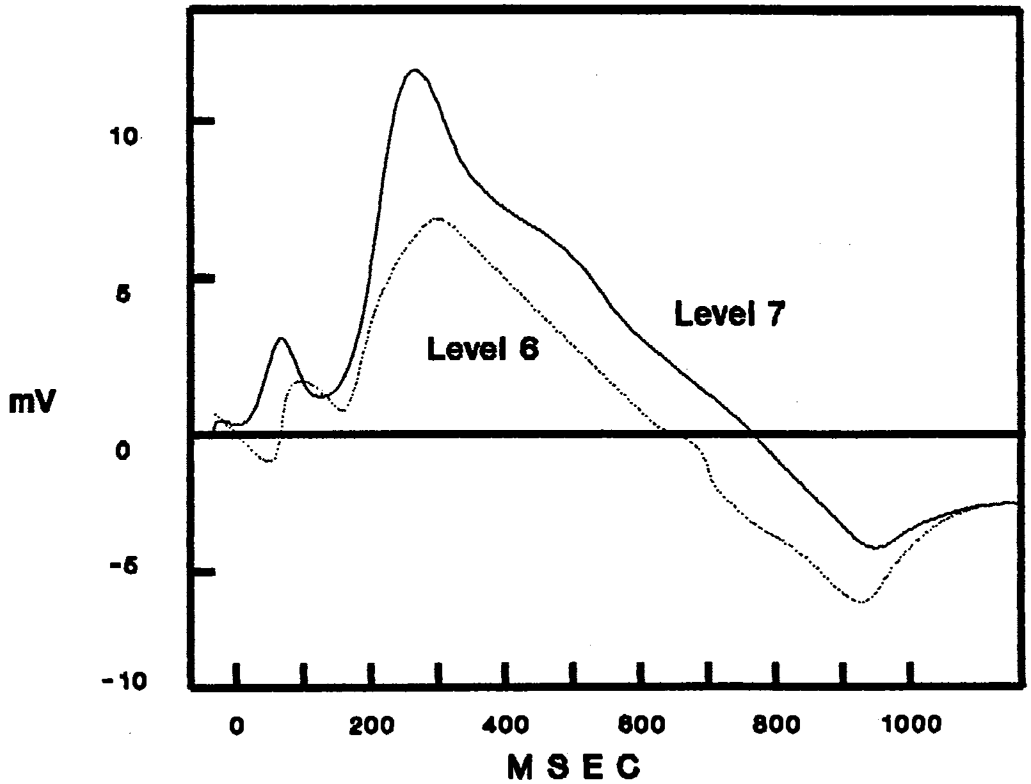

10
5
0
-5
-10
mV
Level 7
Level 6
0
200
400
600
800
1000
MSEC

Figure Caption

<u>Figure 4</u>. The mean P300 latencies at each electrode site were significantly longer at age 10 than at age 11; however, the P300 latency at age 12 was not significantly different from either age 10 or age 11.

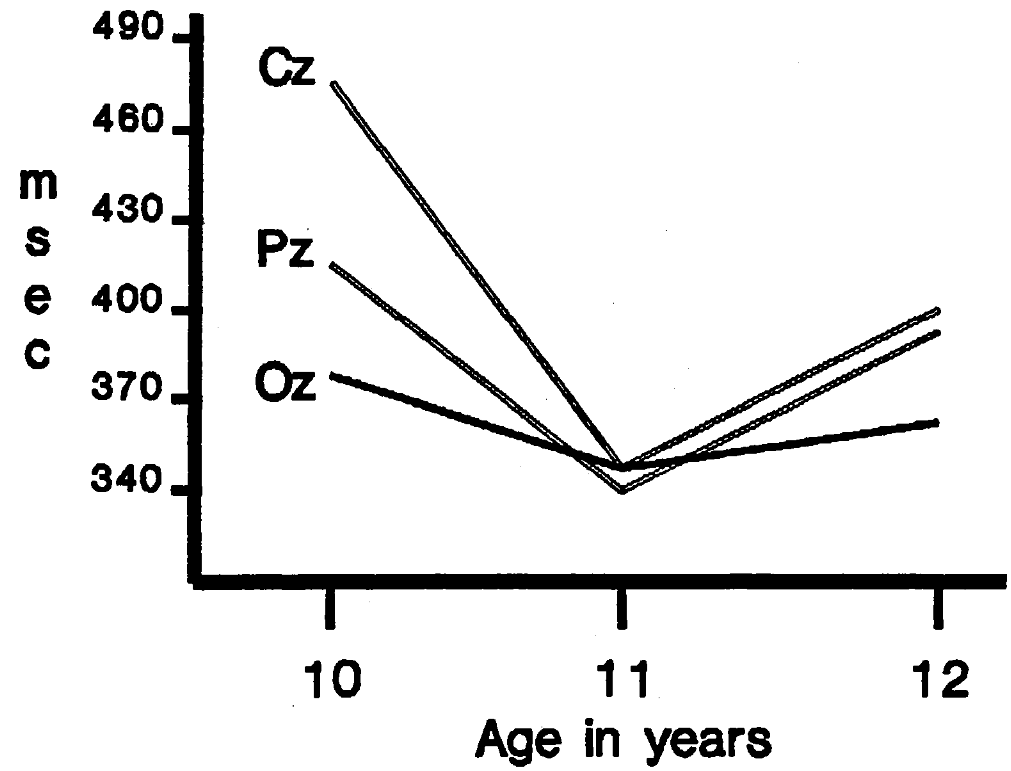

490
460
430
400
370
340
m
s
e
c
Cz
Pz
Oz
10
11
12
Age in years

Figure Caption

Figure 5. This figure shows the degree to which each of the electrode site pairs were synchronized or coupled (0 means 0% coupled, 100 means 100% coupled). The OzPz and PzCz couplings were the most highly synchronized and significantly different from the remaining four couplings. OzFz and PzFz were positioned furthest apart and were significantly different from all the other couplings.

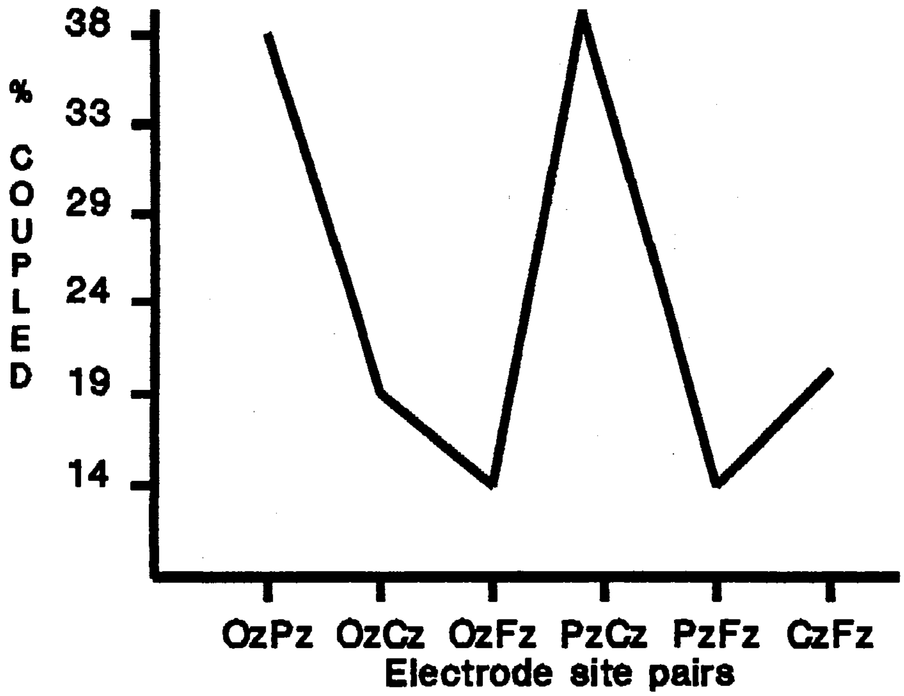
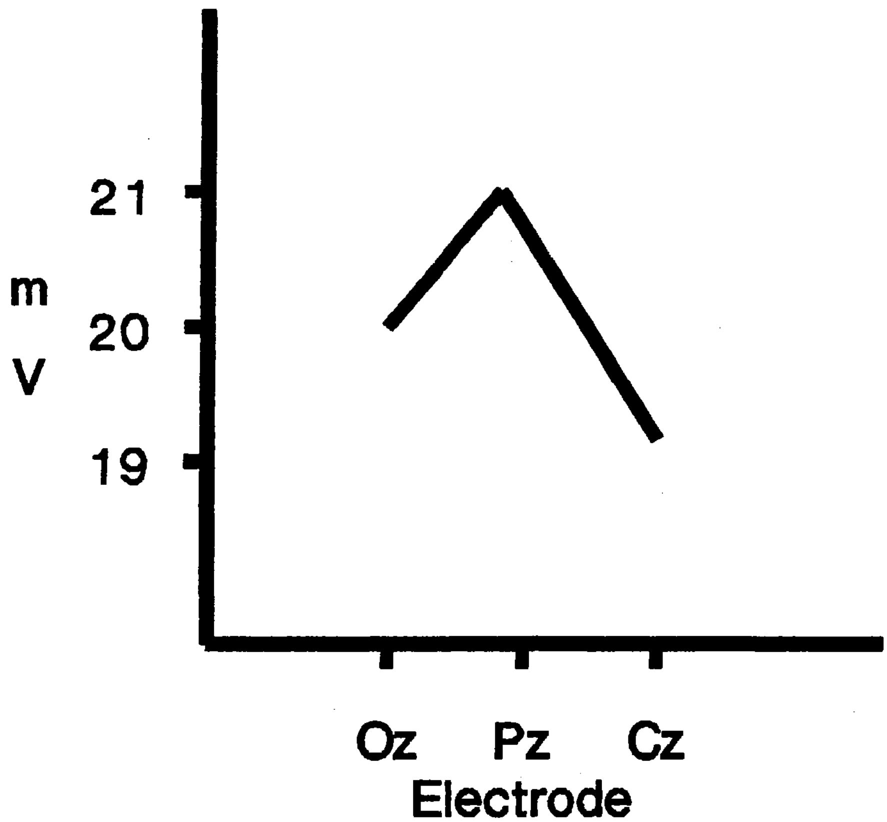

38
33
29
24
19
14
% COUPLED
OzPz
OzCz
OzFz
PzCz
PzFz
CzFz
Electrode site pairs

Figure Caption

Figure 6. When comparing the trial-to-trial amplitude variability for each of the electrode sites, Cz had a significantly smaller amplitude variability than Oz and Pz. Amplitude variability was not significantly different between Oz and Pz.


21
20
19
m
V
Oz
Pz
Cz
Electrode

VITA 2

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Doctor of Philosophy

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