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Feuer, Leonard

**EVENT RELATED POTENTIAL (ERP) CORRELATES OF TEMPORAL
ORDER JUDGMENT**

City University of New York

Ph.D. 1982

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EVENT RELATED POTENTIAL (ERP) CORRELATES OF
TEMPORAL ORDER JUDGMENT

by

LEONARD FEUER

A dissertation submitted to the Graduate Faculty
in Psychology in partial fulfillment of the
requirements for the degree of Doctor of Philosophy,
The City University of New York.

1982

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This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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Abstract

Event Related Potential (ERP) Correlates of Temporal
Order Judgment

by

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Advisor: Dr. Samuel Sutton

Auditory temporal order thresholds and event related potential (ERPs) were obtained from groups of normal children (aged 9-12, N=9) and adults (aged 22-32, N=10) in response to dichotic click stimuli. Subjects were required to discriminate the temporal sequence of the click pairs i.e., right before left (RL) or left before right (LR). Stimuli were delivered to each ear at 30 dB SL for all subjects, at interstimulus intervals (Δt 's) of 25, 50 and 75 msec (adults) and Δt 's of 75 and 125 msec (children). ERPs in response to a binaural feedback stimulus (0 msec Δt) to correct stimulus detections were also recorded. Principal components varimax analysis and an ANOVA were used to analyze the ERPs separately for the discrimination and feedback stimuli for the children and adults combined, and for each group separately.

The adults showed a significantly more sensitive temporal order threshold than the children did. No significant asymmetry in sensitivity occurred as a function of stimulus precedence. In the ERP analysis, the children and adults were matched for: 1) behavioral accuracy ($\Delta t = 50, 75$ msec adults, $75, 125$ msec children); 2) stimulus range ($\Delta t = 25, 75$ msec adults, $75, 125$ msec children); and 3) stimulus interval ($\Delta t = 75$ msec children and adults). In the behavioral match combined groups analysis for the discrimination stimulus three components were found. Slow Wave was a large positive component with a parietal scalp maximum. It was larger in the children than adults, and it was largest over the right hemisphere (C4 and P4) in the adults, and largest over the left hemisphere (C3 and P3) in the children. P350 was a late phasic positive component with a CZ maximum. P350 was largest over the hemisphere contralateral to the lead stimulus. N100/P450 was a complex biphasic factor that tended to be more negative in the adults than children. The component was more positive in response to the easy (long Δt) than hard (short Δt) condition.

For the feedback stimulus, a Slow Wave was also obtained. In addition, a P300 component was largest at CZ, and was larger in the adults than children. For the children, P450 was most positive for the RL stimuli particularly over the right hemisphere; whereas for the adults, P450 was most negative for the RL stimuli with

greatest negativity over the right hemisphere. Finally, a negative baseline shift between the discrimination and feedback stimuli was largest at the central electrodes in the children. Results were discussed with regard to component identification.

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This research was conducted in the Department of Psychophysiology at the New York State Psychiatric Institute.

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INTRODUCTION

Temporal Order Literature Review

The purpose of the present study is to obtain ERP data from matched groups of children and adults actively engaged in a temporal ordering task. Such a study should provide data relevant to the questions of: 1) temporal order processing in relation to cerebral hemispheric specialization, 2) temporal order processing in relation to normal development, 3) the ERP in relation to temporal ordering ability, 4) the ERP in relation to cerebral hemispheric specialization, and 5) the ERP in relation to normal development.

Empirical investigations (i.e., Babkoff and Sutton, 1963; Efron, 1963a, b; Hirsh, 1959; Hirsh and Sherrick, 1961; Kim, 1980; Lackner and Teuber, 1973; Mills and Rollman, 1980, Sherwin and Efron, 1980; and Swisher and Hirsh, 1972) and theoretical reviews (Babkoff, 1978; Bryden, 1967; and Hammond, 1982) of temporal order processing have left unclear the mechanism(s) underlying temporal ordering. Assessment of brain injured individuals (Efron, 1963b; Lackner and Teuber, 1973; Swisher and Hirsh, 1972), putatively brain dysfunctional children (Haggerty and Stamm,

1978; Tallal, 1980) and normal adults (Mills and Rollman, 1980) has suggested that under some conditions temporal ordering ability may involve lateralized CNS mechanisms. However, the possibility of bilateral hemispheric involvement has not been ruled out (Babkoff, 1978; Hammond, 1982; Lackner and Teuber, 1973). Hammond (1982) has recently indicated that insufficient normative data is available about temporal order processing in relation to cerebral hemispheric specialization. The present study investigates behavioral and ERP measures of auditory temporal order perception in matched groups of children and adults.

Perceptual Phenomena Associated With the Lateralization of Transient Stimuli

Initial investigations of temporal order processing were addressed by Hirsh (1959) in the auditory modality, and subsequently by Hirsh and Sherrick (1961) in the visual and somesthetic modalities. In general, experimental paradigms which have assessed temporal order processes have presented discrete identifiable stimuli separated in time by a brief interstimulus interval Δt , and have required subjects to report the sequence of stimulus presentation. In the auditory modality, binaural and/or dichotic clicks or tones have frequently been used to assess temporal ordering ability.

When dichotic click stimuli of equal duration and sensation level are presented to a normal subject, a variety of perceptual phenomena are obtained depending in part on the Δt (Babkoff, 1975; Babkoff and Sutton, 1963; Bekesy, 1960; Hirsh and Sherrick, 1961). When clicks arrive at the two ears simultaneously, subjects report hearing a unitary event located along the midline (depending on a variety of factors, often in the center of the head). As the onset time of the click at one ear is delayed with respect to the click at the other ear by about 20-40 usec, a unitary event continues to be perceived; however, its location is shifted toward the side which receives the first or leading click. As the Δt approaches 1.0 msec most subjects report hearing a unitary event at the ear of the leading stimulus. As the Δt is increased further to about 2.0 - 4.0 msec subjects report hearing two discrete events (the fusion threshold): 1) a relatively loud event at the side of the leading stimulus and 2) a much softer event at the side receiving the later stimulus. As Δt is increased from about 6.0 - 20.0 msec, subjects report hearing two separate events at the two ears which are increasingly more equal in loudness. Finally, at Δt 's greater than about 20.0 msec subjects begin to resolve the temporal sequence of the two clicks (temporal order threshold).

Assessment of Temporal Order Thresholds

Hirsh (1959) demonstrated that a minimum Δt of approximately 17 - 20 msec was required for normal subjects to perceive the correct order of various auditory stimuli at a 75% accuracy level. The thresholds that Hirsh obtained were largely independent of stimulus duration, stimulus frequency and stimulus bandwidth, suggesting that the peripheral auditory system, where differences as small as a few microseconds have physiological significance, might mediate the phenomena of spatial localization and successiveness. Hirsh suggested that, due to the increased time required to process sequential information, central anatomical and physiological processes would probably mediate temporal sequencing ability.

In a subsequent study, Hirsh and Sherrick (1961) demonstrated that the temporal order threshold was relatively invariant within and between sensory modalities. Thus, no significant difference in temporal order threshold was obtained when subjects were required to detect the temporal sequence of: 1) two tones of different pitch delivered monotonically or dichotically, 2) two identical light flashes delivered to different loci in the visual field, 3) two vibratory stimuli delivered to right and left index fingers, or 4) two cross-modal stimuli composed of auditory-visual, visual-tactile or auditory-tactile stimulus pairs.

Thus, it would appear that the CNS requires a minimum of approximately 17-20 msec to resolve the temporal sequence of two independent stimuli. Hirsh did not address the issue of temporal order processing in relation to cerebral hemispheric specialization.

Temporal Order Processing in Relation to Cerebral Hemispheric Specialization

Left Hemisphere Involvement. The idea that the right and left cerebral hemispheres may subserve different functions has been known since the mid-1800's on the basis of the qualitatively different symptomatology associated with unilateral lesions of either hemisphere. More recently, it has been suggested that the operating characteristics or efficiency of information processing of a given hemisphere probably contributes to the apparent lateralization of certain higher functions (Semmes, 1968; Hammond, 1982).

The hypothesis that temporal order processing might be lateralized in the left hemisphere was proposed by Efron (1963a, b). Efron's (1963a) interest initially centered on the perception of simultaneity of identical events delivered to different sensory pathways i.e., right and left homologous loci. Using a modified descending method of limits, normal subjects were required to report when the

perception of two sequential events appeared simultaneous. For right handed individuals, it was shown that a stimulus to the left sensory pathway had to precede a stimulus to the contralateral sensory pathway by 3 to 5 msec in order to be reported as arriving simultaneously. He reasoned that the several msec lead for the left side stimulus was required for transcallosal transmission in order for the neural volleys from each stimulus to reach the left hemisphere at the same time. In a subsequent procedure, he demonstrated that a flash to the left visual field had to precede a flash to the right visual field by 4 msec for normal subjects to report the correct order of stimulus presentation. Thus, there was a left hemisphere advantage for the perception of temporal order and simultaneity in normal subjects. .

Efron (1963b) next addressed the issue of temporal order processing in groups of brain damaged patients in order to determine the effect of lateralized lesions on temporal order performance. Expressive aphasic patients demonstrated the most severe impairment of ordering ability relative to receptive aphasic and non-aphasic brain damaged individuals. Efron suggested that a fundamental mechanism or process related to time labelling of signals appeared to be located in the dominant temporal lobe, with damage to either this region or its radiations resulting in impaired performance.

Support for Efron's suggestion that the left hemisphere is dominant for temporal order processing is derived from

the findings of Mills and Rollman (1980) and in part from the findings of Carmon and Nachson (1971). Mills and Rollman (1980) reported a significant asymmetry in the temporal order threshold for normal subjects using dichotic clicks. They found that the greatest sensitivity was obtained when a click to the right ear preceded a click to the left ear, as opposed to the reverse direction of stimulation. The authors suggested that their results confirmed the hypothesis of left hemisphere superiority for processing temporally ordered information.

Carmon and Nachson (1971) provided additional support for this hypothesis. They demonstrated that patients with left hemisphere lesions required an increase in stimulus exposure time to accurately identify the correct sequence of 3 - 5 continuously presented immediately successive (without an interstimulus interval) visual and auditory stimuli. In contrast, patients with right hemisphere lesions showed no significant difference from neurologically normal control subjects.

A general finding which has emerged from the preceding investigations of normal and brain damaged subjects is that the left hemisphere seems to be dominant for processing temporal order and simultaneity. Thus, the data from Efron (1963a, b), Mills and Rollman (1980) and Carmon and Nachson (1971) suggest that the left hemisphere is dominant for the perception of temporal order and simultaneity. This

suggestion has been extended by Lackner and Teuber (1973) who suggested that the left hemisphere is more competent than the right hemisphere in processing temporal information in general. Lackner and Teuber (1973) demonstrated that patients with left hemisphere lesions showed a more severe impairment than patients with right hemisphere lesions on an auditory fusion threshold task (i.e., perception of single versus double stimulation).

Bilateral Hemispheric Involvement. Evidence has also been obtained which suggests that under certain conditions, both hemispheres assume an active role in temporal order processing. Belmont and Handler (1971) investigated temporal order processing ability in a group of unilaterally right brain damaged patients and matched non-neurological hospitalized control patients. Subjects were required to determine which one of two dichotically presented tones was presented first, i.e., right before left or left before right. Belmont and Handler demonstrated that brain damaged patients performed worse than controls when the lead stimulus was directed to the defective hemisphere (left ear). These data are consistent with a similar finding of Diamond, Snow and Bender (1967) who demonstrated a comparable effect for fusion threshold. Belmont and Handler suggested that damage to a given hemisphere results in a selective delay in information processing. Unfortunately, they did not examine patients with left hemisphere lesions.

However, Swisher and Hirsh (1972) did examine patients with both left and right hemisphere lesions on a task comparable to Belmont and Handler. Swisher and Hirsh found that all brain damaged subjects were impaired relative to normal controls in their ability to order pairs of flashes, clicks and tones. The patients with left hemisphere lesions performed worse than patients with right hemisphere lesions. They reported that auditory temporal order performance was maximally impaired when the lead stimulus was directed to the dysfunctional hemisphere. The authors suggested that many components contribute to the judgements required of temporal ordering tasks, i.e., stimulus modality, stimulus frequency and location of pathology and that their findings neither implicate nor preclude a neural "locus" for temporal order processing.

Additional data in support of the hypothesis of bilateral hemispheric involvement in temporal order processing is available from examination of brain damaged patients (Bender, 1978; Kim, 1980; and Sherwin and Efron, 1980) and putatively brain damaged children (Haggerty and Stamm, 1978). Sherwin and Efron (1980) investigated the effects of unilateral anterior temporal lobectomy on monotic temporal ordering ability in a group of non-aphasic epileptic patients. Two main findings emerged: 1) relative to normal controls, there was a small but significant elevation in the temporal order threshold in response to

stimulation of the ear contralateral to the lesioned hemisphere, and 2) there was a large bilateral elevation in temporal order threshold in patients with more posterior lesions. Sherwin and Efron suggested that deficits in temporal ordering ability as a result of right hemisphere lesions may be under-reported since the lesion responsible for temporal order deficits in the right hemisphere is small and difficult to diagnose.

Kim (1980) has provided evidence that the type of sequencing deficit (verbal or non-verbal) interacts with the laterality of cerebral pathology. Thus, patients with left hemisphere lesions were more impaired on verbal sequencing tasks, whereas patients with right hemisphere lesions were more impaired on non-verbal sequencing tasks. Kim questioned previous reports of left hemisphere superiority for temporal order processing.

Bender (1978) has reported that inability to recite symbols backwards by a person who can do so forwards frequently occurs in cases of "organic mental syndrome" and aphasia. For instance, patients with organic mental syndrome, aphasia and dyslexia showed a greater incidence of failure to reverse serial order than did normal elderly adults. Bender suggested that no specific lesion appears responsible for the reversal deficit.

Data from putatively brain dysfunctional children (i.e., dyslexics) suggested that these subjects show an impairment

in temporal processing ability (auditory fusion and temporal order threshold) indicative of lateralized hemispheric processes. Haggerty and Stamm (1978) demonstrated a significant lengthening of the dichotic click fusion threshold in learning disabled children aged 7 - 9.5. The children with the most severe elevation in fusion threshold were those who displayed a maximal degree of impairment on standardized linguistic tests. The authors suggested this was due to either a marked degree of maturational lag or to left sided temporal dysfunction. Alternatively, the children with a less severe elevation in the fusion threshold were qualitatively different in that their psychometric scores reflected a perceptuomotor disability. This latter group of children was postulated to have a minor degree of maturational lag.

In summary, the previously discussed investigations have demonstrated that temporal order and temporal fusion capacities may be significantly impaired by a lesion of either hemisphere, suggesting that under certain conditions each hemisphere can be involved in the processing of temporal information.

Models of Temporal Order Mechanisms

Lashley (1951), Bryden (1967) and Babkoff (1978) have proposed theoretical models which suggested how the CNS may

process temporally sequential information. Lashley suggested that memory and its associated traces are prerequisites for the occurrence of serially ordered behavior. He suggested that memory traces are static phenomena which exist simultaneously yet maintain spatial differentiation. Recall, according to Lashley, involves a temporal succession of neural activity. The process by which serially ordered behavior occurs involves a selective scanning mechanism which searches through memory trace arrays and results in ordered behavior. Lashley could not, however, define the dynamics or properties of the scanning mechanism.

Because of this deficiency in Lashley's model, Bryden (1967) argued that the problem only shifted from one level to another without without any resolution. Bryden suggested that all stimuli initiate traces which correspond to an eliciting event. Each such trace can be identified in terms of its temporal and spatial characteristics. He further suggested that trace activation results in the activation of a set of mutually inhibitory and disinhibitory ordering systems. Activation of an initial trace would result in inhibition of subsequent traces, and subjective report would result in release of subsequent inhibition. Bryden indicated that complex temporal integrative neuronal activity mediated the ordering system.

Babkoff (1978) has also suggested that auditory temporal lateralization is dependent upon spatio-temporal patterns of

neural activity throughout the auditory system. He suggested that the perception of lateralized click stimuli requires that the cortex integrate volleys of activity initiated at the brainstem level. Perception of a lateralized event was postulated to occur via a comparator mechanism which assessed the neural activity of homologous cortical structures.

In a recent review of the temporal order literature Hammond (1982) has suggested that each cerebral hemisphere most likely performs temporal order discriminations, but that the hemispheres process information at different rates. In this regard, Lackner and Teuber (1973) suggested that the left hemisphere is faster than the right in processing temporal information. Hammond (1982) indicated that each hemisphere probably processes whatever information is directed to it rather than classifying the input as appropriate or inappropriate before either processing it or shuttling it to the other side.

In summary, the models of temporal processing each suggest that spatio-temporal patterns of neural activity probably account for temporal ordering ability.

Despite advances in techniques available to study cerebral electrophysiological activity in relation to sensory and cognitive processing, i.e., the event related potential (ERP), virtually no electrophysiological data is available to address issue(s) of temporal ordering.

Therefore, the present study combines ERP and psychophysical procedures to address the question of temporal order processing.

The Event Related Potential (ERP)

The human event related potential (ERP) is an analogue voltage waveform recorded from the surface of the scalp in response to a discrete sensory stimulus. The ERP is a time-locked bioelectric signal in the range of 1 - 50 microvolts. Due to its small amplitude, the ERP waveform is obscured by the larger ongoing electroencephalogram (EEG). Therefore, in order to observe it, sensory stimuli are repeated and waveforms are averaged across trials. Since the ERP is time locked to the stimulus whereas the background EEG is not, the averaged event related potential emerges as the background EEG cancels itself out. The human averaged ERP was first described by Dawson in 1954 (Dawson, 1954).

An ERP is not a unitary phenomenon. Instead, it is a result of multiple sources of electrical activity referred to as components (Friedman, Vaughan, and Kimling, 1981; Picton, Hillyard and Krause, 1974; Picton and Stuss, 1980; and Sutton and Ruchkin, 1981) with each component occupying a temporal and spatial dimension. Until recently, the ERP literature has, in general quantified, and therefore implicitly defined, components in terms of their polarity,

sequence, peak amplitude and peak latency. Thus, a positive component observed at a latency of about 300 msec has frequently been referred to as P300 (Donchin, Callaway, Cooper, Desmedt, Goff, Hillyard and Sutton, 1977).

Different components have been identified which vary lawfully in relation to stimulus parameters, the nature of the task and subject variables. Components which are contingent on stimulus parameters, have been referred to as exogenous components, whereas components which are less dependent on the physical properties of the stimulus or which may occur in the absence of a physical stimulus have been referred to as endogenous components.

Within the past few years, studies have suggested that the ERP is more complicated than it was previously thought to be. Part of the complexity has emerged from studies which have demonstrated a number of new ERP components. For example, Courchesne (1977) reported a long latency high amplitude positive (Pc) and negative (Nc) component in infants as young as six months of age. N.K. Squires, K.C. Squires, and Hillyard (1975) demonstrated the existence of two late positive components (P3a and Slow Wave) distinct from the more classical P300 or P3b component (Sutton, Tueting, Zubin and John, 1967).

The use of multivariate analytic techniques, i.e., Principal Components Varimax Analysis (PCVA), to analyze ERP waveforms has demonstrated that the sequential peaks and

troughs of the ERP are not mutually independent. Instead, ERP components tend to overlap, i.e., they share in part the same temporal and spatial domain (Sutton and Ruchkin, 1981; Ruchkin, Sutton and Steg, 1980; Friedman et al 1981b; Donchin and Heffley, 1978). One implication of this finding is that it may be misleading to quantify a component solely in terms of its peak amplitude and peak latency since an averaged peak may be a composite of two or more components. Sutton and Ruchkin (1981) have pointed out that two overlapping components may vary inversely as a function of the same experimental condition leaving the averaged peak amplitude relatively unchanged. PCVA then has become a useful technique to: 1) assist in the identification of independent sources of common variance within an ERP waveform and 2) permit assessment of the effects of experimental manipulation on each of the principal components.

As alluded to earlier, the ERP literature in relation to temporal order processing is extremely limited. Molfese (1980) recently presented data which he interpreted as localizing a temporal processing mechanism in the right hemisphere. He delivered two different pitch tones differing in tone onset time by either 0, 20, 40 or 60 msec to normal college students binaurally through a loudspeaker. The subjects were requested to passively attend to the stimuli. Molfese reported that the data could be

represented by nine independent factors which accounted for 80.8% of the variance. Four of the factors, which accounted for 34.9% of the variance, were significantly influenced by the asynchronous onsets of the stimuli. In three of these four factors, the ability to discriminate between the different stimuli was observed bilaterally, i.e., in both hemispheres. One factor which accounted for 8.1% of the variance showed a significant hemisphere by stimulus onset asynchrony interaction, i.e., a 400 msec negative component was larger over the right than left hemisphere for stimulus onset asynchronies of 40 and 60 msec compared to stimulus onset asynchronies of 0 and 20 msec. Although Molfese cited this as evidence of a right hemisphere temporal processing mechanism, this same factor could differentiate different stimulus onset asynchronies in the left hemisphere. Molfese's suggestion that the right hemisphere has a special role in temporal processing should be considered as tentative at best, since a greater number of factors, and percentage of variance of the factors, implicate bilateral as opposed to unilateral processing of stimulus onset asynchronies. Furthermore, since no task was required of the subject, it is not clear what information the subjects obtained from the stimuli.

Effects Of Age On The ERP

Numerous studies have investigated effects of age on the ERP. Generalizations and conclusions in this regard are difficult to make due to differences between studies in: 1) stimulus modality, 2) experimental paradigm, 3) subject task, 4) subject age, 5) electrode location, 6) components measured and 7) analytic techniques. Relevant studies will be reviewed by stimulus modality and component. Within each section, data will be reviewed first from the early components, and then from the later components.

Auditory Stimuli.

N0-P1. Barnet, Ohlrich, Weiss and Shanks (1975) and Ohlrich, Barnet, Weiss and Shanks (1978) investigated auditory ERPs from sleeping children during the first three years of life. These studies demonstrated that an early N0-P1 component, measured peak to peak, increased in amplitude significantly as a function of age. No significant changes in latency were found for either N0 (15-60 msec latency) or P1 across age groups.

P1-N1. Barnet et al (1975) and Ohlrich et al (1975) also reported that a P1-N1 component, measured peak to peak, was larger in the older children. No other studies have reported significant age related effects for P1-N1.

N1. Satterfield and Braley (1977) recorded auditory ERPs from groups of normal children six to seven and ten to twelve years of age. The children viewed cartoons while ERPs were recorded to ostensibly unattended click stimuli. The latency of N1 was significantly longer in the older children.

Goodin, Squires, Henderson and Starr (1978) required subjects to detect rare auditory stimuli which were randomly intermixed with more frequent auditory stimuli. N1 latency was found to occur significantly later in elderly compared to young subjects (ages 8-80).

N1-P2. Barnet et al (1975), Satterfield and Braley (1977) and Goodin et al (1978) have reported data for N1-P2 in relation to development. Barnet et al found that N1-P2 decreased significantly in amplitude in sleeping children over the first three years of life. Similarly, Satterfield and Braley (1977) found a decrease in the amplitude of N1-P2 between the ages of six to twelve. However, Goodin et al (1978) found no significant change in amplitude for N1-P2 from age eight to fifteen, but then decreased significantly in amplitude at a rate of .02uv/yr until age 80. Goodin et al (1978) also demonstrated a significant change in the scalp distribution of N1-P2 as a function of age. For children, N1-P2 was maximal at PZ, and with increasing age, the maximal amplitude shifted to a normal adult pattern with a fronto-central maximum.

P2. Pfefferbaum, Ford, Roth, Hopkins and Kopell (1979) have reported data for P2 measured peak to baseline in relation to development, while Barnet et al (1975) and Goodin et al (1978) have presented data for P2 latency in relation to development.

Pfefferbaum et al (1979) found that the amplitude of P2 was largest at CZ and increased as a function of stimulus intensity for normal young adults (20-28). An increase in latency of P2 as a function of age (8-80) has been found by Goodin et al (1978). In contrast, Barnet et al (1975) demonstrated that the latency of P2, in sleeping children, decreased with age across the first three years of life. However, the data from Barnet et al were obtained under markedly different conditions from the other relevant studies.

P2-N2. Barnet et al (1975) and Satterfield and Braley (1977) have reported data for P2-N2 measured peak to peak, in relation to development. Barnet et al (1975) reported that P2-N2 increased significantly in amplitude over the first three years of life in sleeping children, whereas Satterfield and Braley (1977) demonstrated that the amplitude of P2-N2 decreased in amplitude between the ages of six and twelve. However, in addition to the age differences between the subjects in each study, there was a marked difference in their state of arousal.

N2. Friedman, Brown, Cornblatt, Vaughan and Erlenmeyer-Kimling (1981) recently recorded auditory ERPs from 70 adolescents, 11 - 18 years of age. Subjects were required to detect a target pitch change or a missing stimulus, each of which occurred at a probability of 17%. Peak to baseline measurement and PCVA were used to assess N250 (N2) in relation to development. N250 was maximally distributed at FZ; in addition, N250 decreased in amplitude as a function of increased age. At all ages, the N250 component was more positive at PZ for a relevant pitch change as opposed to an irrelevant pitch change. Friedman et al (1981a) suggested that younger children may characteristically show less positivity than older children in the ERP; furthermore, the smaller positivity in the younger children may be the result of a physiological difference, a difference in mode of information processing, or an interaction of the two.

Barnet et al (1975), Satterfield and Braley (1977) and Goodin et al (1978) presented data for N2 latency in relation to development. Barnet et al (1975) reported a significant decrease in latency for N2 over the first three years of life in children who were asleep. Similarly, Goodin et al (1978) demonstrated a significant decrease in latency of N2 between the ages of eight and fifteen, which was followed by a gradual increase in N2 latency until age 80. In contrast, Satterfield and Braley (1977) found a

significant increase in N2 latency from six to twelve years of age.

N2-P3. Barnet et al (1975) and Goodin et al (1978) presented data for N2-P3 in relation to development. Barnet et al (1975) reported that N2-P3 increased significantly in amplitude over the first three years of life in sleeping children. Goodin et al (1978) demonstrated that N2-P3 showed a tendency to increase (though nonsignificantly) from age eight to fifteen, but then decreased significantly from age fifteen to eighty at a rate of .02uv/yr. In addition, Goodin et al (1978) found a significant change in the scalp distribution of N2-P3 as a function of age. In children, the N2-P3 component showed a maximal distribution at CZ relative to FZ and PZ. Young adults showed the same scalp distribution as the children; however, with increasing age, the amplitude of N2-P3 decreased at CZ relative to FZ and PZ.

P3. Pfefferbaum, Ford, Roth and Kopell (1980) and Friedman et al (1981a) have reported data for a late positive component (P300) in relation to development measured either peak to baseline, or via a PCVA. Barnet et al (1975), Goodin et al (1978) and Friedman et al (1981a) presented data for P300 latency in relation to development.

Pfefferbaum et al (1980) demonstrated that normal young adults (22.5) showed a maximal amplitude P3 at CZ; in response to auditory target stimuli. However, Friedman et al (1981a) showed no changes in a P350 component measured peak to baseline or via a PCVA as a function of age.

In contrast with the amplitude data, the findings for P3 latency have been somewhat more sensitive to differences in age between subjects. Barnet et al (1975), Goodin et al (1978) and Friedman et al (1981a) measured the latency of a late positive (P300) component in relation to age. Between the ages of eight and fifteen, there was a marked decrease in the latency of P3 which was followed by a gradual increase in latency until age 80 (Goodin et al, 1978). Throughout adolescence (11-18) Friedman et al (1981a) failed to demonstrate a change in P350 latency. Barnet et al (1975) demonstrated that P3 latency decreased over the first three years of life. However, it is unlikely that the P3 component reported by Barnet et al (1975) is the same as the late positive endogenous P3 component reported in the previous studies due to the fact that Barnet et al were recording from sleeping children as opposed to actively attending subjects.

In summary, the evidence suggests that there is a tendency for the latency of the late positive component (P300) to decrease throughout childhood and increase throughout adulthood in alert, attentive subjects.

Slow Wave. Only two studies have investigated the Slow Wave component from a developmental standpoint: Pfefferbaum et al (1980) and Friedman et al (1981a). Slow wave has been found to be maximally positive at PZ and maximally negative at FZ in young adults (Pfefferbaum et al, 1980) and adolescents (Friedman et al, 1981a). The negative portion of Slow Wave has been shown to decrease in amplitude with age (Friedman et al, 1981a; Pfefferbaum et al, 1980).

Visual Stimuli. Investigation of ERP development utilizing visual stimulation are reviewed for endogenous components since the late components can be obtained independent of stimulus modality.

N2. Courchesne (1979) and Daruna, Karrer, Cone and Warren (1979) presented data for N2 in relation to development. Courchesne demonstrated that the latency of N2 decreased as a function of age between 6 - 36 years of age in response to target stimuli.

A significant correlation between N2 latency and reaction time was found in response to a visual stimulus for children aged six to eight and preadolescents aged ten to thirteen; but not for adolescents aged sixteen to eighteen (Daruna et al 1979). The authors suggested that the older children were able to dissociate response initiation from stimulus identification processes indexed by N2 whereas the

younger children could not. Daruna et al (1979) reported that N2 latency decreased as a function of age, but not significantly.

Late Positive Component (P3). Several studies have investigated a late positive component presumed to be P300, in relation to development (Courchesne, 1978; 1979; Kurtzberg, Vaughan and Kreuzer, 1979; Marsh, 1975; Otto, Benignus, Seiple, Loiselle and Hatcher, 1980; and Shelburne, 1972; 1973).

Shelburne (1972, 1973) investigated visual ERPs from 20 normal children age 8 - 12, and from eight normal adults with a mean age of 24. Consonant-vowel-consonant (CVC) trigrams were presented to each subject. Subjects were required to indicate whether or not the third consonant completed a word or a nonsense syllable. He found that in both age groups subjects who performed the task correctly showed a larger positive component (presumably P300) to the third position letter than to the prior letters. However, subjects who performed poorly on the task did not show this effect. No consistent differences in the VEP were reported between children and adults.

Marsh (1975) recorded visual ERPs from a group of young male subjects 21 - 26 years of age. Subjects were shown a sequence of one to five numbers followed by a test number. The subjects were required to indicate as quickly as

possible whether or not the test number was included amongst the initial stimuli. Amplitude and latency measures were obtained for a late positive component (LPC, about 500 msec latency) to the test stimuli. Increasing the number of items in the initial list resulted in a decreased amplitude LPC. The subjects showed a significantly larger right than left hemisphere response. The LPC latency increased significantly as a function of list length at FZ, CZ and PZ.

A late positive component (LPC) was investigated by Kurtzberg et al (1979) from a group of ten children over a three year period. The children were required to detect infrequent visual target stimuli amongst more frequent non-target visual stimuli. At each age, a LPC was obtained to the signal stimuli. With increasing age, the LPC was reported to become more prominent and demarcated in the parietal region. There was also a tendency for the latency of the late positive component to decrease with increased age. At occipital and central regions the left hemisphere LPCs were consistently larger than the right hemisphere responses. However, the parietal and temporal electrode locations showed a shift in lateralization from a left sided maximum to a right sided maximum with increasing age. The authors suggested that this shift might reflect the development of a right parietal cortex mechanism for processing non-verbal visual information. Unfortunately, no statistical analyses of the data were presented.

Courchesne (1978; 1979) demonstrated that the ERPs in response to target stimuli were similar in morphology for subjects from 6 - 36 years of age. However, significant developmental effects in response to target stimuli involved a decrease in amplitude and latency of a parietal maximum P300 component as a function of increased age.

In summary, the data for the late positive component seems to show a decrease in latency throughout childhood and adolescence, which is then followed by a gradual increase as a function of increased age. The data with respect to amplitude of the late positive component has been less consistent.

Slow Negative and Positive Components: Nc and Pc.

Several investigations have reported high amplitude negative and or positive components in children which appear qualitatively different from components reported in adults. Symmes and Eisengart (1971) recorded visual ERPs from 79 normal children aged five to eleven. They reported a large (20 - 40 uv) negative component about 300 - 500 msec after subjects were presented cartoon stimuli and instructed to remember them. The late negative component was significantly smaller when the stimuli were presented out of focus or when blank flashes were presented. The authors suggested that this late negative component might reflect the subjects' perception of meaningful visual stimuli.

Courchesne (1977, 1978, and 1979), in a series of studies, investigated ERPs, under a variety of conditions, from infancy to adulthood. He initially reported that novel non-target and frequent non-target visual stimuli result in markedly different ERPs in children, but result in similar ERPs in adults. The adults' waveforms demonstrated a typical late positive P300 component to the novel visual stimuli (Courchesne, Hillyard and Galambos, 1975). In contrast, the children's ERPs were characterized by the presence of a high amplitude, long latency, long duration negative (Nc) and positive (Pc) component to both the novel and non-target stimuli. These components were shown to occur in six month old infants as well as in older children. The Nc component decreased in amplitude and latency throughout childhood (Courchesne 1979). In addition, the Nc component was larger in amplitude and longer in latency for novel stimuli than for frequent stimuli. The Pc component was largest in amplitude between six to eight years of age and then decreased steadily in both amplitude and latency until adulthood. The Pc component did not discriminate novel from frequent stimuli.

Courchesne suggested that the Nc component might reflect the perception of attention getting events. He also suggested that the Pc component might be related to the development of organizational and/or categorization ability on the evidence that children have been reported to develop

categorizing behavior at the age at which Pc is at its' maximum.

Similar long latency negative (350-450 msec) and positive (1000-1200 msec) components were found by Otto et al (1980) in a group of children 1-6 years of age. The children were asked to watch cartoons while rare and frequent tones were presented via a loudspeaker. The positive component was found to habituate rapidly across trials. The duration of the negative component increased across trials and encroached upon the interstimulus interval. Otto et al (1980) suggested that the positive wave might be an analog of P3 (not PC); and that the negative wave might represent a CNV analog (not NC).

ERP Asymmetry

Numerous studies have investigated bilateral scalp ERPs in attempts to determine if the ERP reflects interhemispheric differences in function. In particular, Andreassi, DeSimone, Friend and Grota, 1975; Botte, 1974; Butler, Keidel and Spreng, 1969; McCallum and Curry, 1980; Rosenzweig and Rosenblith, 1950; and Wolpaw and Penry, 1975; have demonstrated larger amplitude and shorter latency exogenous components over the hemisphere contralateral to a sensory stimulus in comparison with the ipsilateral response. These results seem to reflect the physiological dominance of the crossed sensory pathways.

Thus, the latency of P1 and N1 over the hemisphere contralateral to an auditory stimulus was shorter than over the hemisphere ipsilateral to the stimulus (Butler et al, 1969). A similar (but non-significant) lateralized difference was observed for the amplitude of N1 and P1. Additional data in support of the dominance of the crossed sensory pathways show a larger positive peak Ta (105-110 msec) and negative peak Tb (150-160 msec) at temporal electrode placements over the hemisphere contralateral to the side of stimulation as opposed to the hemisphere ipsilateral to the stimulus (Wolpaw and Penry, 1975). A similar dominance effect was observed for the same components with respect to latency. McCallum and Curry (1980) reported similar amplitude and latency effects for an N1c component (129 msec) and a P3 component (but not significant for P3).

In contrast with the studies which have assessed the dominance of the crossed sensory pathways, the relationship of ERP asymmetries to functional cerebral specialization has remained more of an open question. Small ERP differences between the hemispheres have been repeatedly demonstrated, however Friedman, Simson, Ritter and Rapin (1975) and Donchin, Kutas and McCarthy (1977) have been extremely critical of many of these studies because of various methodological issues. One of the methodological issues which has received insufficient attention in lateralization

studies, is the issue of electrode reference. Garneski and Steelman (1958) reported that it is necessary to equate the resistance of reference electrodes when they are linked together. This is necessary especially in lateralization studies since a difference in resistance in one of two linked reference electrodes was shown to result in an increase in amplitude by as much as 20% over the scalp electrode on the side of the lower reference resistance (Garneski and Steelman, 1958). None of the studies reviewed below has dealt with the problem of matching reference electrode resistance.

A selective but representative review of the ERP literature addressing electrophysiological correlates of functional cerebral hemisphere specialization will be presented.

Auditory Stimuli. Shenkenberg and Dustman (1970) investigated bilateral ERPs in response to binaural click stimuli. ERPs were obtained from 80 male and 80 female subjects aged 4-86 using C3 and C4 referenced to linked ears. The subjects were not required to perform a task. No hemispheric differences on measures of cumulative ERP voltage, peak to peak amplitude, or peak latency were obtained.

In contrast, Cohn (1971) reported that click stimuli resulted in a larger amplitude positive component (14 msec

latency) over the right hemisphere, whereas verbal stimuli resulted in either a larger amplitude response over the left hemisphere, or an equal amplitude response over both hemispheres. He recorded ERPs to 10 msec duration clicks and to single syllable spoken words of 150 msec duration. Stimuli were presented binaurally at a rate of 1/sec. ERPs were recorded from loci 2 cm lateral of the mid-sagittal line. Cohn suggested that the click stimuli were processed predominantly in the right hemisphere; whereas the verbal stimuli were processed bilaterally or in the left hemisphere. The 14 msec latency component referred to in this study is an unusually short latency component which must be considered questionable with the parameters of the recording system employed.

ERPs were obtained from ten normal right handed subjects in response to common phonemes which required a linguistic or non-linguistic discrimination (Wood, Goff and Day, 1971). The ERPs were recorded from C3, C4, T3 and T4 referenced to linked earlobes, while stimuli were delivered binaurally at 65 dB SL against a background of white noise. At latencies greater than 250 msec there was a significant difference in amplitude at C3 and T3 as a function of experimental condition. The authors suggested that differential neural activity occurred within the left hemisphere as a function of differential processing requirements of a given stimulus. It is not clear why right hemisphere differences did not

emerge since right hemisphere function has been implicated in the non-linguistic task employed.

A significantly larger N1 component over the left than right hemisphere was obtained by Morrell and Salamy (1971) in response to binaural nonsense stimuli at a comfortable listening intensity. Subjects were required to report each stimulus presented while ERPs were recorded from bilateral frontal, central and temporal-parietal electrodes referenced to linked earlobes. The asymmetry was largest at the temporal-parietal leads. It was suggested that the effects might be attributable to differences in transmission of neural activity from deeper to superficial layers of temporal-parietal cortex. However, Friedman et al (1975) have criticized Morrell and Salamy (1971) for failure to use a non-verbal control stimulus.

Matsumiya, Tagliamsco, Lombrosos and Goodglass (1972) recorded auditory ERPs to binaurally presented stimuli using bipolar recordings W1-P3 and W2-P4. Four conditions of stimulation were presented, 1) undiscriminated words, (four monosyllabic words intermixed with sounds of different mechanical noises. Subjects were required to tally the number of words) 2) undiscriminated sounds, (sound effects generated by different mechanical noises intermixed with words of condition 1. Subjects were required to tally the number of sounds). 3) discriminated sounds, (the same sounds as in condition 2, however, subjects were required to

discriminate the different categories of sound stimuli) and 4) meaningful speech. Six out of nine subjects showed a larger W wave (a positive component with a 100 msec latency) over the left than right hemisphere in all conditions. The largest degree of asymmetry was obtained to the meaningful speech whereas the least asymmetry occurred to tallying of stimuli. The authors suggested that the significance of a stimulus to a subject is more important than its physical parameters in determining asymmetry.

In order to determine if ERP differences parallel the right ear advantage often reported for verbal stimuli in dichotic listening tasks, Halland (1974) recorded auditory ERPs to dichotic, monaural, and diotic verbal stimuli. ERPs were recorded from normal right handed males from CZ, T3, T4, F7 and F8 referenced to linked earlobes. Stimuli consisted of CVC trigrams. A late positive component (160-306 msec latency) was found to be significantly larger over the right hemisphere than left hemisphere in all conditions. This component did not vary as a function of condition, nor was the magnitude of the asymmetry related to condition. He suggested that the positive component could be associated with the linguistic nature of the task and the maintenance of a verbal set. Halland's finding is unusual in the sense that the ERP was larger over the right hemisphere during a verbal task designed to engage the left hemisphere.

Differential semantic usage of an identical word (i.e., noun or verb form) did result in a lateralized difference in the ERP (Brown, Marsh and Smith, 1973). The data indicated that the correlation of the waveforms to noun and verb forms of the same word was lower over the left hemisphere than the right hemisphere, suggesting less homogeneity of activity within the left than the right hemisphere to the different stimulus contexts.

Davis and Wada (1974) recorded auditory and visual ERPs from a group of normal, presumably left hemisphere speech dominant, subjects and from five left hemisphere and five right hemisphere speech dominant epileptic patients, prior to surgery. Auditory stimuli (clicks) and visual stimuli (diffuse flashes) were presented to the subjects at random with no task instructions. ERPs were recorded from O1, O2, T1 and T2 referenced to linked ears. Auditory stimuli resulted in greater within-hemisphere correlation over the speech dominant hemisphere, whereas visual stimuli resulted in greater within-hemisphere correlation over the non-speech dominant hemisphere. The authors suggested that the asymmetric correlation might be related to asymmetric perception of auditory and visual forms.

Molfese, Freeman and Palermo (1975) recorded bilateral temporal auditory ERPs from infants (1 week - 10 months), children (4 - 11 years) and adults (23 - 29 years) in response to syllables, words and nonspeech acoustic stimuli

(C major piano chord). Speech stimuli resulted in a larger amplitude peak to peak N1-P2 component over the left than the right hemisphere. A larger N1-P2 component was found over the right hemisphere than the left in response to nonverbal stimuli. The magnitude of the asymmetry was reported to decrease as a function of increased age.

D. W. Shucard, J. L. Shucard and Thomas (1977) demonstrated that lateralized bipolar ERPs (T3-CZ, T4-CZ) in response to probe stimuli showed differential rates of recovery (in a recovery cycle paradigm) contingent on differential patterns of hemispheric utilization. When subjects were engaged in a verbal task, the bipolar ERP over the left hemisphere was larger than over the right hemisphere. Conversely, when subjects were engaged in a musical task, the bipolar ERP was larger over the right than the left hemisphere. The authors suggested that the larger lateralized bipolar ERP amplitude is indicative of a smaller lateralized response since the lateral electrodes were referenced to a common active lead and that the decreased amplitude over the engaged hemisphere might reflect the decreased neuronal pool available for processing of the probe stimuli.

The credibility of much of the preceeding ERP asymmetry literature has been questioned by Friedman et al (1975). They recorded auditory ERPs in response to monosyllabic words and different nonverbal sounds from PZ and right and

left temporal-parietal leads midway between PZ and the mastoid, referenced to the tip of the nose. The stimuli were presented binaurally at a comfortable listening level under three task conditions: passive listening, and vigilance conditions where identical stimuli were presented alternately as signals or nonsignals. Few hemispheric asymmetries were found. These occurred for N1 in response to signal word stimuli and for P300 in response to nonsignal word stimuli. The authors felt that the asymmetries were too few and unsystematic to interpret adequately.

This view has been supported by Galambos, Benson, Smith, Schulman-Galambos, and Osier (1975). Galambos et al recorded auditory ERPs in response to natural speech syllables and pure tone stimuli from CZ, and right and left parietal association leads referenced to linked earlobes. The ERP waveform in response to speech, tones and clicks were similar in morphology. No overall significant differences in amplitude were demonstrated for amplitude or latency measures for syllabic or tonal stimuli, as tested by an ANOVA. However, the Wilcoxon test showed that the P3 component to target syllabic stimuli was larger over the left than right hemisphere. The authors suggested that the "interhemispheric electrophysiological differences reported to date, however, are so tiny as to be barely believable. Hence, either the evoked response method is virtually blind to the crucial events we believe must be there, or the

hemispheric differences are barely present in the conditions under which the measurements are currently being made."

Recently, Neville (1980) has pointed out that ERP studies which attempt to investigate lateralized processes should be difficult enough to induce a behavioral asymmetry. In this manner, an investigator would have data indicating direction of hemispheric utilization if any. Neville (1980, see section on visual ERP asymmetry) has demonstrated a significant ERP asymmetry using this strategy. Similarly, Krynicki (1976) has stressed the need to obtain behavioral data in conjunction with electrophysiological data.

In summary, results of studies investigating ERP correlates of functional cerebral asymmetries have been equivocal. Utilization of simple stimuli under conditions of passive attention, and utilization of more complex auditory stimulation under conditions of active attention have demonstrated significant lateralized ERP differences under certain experimental conditions; however, reports of negative findings have been cited.

Visual Stimuli. Investigations which have assessed ERP asymmetries utilizing visual stimulation have generally presented either non-patterned diffuse blank flashes or patterned stimuli of a linguistic or nonlinguistic nature.

In regard to studies which have used non-patterned diffuse flashes of light, Shenkenberg and Dustman (1970)

recorded visual ERPs from normal subjects between the ages of 4-86 from O1 and O2 referenced to linked earlobes. No task was required of the subjects. They found that a component in the 100-200 msec latency region was significantly larger over the right than the left hemisphere. Shenkenberg, Dustman and Beck (1972) reported a similar finding at central electrode placements (i.e., C4 > C3). Patients with senile dementia and alcoholism showed a nonsignificant asymmetry in the same direction (Shenkenberg et al, 1972).

Harmony, Ricardo, Otero, Fernandez, Llorente and Valdes (1973) also recorded visual ERPs from 139 normal subjects in response to diffuse light stimuli. Data was recorded from C3, C4, O1, O2, T3 and T4 referenced to A1 and A2. It is not clear if the ear electrodes were linked or not. No task was required of the subject. No significant hemispheric asymmetry was found for latency, amplitude, interhemispheric correlation or signal energy.

Porjesz and Begleiter (1975) recorded visual ERPs to a 5cm^2 visual stimulus from C3, C4, O1 and O2 referenced to linked ears. No task was required of the subject. At the central electrodes, no significant asymmetry was found. However, at occipital electrodes, significantly larger N1-P2 and P2-N2 components were found over the right than the left hemisphere.

Vella, Butler and Glass (1972) recorded visual ERPs from bipolar leads: OZ-02, OZ-01, 02-T6 and 01-T5 in response to checkerboard grids delivered to each hemiretina. The ERPs from the right temporal leads were larger than those from the left regardless of which hemiretina was stimulated. The authors suggested that the asymmetry represented a difference in excitability between the hemispheres specific to checkerboard patterns, since the asymmetry was abolished for blank flashes.

Several studies have required differential tasks of the subject in order to manipulate hemispheric utilization. Galin and Ellis (1975) recorded bipolar visual ERPs from P3, P4, T3 and T4 with all electrodes referenced to CZ. ERPs were recorded to unattended probe flash stimuli while subjects performed one of two tasks designed to induce alpha asymmetry over either hemisphere, block designs or writing. For all electrodes, the right hemisphere to left hemisphere alpha power ratio was greater during the writing task than during the block design task; for all electrodes the right to left power ratio of the ERP from 100-350 msec was greater during writing than during the block design task. In addition, a late parietal positivity (250-280 msec) and a late parietal negativity (320-350 msec) showed a larger right to left ratio during the writing task. Galin and Ellis suggested that the overall power and amplitude characteristics of the ERP reflect the lateralization of

cognitive processes and that the asymmetry may be in part dependent on the alpha asymmetry.

More complex patterned stimuli were used by Buchsbaum and Fedio (1970) to investigate interhemispheric differences in ERPs. Verbal and nonverbal stimuli were presented to each hemiretina in sixteen normal right handed subjects. Verbal stimuli were of 50 msec duration and consisted of either three letter words, or nonverbal nonsense stimuli of random dot patterns. ERPs were recorded from O1 and O2 referenced to ipsilateral earlobes. The verbal and nonsense patterns evoked dissimilar waveforms from each hemisphere and, in addition, left hemiretinal stimulation yielded ERPs which resulted in greater discrimination between words and patterns than right hemiretinal stimulation.

Shelburne (1972, 1973) investigated visual ERPs in normal children and adults to word and nonsense stimuli. ERPs were recorded from CZ, P3 and P4 referenced to linked ears. The stimuli were CVC trigrams in which the final letter defined the trigram as a nonsense syllable or word. The subject had to report whether a word or nonsense syllable was presented. A late positive component (P300) was largest to the third position stimulus, but no consistent interhemispheric differences were obtained.

Preston, Guthrie and Childs (1974) investigated visual ERPs from reading disabled and two normal control groups matched for: 1) age and IQ, and 2) reading level and IQ.

ERPs were recorded from P3, P4, O1, O2 and CZ referenced to A1. The stimuli were 50 msec in duration and were either blank flashes or the word 'cat'. The study showed that the reading disabled children displayed a reduced amplitude relative to the normal control subjects of an N180 component at the P3 electrode. The authors suggested that the reduced amplitude in the reading disabled subjects might reflect a less adequate mode of neural processing in an area critical to the reading process.

Kutas and Hillyard (1980) demonstrated that a prolonged late positive component (probably Slow Wave) was larger over the left than right hemisphere when subjects were required to read words presented within the context of a sentence. In contrast, the same Slow Wave component occurred with equal amplitude over both hemispheres in response to a warning stimulus and a single word repeated continuously. Kutas and Hillyard (1980) suggested that the tonic slow wave components may be more revealing of hemispheric specialization than the more phasic ERP components due to a similarity of the lateralization of the Slow Wave with an asymmetry of a slow wave reported by McAdam and Whitaker (1971) prior to speech production.

Neville (1980) reported that a late positive component 300 msec - 1 sec in latency, was larger over the right than left hemisphere after the onset of a visual spatial stimulus designed to engage the right hemisphere. Subjects showed a

significant left field advantage in response to the visual spatial stimulus. In contrast, a verbal (left hemisphere) analogue of the same task resulted in a larger positive component (200 msec latency) over the left hemisphere. Neville suggested that the observed asymmetries may reflect a different time course of specialized processing for the two tasks.

Rationale

The preceeding reviews of the literature have focused on issues of temporal order processing, ERP asymmetry, and ERP development. The limited electrophysiological literature available in reference to temporal order processing, in conjunction with the sensitivity of the ERP to sensory and cognitive processes suggests that the ERP could provide a better understanding of temporal order processing. Since the temporal order literature has suggested a bilateral hemispheric involvement (Kim, 1980; Sherwin and Efron, 1980; Swisher and Hirsh, 1972), an electrophysiological investigation of temporal order processes should measure bilateral ERPs from an experimental paradigm designed to engage (utilize) each cerebral hemisphere.

The perception of the temporal sequence of dichotic clicks is a task well suited for such a study for several reasons. First, it requires that the subject actively

attend to stimuli directed to each hemisphere. Second, the technique yields a measure of performance accuracy. Finally, the paradigm has a unique advantage over paradigms previously used to assess differences in ERPs between the hemispheres. In previous studies which have reported ERP asymmetries, it was never clear if the findings were due to the physical differences in the stimuli used to engage the hemispheres or to the differences in cognitive set associated with the stimuli. However, with the dichotic click stimuli, except for the sequence in stimulus presentation (right before left or left before right) the stimuli are identical. Therefore, hemispheric differences could not be related to gross differences in the composition of the stimuli.

Investigation of temporal order recall in children (Bakker, 1972) has demonstrated a significant improvement in the recall of temporal sequencing ability as a function of age from six to eleven. However, direct comparisons between children and adults on measures of temporal order thresholds are lacking. Similarly lacking are well controlled cross-sectional ERP developmental studies in which subjects performed tasks designed to engage each hemisphere. Therefore, the present study investigates temporal order processing from a group of children and adults on an identical temporal order processing task.

Hypotheses

The preceeding literature reviews have left considerable uncertainty concerning the involvement of each hemisphere in temporal order processing. As a result, two positions may be tested which lead to different hypotheses. The first position suggests that the left hemisphere is dominant for temporal order processing. Accordingly, it is hypothesized that a) the temporal order threshold will be more sensitive for dichotic click stimuli when the right stimulus preceeds the left stimulus, b) the ERP will show larger amplitude components over the left hemisphere than the right hemisphere regardless of the stimulus sequence and c) there will be an asymmetry in the detection accuracy in the constant stimulus ERP paradigm favoring the right before left condition. In contrast, the second position suggests that both hemispheres mediate temporal order processes. According to this position a) there should be no difference in the psychophysical thresholds or detection accuracies as a function of which stimulus came first, however b) there should be a significant difference in the ERP amplitude between the hemispheres as a function of the subjects perception of the event, i.e., if the subject reports an event as occurring right before left, than the left hemisphere ERP should be larger than the right hemisphere ERP. Similarly, if the subject reports an event as occurring

left before right, then the right hemisphere ERP should be larger than the left hemisphere ERP.

METHOD

The apparatus and general procedures were designed to obtain: 1) monaural thresholds, 2) temporal order thresholds and 3) ERPs in response to dichotic clicks. In the monaural threshold procedure, subjects were required to determine in which one of two observation intervals a stimulus was presented and in the subsequent procedures they were required to detect the temporal sequence of the dichotic click stimuli.

Subjects

Subjects were normal right handed males between the ages of 9-12 (child group N=9) or 22-32 (adult group N=10). Subject handedness was determined by verbal report before testing. In addition, the Edinburgh handedness questionnaire was administered post-testing to 14 of the 19 subjects (5 of the subjects could not be reached). The children had a mean handedness quotient of 73 and the adults had a mean handedness quotient of 89. All subjects were paid \$5/hour for their participation in the study and subjects were recruited via bulletin board announcements at the New York State Psychiatric Institute, the Columbia-Presbyterian Medical Center and Queens College of the City University of

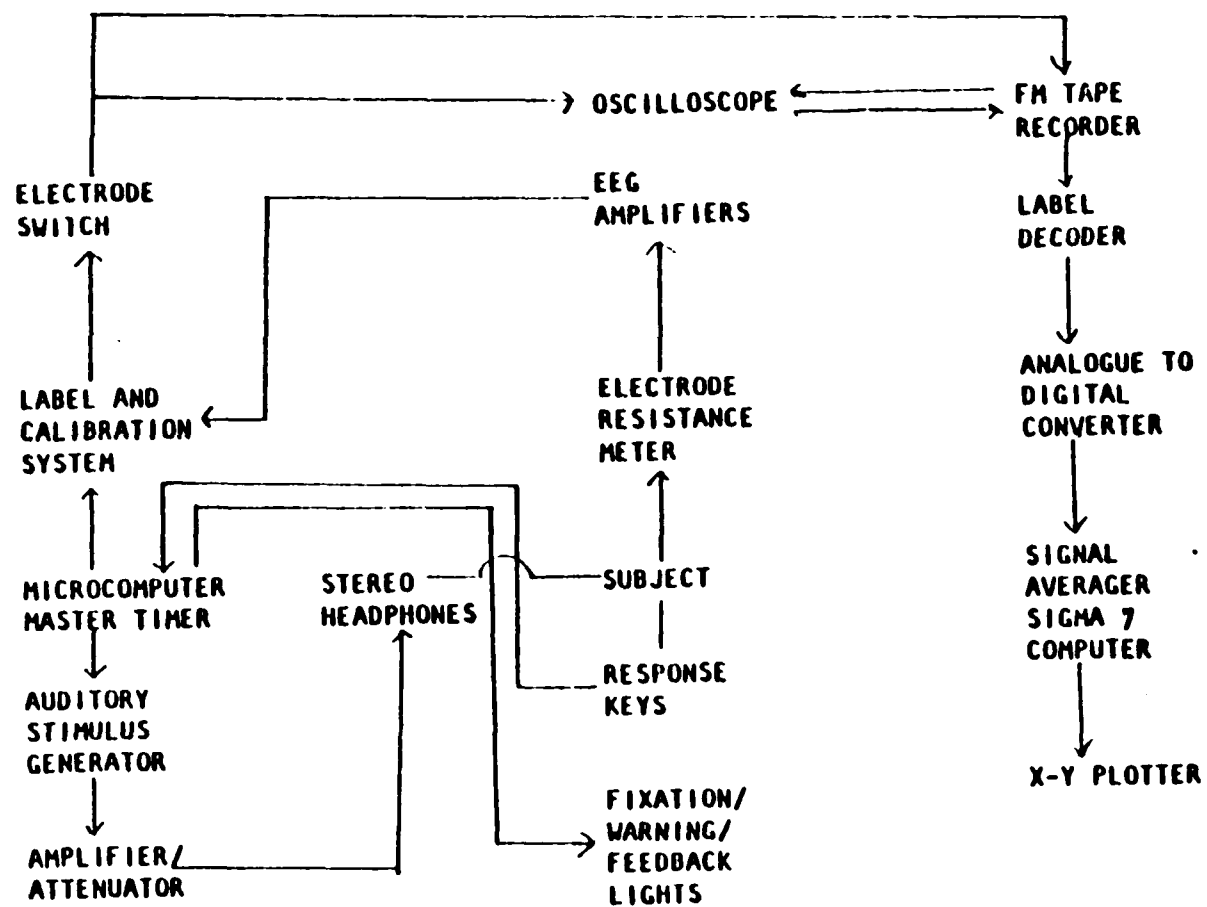
New York. They were sons of medical center personnel, employees of the medical center or graduate or medical students. Subjects were screened to exclude individuals with hearing disorders, reading, arithmetic and/or other learning disorders. Both children and adults were administered a verbal IQ test (children given WISC-R, adults given Full Range Picture Vocabulary Test) and matched on a group basis for verbal IQ. The children had a mean IQ of 114 with a range of 092 to 131. The adults had a mean IQ of 119 with a range of 114 to 122.

Instrumentation

A simplified block diagram of the instrumentation is shown in Figure 1. A Kim-1 and Rockwell Aim microcomputer were programmed in assembly language to provide real time control of each of the three experimental procedures.

A panel containing two pairs of subject response keys and two pairs of warning/feedback lights (LEDs) were mounted on a wooden armrest on the right side of the subject's chair. During the ERP procedure, a fixation light (LED) was placed at eye level approximately two meters in front of the subject.

Figure 1. Schematic block diagram of apparatus.



Stimuli

The auditory stimuli were clicks of one msec duration produced by the discharge of a capacitor. They were delivered either monaurally or dichotically through Sennheiser HD-224X calibrated and matched stereo headphones. Figure 2 shows the frequency response calibration curve of each earphone as supplied by the manufacturer. The stimulus intensity for the temporal order and event related potential procedures could be adjusted independently for each ear in 1 dB steps by a Hewlett-Packard attenuator (Model 350 D).

Electrode Placement and EEG Amplification

Beckman biopotential skin electrodes were attached to the scalp at five locations, CZ, C3, C4, P3, and P4 (10-20 International Electrode System, Jasper, 1958). Linked reference electrodes were located at the back of each earlobe, and a ground electrode was located at the back of the neck. In addition, an electrode referred to linked earlobes was placed below the midpoint of the right eye to record the subject's eye movements. The output of this channel was used to edit out trials containing excessive eye movements and to compare the residual data of the eye channel with that of the scalp electrode channels.

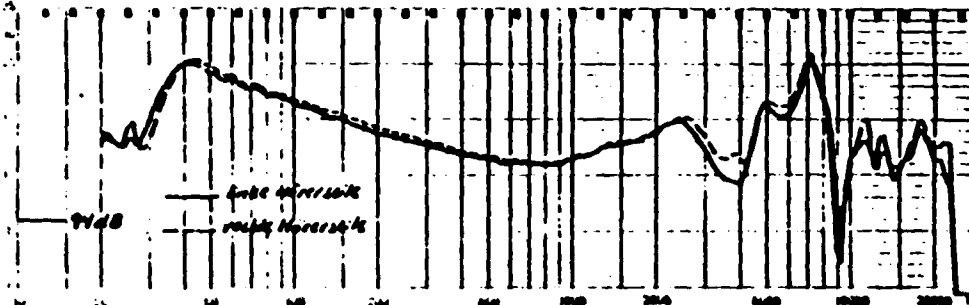
Figure 2. Frequency response curve of each earphone as supplied by manufacturer.

SENHEISER 
electronics

speakers and P-E systems for
 * Typ 4753 (phon)
 mit Aufhängesystem 20kg, 40kg, 50kg

Typ: HD 224 X (2)

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After the appropriate electrode sites were located by standard measuring procedures, the skin was cleansed with alcohol and rubbed with a commercial abrasive facial sponge (Buf Puf). For some subjects with relatively high electrode resistance, Cambridge electrode jelly was used with the sponge. The scalp electrode cups were filled with Grass electrode cream (EC2). A piece of gauze pressed down on top of the electrode formed an adhesion with the electrode cream securing the electrode to the scalp. Cambridge electrode jelly and adhesive electrode collars were used to apply all non-scalp electrodes. This technique yielded low closely matched electrode resistances (generally less than 1K ohms). The range of accepted electrode resistances was up to 5K ohms.

The electrodes were connected to a variable resistance meter located directly behind the subject, to permit equalization of the electrode resistance of the two reference electrodes (Garneski and Steelman, 1958). Electrode resistance was measured immediately prior to the onset of ERP data collection and the resistance of the reference electrodes was rebalanced each time the headphones were replaced after a rest period, approximately every fifth or sixth block of trials. At the conclusion of each session, the electrode resistances were remeasured to check that no channels exceeded the resistance criterion. In general, electrode resistance decreased throughout the session.

The EEG was amplified 5K by modified battery-operated Princeton Applied Research (PAR-Model 113) amplifiers. This level of amplification was chosen after several pilot subjects had been tested with an amplification gain of 10K, and it had been shown that this amplification, for some children, exceeded the input limits ($\pm .5v$) of the FM tape recorder, resulting in a clipped EEG signal. The low frequency cutoff was set to a time constant of 5.3 sec and the high frequency cutoff was set at 100 hz.

The amplified EEG signal was fed through a calibration and labeling system prior to being recorded on FM analogue tape (Sangamo #3500) at 3 3/4 IPS. Under microcomputer control, a calibration signal (equivalent to -30uv square wave) occurred on each data channel 900 msec after stimulus onset and provided a means of scaling the ERP data relative to a known voltage source. It also provided the computer with a means of testing and rejecting trials for excessive noise or a missing calibration pulse.

The label system signal, introduced immediately after the calibration signal, consisted of a four bit binary code that identified each stimulus condition as well as the subject's response. The code consisted of a positive or negative voltage deflection ($\pm .5V$) on each of the first four channels (1 bit/ channel) of the recording system. By this system, data could be retrieved as a function of stimulus condition and/or subject response. Finally, a

control pulse was deposited on channel 7 to signify the end of each trial. This occurred at a fixed time after stimulus onset, and served as a means of triggering the data retrieval system.

Data was monitored at the input and output of the tape recorder on a Tektronix 564B dual trace storage oscilloscope. The monitoring procedure permitted the experimenter to determine whether the data was recorded cleanly, i.e., that there was no system or subject movement artifact during the trial. If any contaminating noise persisted for several trials, then data acquisition was interrupted until the problem could be resolved.

Calibration of Equipment

Complete calibration of all amplifiers for gain, DC level and common mode rejection was done prior to pilot data collection. Any amplifier that would not maintain a stable calibration over a two week period was repaired. During the data collection period, amplifier calibration was monitored approximately every third week and was rarely found to exceed the tolerance limits. The FM tape recorder was calibrated for DC level and gain immediately prior to the onset of data collection for the children and adults.

Data Retrieval System

Data retrieval from tape and its analysis was accomplished at the Queens College Computer Center of the City University of New York. The analogue tapes were read off a 7 track Honeywell FM tape recorder (Model 3600) at 30 IPS. The recorder output was fed to an interface circuit which triggered an analogue to digital conversion process on the Xerox Sigma 6 computer. The interface circuit read the control pulse trigger and decoded the four channels of binary labels. It required that the control pulse and label pulses met strict amplitude and latency criteria to prevent noise from triggering the computer erroneously or noisy label pulses from being misinterpreted. The six data channels were sampled and digitized sequentially, starting with channel one, every 5 msec, for a total of 5000 msec/trial. A 12 usec lag time was introduced as the A/D converter switched to the next channel. Thus, channel 6 was digitized 60 usec later than channel 1. The digitized data and label identification codes were stored on digital tape for later analysis.

Scaling and Data Editing

All subsequent analyses were performed on a Xerox Sigma 7 computer. Each digitized trial was initially tested to determine that a calibration pulse was present.

Two digitized points from each of the zero and -30 uv limbs of the calibration pulse were averaged. If the noise level of the zero or -30 uv segments exceeded 15% of 30 uv, then the trial on that channel was discarded from further analysis.

Data (between stimulus onset and the calibration pulse) were next examined for excessive eye movement artifact. All channels of data on a trial that contained a voltage deflection greater than ± 150 uv on the eye channel were eliminated from further analysis. A secondary test was used to check for other, non-eye, movement artifact. If any channel contained a voltage deflection greater than ± 200 uv then that channel alone was eliminated from further analysis. Although the eye channel criterion of ± 150 uv may be considered lax, it was necessary because the data from the group of children showed a large mean DC offset of about -60 uv. This was probably due to drift of the FM tape recorder. A stricter rejection criterion would have resulted in the loss of many trials which contained only a small eye movement. Therefore, it was decided to use a ± 150 uv criterion and to compare the non-rejected data from the eye channel with that of the EEG channels.

Data Reduction

Conventional averaged ERPs were computed for each subject for each nested stimulus condition for correct detections and were plotted by a Cal Comp plotter. A numerical printout of the mean amplitude and standard deviation of each ERP time-point was also obtained. Each averaged ERP was saved in a master file on disc to permit computation of cross subject averages.

Procedure

Subjects were seated in a modified dental chair located in a dimly lighted, sound attenuated room. The height of the chair and headrest were adjusted to achieve maximum subject comfort which was consistent with data acquisition and minimization of movement artifact. Subjects were monitored on a closed circuit TV throughout the experiment.

All subjects participated in three experimental procedures: 1) determination of monaural threshold, 2) determination of temporal order threshold, and 3) a temporal order event related potential procedure. They were initially tested on the monaural threshold procedure to determine that they did not have a gross hearing deficit in either ear, and to permit setting the dichotic stimuli at equal sensation level for the two ears. They were then

tested on a temporal order threshold and ERP procedures. The order of these three procedures was, by necessity, the same in all subjects.

Monaural Threshold Procedure

An adaptive staircase procedure (Corwin, Kintz and Beaty, 1980) which was used to determine a 71% monaural threshold for each ear required a total of approximately 15 min. The trial structure was a two-interval forced-choice paradigm. The subject was instructed to watch a panel containing two pairs of warning/feedback lights placed in front of him. If the pair of lights on the left side were turned on, then the subject was to pay attention for a stimulus on the left; if the pair of lights on the right side were turned on, then the subject was to attend for a stimulus on the right.

At the start of each trial, the appropriate pair of lights was turned on to designate the ear to be attended and to mark the start of an observation interval. The observation interval lasted one second, and the lights were turned off at the end of the interval for one half second. The same pair of lights were then turned on again to designate the start of the second observation interval (also one second). The observation interval in which the stimulus was presented was chosen at random. The stimulus was always

delivered exactly at the midpoint of the chosen interval. At the conclusion of the second observation interval, the subject was required to indicate the observation interval in which the stimulus was judged to have been delivered by pressing the appropriate response key within 3 sec after the conclusion of the second observation interval. If no response occurred within this time, the trial was rejected and immediately repeated. (Subjects were not told that trials were repeated when the response was not within criterion limits). Subjects were given feedback with respect to each detection by turning on the light directly in front of the key they had pressed, if they had responded correctly. The feedback lights remained off for incorrect responses.

The entire sequence of the threshold procedure was under microcomputer control. The sequence of left or right ear presentations was determined by a sequence of random numbers generated by the computer, and tested for randomness by a runs test.

The stepping rules to determine a 71% correct detection level were that two consecutive correct responses be obtained for a given stimulus level before making the task more difficult, and that only one error be obtained before making the task easier (Wetherill and Levitt, 1965). The Corwin et al (1980) procedure requires that large step sizes be made initially at suprathreshold levels until eight

reversals in the direction of the staircase occur. At that point, data collection continues using smaller step sizes. The new stimulus level is set at the mean value of the peaks and troughs of the eight reversals. Data collection continues until an additional eight reversals occur. The final threshold is the mean value of the final eight peaks and troughs of the curve. Pilot testing indicated that 8 dB was appropriate for the large step size and that 1 dB was appropriate for the small step size. The stimulus intensity was then set at 30 dB SL for each ear for all subjects.

Temporal Order Threshold

An adaptive staircase procedure, similar to the monaural threshold procedure (Corwin et al, 1980) was used to practice the subjects on the perception of temporal order of dichotic clicks and to determine thresholds for the perception of temporal order (one for right before left (RL) and one for left before right (LR)). This procedure was run because the temporal order discrimination task is difficult and therefore subject to practice effects. It was necessary to eliminate most of the practice effect before running the ERP procedure.

For the temporal order threshold procedure, the trial structure was a two-alternative forced-choice paradigm. A pair of warning/feedback lights were turned on one second

before presentation of a pair of dichotic clicks (right before left, RL; or left before right, LR). The subjects were required to indicate which click was presented first (R or L) by pressing the appropriate response key within three sec of stimulus onset. They were provided feedback for correct detections by a light directly in front of the response key. No direct feedback was given for errors, although feedback was implicit, i.e., if the light did not go on it signified an error.

Subjects were initially practiced for a block of 16 trials starting at an interstimulus interval of 144 msec to ensure that they understood the task. The staircase was then started using a large step size (10 msec) until 8 reversals occurred, at which point a small step size (1 msec) was used. An exception to this rule occurred if the staircase reached an interstimulus interval of 32 msec before 8 reversals occurred. In this case, the 1 msec step size replaced the 10 msec step size to prevent the staircase from moving to the second limb of the V shaped curve relating percent detection to t . Data collection continued until 8 reversals on the same limb of the curve occurred at the 1 msec step size. The threshold was taken to be the mean of the eight peaks and troughs obtained at the 1 msec step size.

Event Related Potential Procedure

A pair of dichotic clicks (RL or LR) was presented on each trial. Fixed Δt s (intervals between stimuli) within the psychometric range were used: 75 and 125 msec for the children, and 25, 50, and 75 msec for the adults. All stimulus conditions were completely randomized within each block of trials (N=30) and data collection continued until at least 50 correct detections occurred for each stimulus condition.

The trial structure consisted of a two-alternative forced-choice paradigm similar to the temporal order and monaural threshold tasks. A warning/fixation light was turned on 1 sec before the stimuli to prepare the subject for the trial. Subjects were instructed to fixate the light and to avoid blinking or moving while the light remained on. The fixation light was turned off 1050 msec after the stimuli were delivered at which point the subject was required to indicate which click (right or left) was presented first by pressing the appropriate response key. A 2 sec window was allowed for the subject's response. At the conclusion of the response window, a feedback stimulus (binaural click) was presented for trials correctly perceived. No direct feedback was given for incorrect responses. ERPs were obtained in response to the discrimination stimuli and the feedback stimuli. Trials

which were either anticipated or missed were immediately repeated.

Data Analysis

Averaged ERPs from each experimental condition from each electrode for each subject were entered into a master file. The analysis epoch of each ERP extended from 170 msec prior to and 900 msec after stimulus onset. The baseline was calculated as the median voltage of the data points prior to stimulus onset. ERP amplitudes were derived by subtracting the median baseline amplitude of each ERP from each data point along the waveform. S1-B1 represents the discrimination stimulus waveform minus the discrimination stimulus baseline; S2-B2 represents the feedback stimulus waveform minus the feedback stimulus baseline. An additional ERP was derived by subtracting the median baseline for the discrimination stimulus from each data point along the respective feedback stimulus waveform (S2-B1). The rationale for the present analysis is that it might detect systematic shifts in the baseline EEG between the discrimination and feedback stimuli that would otherwise remain undetected in the previous analysis. Statistical analyses were conducted separately on each of these three waveforms: 1) discrimination stimulus, 2) feedback stimulus, and 3) feedback stimulus referred to the discrimination stimulus baseline.

Since different Δt s were used for the two subject groups, separate analyses were conducted on each of the three sets of measures (S1-B1, S2-B2, S2-B1) according to three criteria: 1) behavioral match, 2) stimulus range, and 3) stimulus interval match. The behavioral match criterion served as the primary analysis, whereas the stimulus range and interval match analyses served as control analyses. In the behavioral match analysis, the subject groups were compared on the data obtained from the Δt s which yielded the closest match for behavioral accuracy (percent correct) in the easy and hard conditions. These were, for the children, 75 msec (hard), which yielded a hit rate of 73% and 125 msec (easy) which yielded a hit rate of 80.5%, and for the adults, 50 msec (hard), which yielded 74.5% correct and 75 msec (easy), which yielded 83% correct.

In the range match analysis, groups were compared on the data obtained from the stimuli which maintained a difference of 50 msec between the easy and hard conditions i.e., children 75 and 125 msec (hit rates of 73% and 80.5%); adults 25 and 75 msec (hit rates of 61% and 83%). In the interval match analysis, the groups were compared on the data obtained in response to the same Δt , 75 msec (children = 73% hit rate; adults = 83% hit rate).

An additional control analysis was conducted, using the behavioral match procedure, to compare the averaged waveforms obtained from the eye channel with the waveforms

to determine the relationship of ocular activity to the ERP. If the factor scores were larger at the scalp electrodes than at the eye electrode, it would suggest that the source of the activity was extra-ocular. If, for example, the activity is originating at parietal scalp, it should decrease monotonically in amplitude from parietal scalp to the eye electrode. Alternatively, if the factor loadings of the eye channel were inverted in polarity and larger than the factor loadings of the scalp electrodes, it would suggest that the source of the activity might be the eye. Finally, if the factor loadings of the eye channel were inverted in polarity and less than the factor loadings of the scalp electrodes, it would suggest that part of the activity recorded at the scalp may be ocular in origin. Finally, a correlation obtained from the scalp electrodes. This analysis was run separately for each group to determine if the ERP components varied meaningfully in relation to the temporal order threshold, the hit rate, subject age or IQ.

The corrected ERPs (i.e., with the baseline subtracted) from each type of analysis epoch (S1-B1, S2-B2, S2-B1) were next entered into separate principal components cross products varimax analyses (PCVA) (BMDP4M). Prior to running the PCVA, every pair of adjacent data points was averaged, to accomodate the limited memory of the computer. Thus, all analyses were performed on ERPs with a resolution of 10 msec per data point. For the behavioral and range match analyses,

a total of 380 ERP waveforms entered into each PCVA i.e., adult vs child (2) X RL vs LR (2) X easy vs hard (2) X electrode (5) X subjects (9.5) for the behavioral and range match analyses. For the control analysis, which included data from the eye channel, 456 waveforms (6 electrodes) entered into the analysis, and for the interval match 190 waveforms (adults vs child (2) X RL vs LR (2) X electrode (5) X subjects (9.5)).

Repeated measures analyses of variance (ANOVA) (BMDP2V) were conducted to test the statistical significance of the weighting coefficients for each of the principal components extracted by the PCVA. Two ANOVA's were run on each factor. In the first, subject group (child or adult) was entered as a grouping factor; stimulus precedence (RL or LR), stimulus difficulty (easy or hard) and electrode placement (CZ, C3, C4, P3, and P4) were entered as repeated measures factors. In the second analysis, difference scores between lateral electrode placements (C3-C4; P3-P4) were used in order to determine if significant lateralized ERP asymmetries were present; data of the CZ electrode were not utilized.

Repeated measures analyses of variance, such as were used here, assume homogeneity of population variances and covariances; and violations of these assumptions result in a test which is susceptible to Type I error (Jennings and Woods, 1978). In order to deal with this problem, Jennings and Woods suggested reducing the degrees of freedom by a

correction factor, epsilon, derived from the sample variance covariance matrix. This correction factor was calculated and the degrees of freedom were adjusted appropriately before determining the significance of the F values. In addition, the $p < .01$ level was established as the confidence limit, in respect to the relatively large number of statistical tests performed.

RESULTS

The behavioral data from the threshold procedures will be dealt with first. ERP data will then be presented from the combined subjects analysis in the following sequence: 1) discrimination stimulus referred to the discrimination stimulus baseline (S1-B1), 2) feedback stimulus referred to the feedback stimulus baseline (S2-B2) and 3) feedback stimulus referred to the discrimination stimulus baseline (S2-B1). Within each ERP epoch data will be examined from the behavioral, range and interval match analyses. Of these, the behavioral match analysis will be presented comprehensively, while data from the range match interval match analyses, which are viewed as controls will be reviewed only to the extent that they differ from the behavioral match analysis. Data will then be presented from the separate groups analyses and the control analyses which included the eye channel. Finally, data from correlational analyses will be examined.

Behavioral Results

Monaural Threshold

Neither the difference in threshold sensitivity between children and adults nor between the left ear and right ear (Table 1) reached statistical significance. However, the effect of age approached significance ($p=.024$) with the adults showing greater sensitivity. The interaction between age and ear was not statistically significant.

Temporal Order Threshold

The adults were significantly ($p<.01$) more sensitive than the children in their perception of temporal order of dichotic clicks (Table 2). The mean temporal order threshold (mean of RL and LR conditions) was 27.4 msec for the adults and 49.9 msec for the children. No significant difference emerged in the temporal order threshold as a function of stimulus precedence, nor was there an interaction between age and stimulus precedence.

Behavioral Data During ERP Recording

Behavioral Match. Table 3 summarizes the means, F and P values for all three matches. In the behavioral match, there

	LEFT EAR	RIGHT EAR		F	P
CHILD	57.7	59.9	58.8	AGE 6.10	.02
ADULT	63.7	64.0	63.8	EAR 1.35	.26
	60.8	62.1		A X E 0.78	.39

Table 1. Monaural threshold sensitivity (dB).

	RL	LR		F	P
CHILD	48.7	51.2	49.9	AGE 15.93	.01
ADULT	24.3	30.4	27.4	PREC 00.50	.49
	35.8	40.3		A X P 00.78	.77

Table 2. Temporal order threshold sensitivity (msec).
 RL= right before left, LR= left before right.

	INT	HIT RATE	INT	HIT RATE	INT	HIT RATE	INT	HIT RATE	INT	HIT RATE
RL										
CHILD	75	69.0	125	77.3	75	69.0	125	77.3	75	69.0
ADULT	50	76.0	75	84.2	25	60.4	75	84.2	75	84.2
LR										
CHILD	75	75.6	125	82.3	75	75.6	125	82.3	75	75.6
ADULT	50	72.8	75	81.7	25	62.3	75	81.7	75	81.7
	F	P			F	P			F	P
AGE	0.39	0.54			1.06	0.32			7.44	0.01
DIFF	51.97	0.01			83.01	0.01			NA	NA
PREC	0.25	0.62			1.25	0.28			0.38	0.55
D X A	0.20	0.66			19.97	0.01			NA	NA
P X A	2.17	0.16			1.09	0.31			1.89	0.19
D X P	0.03	0.85			0.65	0.43			NA	NA
DXPXA	0.24	0.63			0.09	0.77			NA	NA

Table 3. Behavioral data during the ERP recording, all matches.
 RL= right before left, LR= left before right, INT= t.

there was the expected main effect of stimulus difficulty (interval) ($F=51.97$, $p<.01$), accuracy being greater for the the longer intervals. No main effect of age or precedence was found and no interactions even approached statistical significance.

Range Match. As expected, a main effect of stimulus difficulty was found ($p<.01$). In addition, a significant interaction between stimulus difficulty and age ($p<.01$) was obtained, reflecting the fact that the different intervals used for the children and adults, in order to match for range, yielded a greater difference in sensitivity between the easy and hard conditions for the adults (23%) than for the children (10%). No other interactions were statistically significant.

Interval Match. At the 75 msec interval, the main effect of age reached statistical significance ($p<.014$; greater sensitivity for the adults). There was no significant effect of precedence nor a significant interaction between age and precedence.

ERP Results

Combined Groups Analyses

Discrimination Stimulus Epoch. Averaged cross-subject ERP waveforms in response to the discrimination stimuli for the behavioral match are shown for children (Figure 3) and for adults (Figure 4). A number of differences between children and adults can be seen by inspection of these figures. In particular, children show greater amplitude Slow Wave than the adults in all conditions and at all electrodes, adults show a greater amplitude N100 component, particularly at the central electrodes and children show a larger phasic positivity in the 300 msec region component to the easy (Δt 125) than to the hard condition (Δt 75) as can be seen most clearly at the central electrodes for the RL condition.

Figure 5 presents the cross-subject averages from each subject group and each electrode collapsed across stimulus precedence and stimulus difficulty for the discrimination stimulus and the feedback stimulus. For the discrimination stimulus, N100 appears larger in the adults at the central electrodes; and Slow Wave appears larger for the children at the parietal electrodes. For the feedback stimulus, P300 appears larger in the adults than the children at the central electrodes.

PCVA Analyses. Figure 6 shows the ERP basis waveforms (Rotated Factor Loadings) obtained in response to correctly detected discrimination stimuli. Three principal components, labeled F:1, F:2, and F:3, were obtained.

Figure 3. Conventional cross subject ERP averages for the children from all experimental conditions (rows: RL 75, RL 125, LR 75, LR 125) and all electrodes (columns: CZ, C3, C4, P3, P4, EYE) for the discrimination stimulus. Stimulus onset occurs at time 0; each hash mark represents 100 msec. Negative voltage is up.

CHILD
DISCRIMINATION

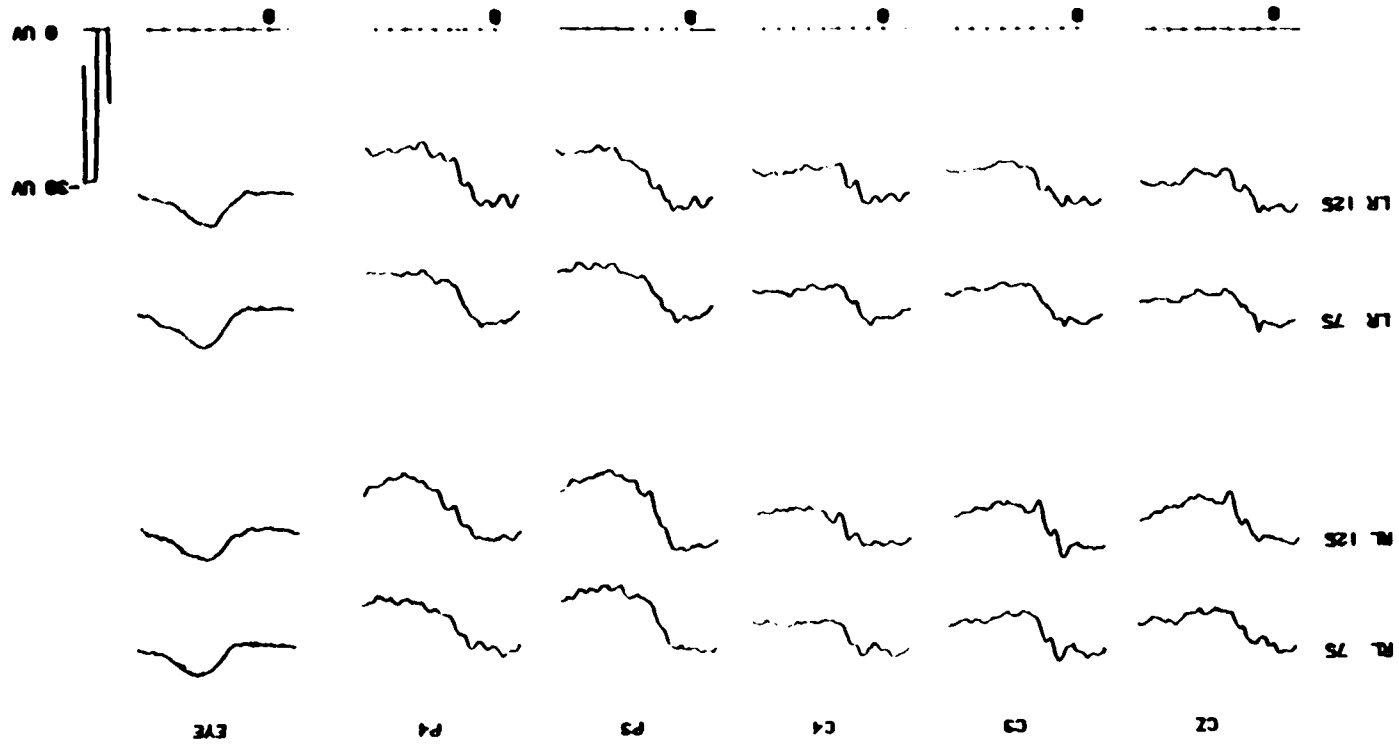


Figure 4. Conventional cross subject ERP averages for the adults from all experimental conditions (rows: RL 50, RL 75, LR 50, LR 75) and all electrodes (columns: CZ, C3, C4, P3, P4, EYE) for the discrimination stimulus. Stimulus onset occurs at time 0; each hash mark represents 100 msec. Negative voltage is up.

ADULT
DISCRIMINATION

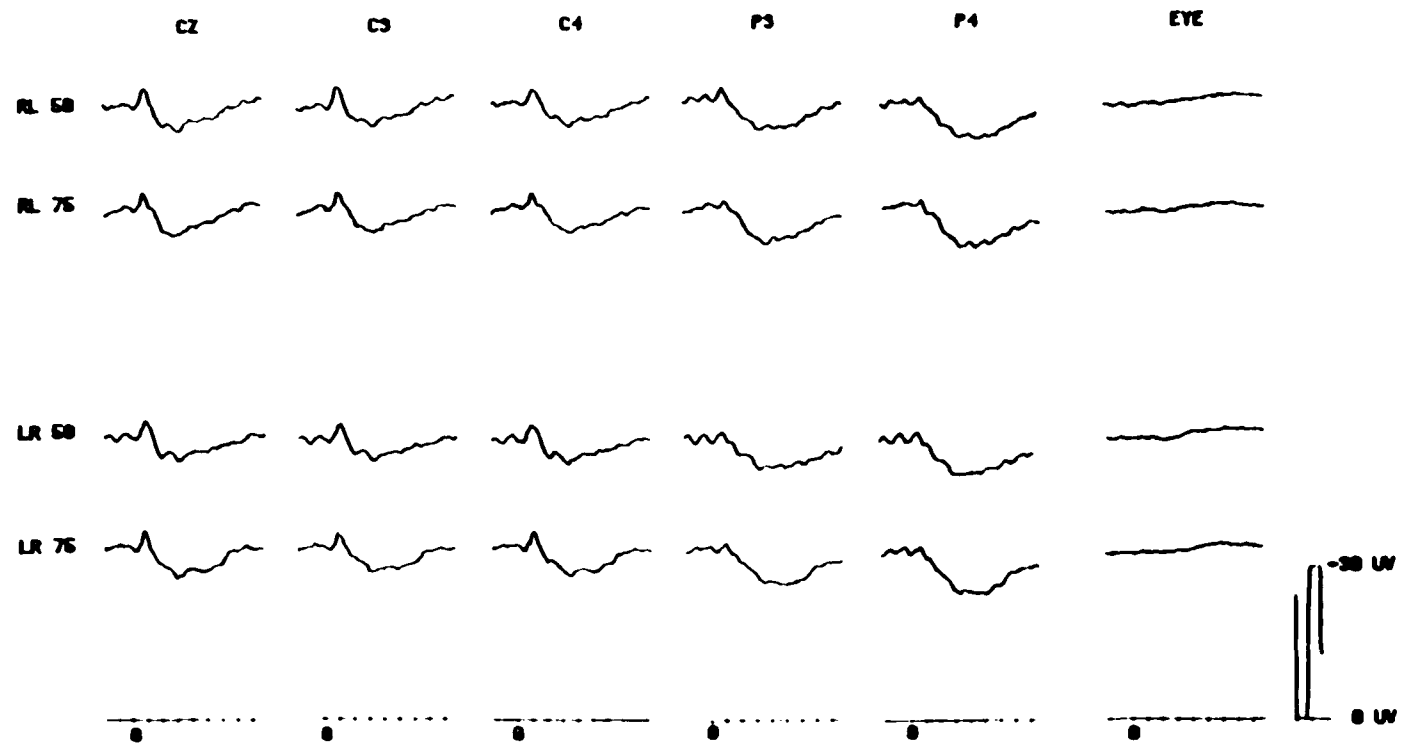


Figure 5. Conventional cross subject ERP averages for the children and adults collapsed across levels of stimulus difficulty and stimulus precedence for all electrodes (CZ, C3, C4, P3, P4, EYE) for the discrimination stimulus (top two rows) and the feedback stimulus (bottom two rows). Stimulus onset occurs at time 0. Abscissa the same as Figure 3.

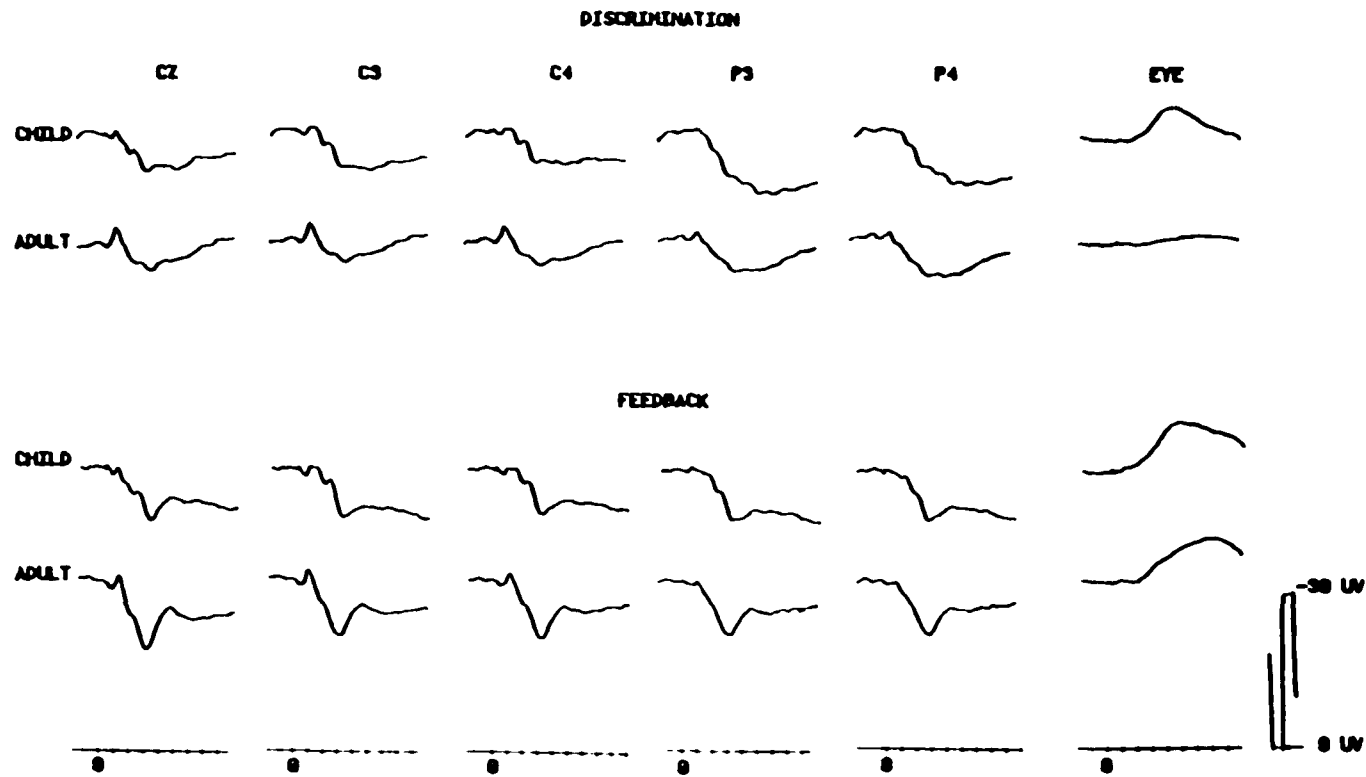
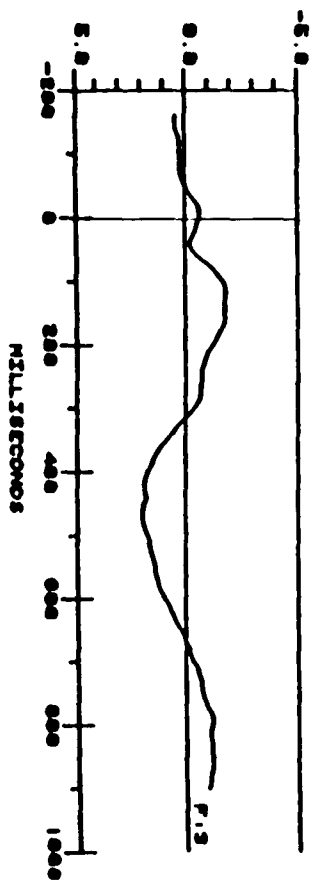
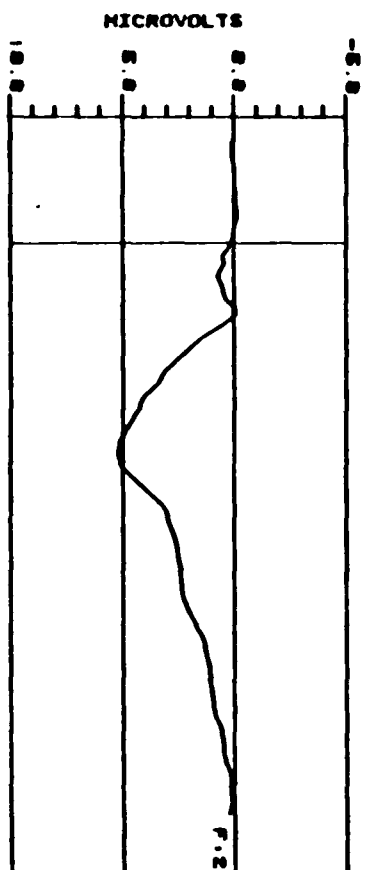
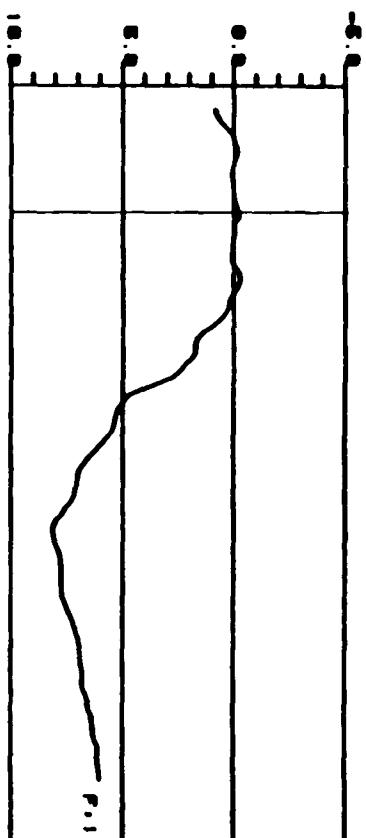


Figure 6. The basis waveforms (rotated factor loadings, microvolts) for the children and adults, for all scalp electrodes, for all experimental conditions for the discrimination stimulus. F:1= Factor I, F:2= Factor II, F:3= Factor III. Stimulus onset occurs at time 0.

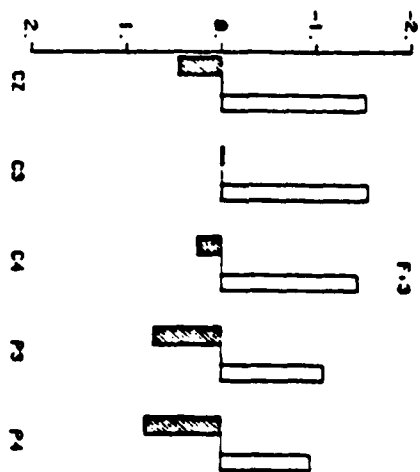
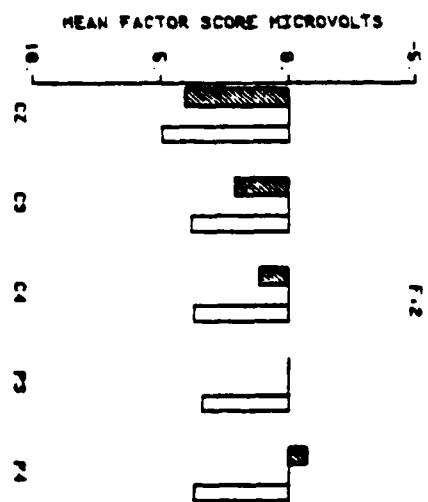
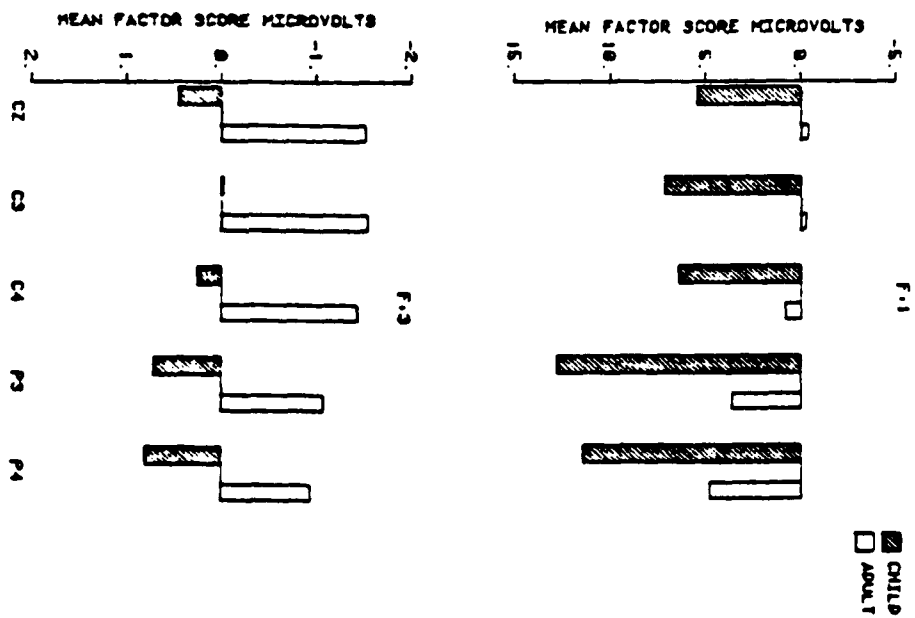
DERIVATION



Factor I (Figure 5) was a long duration tonic positive component. This component was tentatively identified as Slow Wave. (The evidence for component identification will be reviewed in the Discussion chapter). The Slow Wave component had an onset latency of approximately 175 msec, reaching a peak amplitude at 500 msec. The peak was followed by a positivity which was sustained for the duration of the analysis epoch. Even 900 msec after stimulus onset, stimulus, the Slow Wave component remained positive to the baseline. This sustained positivity in the late portion of the epoch can be clearly seen in the cross subject averages (Figures 3, 4 and 5).

Figure 7 compares the topographic distribution of mean amplitude for Factors I, II and III for children and adults. The data is collapsed across stimulus precedence and stimulus difficulty. (In plots of PCVA, except for electrode site, data is generally collapsed across experimental conditions for which differences were not obtained). The organization of the data in Figure 7 is directly comparable with that in Figure 5. For Factor I (Slow Wave), the main effects of electrode ($F=54.23$, $p<.01$) and age ($F=11.62$, $p<.01$) were significant (Table 4). Slow Wave was largest at the parietal electrodes (Figure 7) and children showed a larger amplitude Slow Wave than the adults at all electrode sites (Figure 7 and also Figures 3, 4 and 5). The main effects of electrode and age were the same for the range and interval match analysis (Table 4).

Figure 7. The mean factor scores (microvolts) as a function of electrode (CZ, C3, C4, P3, P4) and age collapsed across stimulus difficulty and stimulus precedence, for all factors, for the discrimination stimulus. F:1= Factor I, F:2= Factor II, F:3= Factor III.



<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>BM</u>	<u>Rdf</u>	<u>RM</u>	<u>Rdf</u>	<u>IM</u>
A(AGE)	1,17	1,17	11.62*	1,17	12.66*	1,17	11.91*
P(PRECEDENCE)	1,17	1,17	0.42	1,17	1.29	1,17	0.00
D(DIFFICULTY)	1,17	1,17	2.18	1,17	2.11	1,17	X.XX
E(ELECTRODE)	4,68	3,47	54.23*	3,46	52.26*	1,17	49.04*
P X A	1,17	1,17	3.95	1,17	1.53	1,17	1.98
D X A	1,17	1,17	0.33	1,17	0.13	1,17	X.XX
E X A	4,68	3,47	3.65	3,46	3.81	1,17	2.67
P X D	1,17	1,17	0.27	1,17	0.23	1,17	X.XX
P X E	4,68	3,47	3.63	3,46	2.72	1,17	2.47
D X E	4,68	3,47	0.76	3,46	1.36	1,17	X.XX
P X D X A	1,17	1,17	1.42	1,17	4.80	1,17	X.XX
P X E X A	4,68	3,47	1.43	3,46	1.89	1,17	0.32
D X E X A	4,68	3,47	0.62	3,46	0.33	1,17	X.XX
P X D X E	4,68	3,47	0.38	3,46	0.69	1,17	X.XX
P X D X E X A	4,68	3,47	0.07	3,46	0.15	1,17	X.XX

Table 4. Factor I discrimination stimulus, all electrode analysis. df= degrees of freedom, Rdf= reduced degrees of freedom, BM= behavioral match, RM= range match, IM= interval match.

*p<.01

Slow Wave was largest at the right hemisphere electrodes (C4 and P4) for the adults and at the left hemisphere electrodes (C3 and P3) for the children (Figure 7). This age by electrode interaction appeared as a trend ($F=3.65$, $p<.05$) in the behavioral match ANOVA (Table 4) but emerged more clearly in the lateral difference score ANOVA (Table 5). There was a significant main effect of age ($F=11.28$, $p<.01$) with regard to lateralization of Slow Wave which can be seen in both Figures 3 and 7. Again, Slow Wave was larger over the left hemisphere electrodes in the children; and larger over the right hemisphere electrodes in the adults (also see Figure 4). The same lateralization effect for Slow Wave was obtained in the range match analysis (Table 5). However, in the interval match analysis (Table 5) the lateralization of Slow Wave as a function of age interaction only reached the .05 level of confidence.

Factor II (Figure 6) was a phasic positive component in the 300 msec region. It had an onset latency of approximately 125 msec, reached a peak amplitude at 350 msec, and then showed a slow return to baseline at about 850 msec. Slow Wave (Factor I) and the phasic positivity showed a substantial degree of both temporal (Figure 6) and spatial (Figure 7) overlap.

The main effect of electrode was significant for Factor II ($F=10.47$, $p<.01$) (Table 6) with the Factor largest at CZ (Figure 7). The phasic positive component was most clearly

<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>BM</u>	<u>Rdf</u>	<u>RM</u>	<u>Rdf</u>	<u>IM</u>
A(AGE)	1,17	1,17	11.28*	1,17	10.12*	1,17	7.57
P(PRECEDENCE)	1,17	1,17	1.56	1,17	1.41	1,17	1.51
D(DIFFICULTY)	1,17	1,17	0.08	1,17	0.00	1,17	X.XX
E(ELECTRODE)	1,17	1,17	0.18	1,17	0.21	1,17	0.23
P X A	1,17	1,17	0.05	1,17	0.02	1,17	0.00
D X A	1,17	1,17	0.11	1,17	0.35	1,17	X.XX
E X A	1,17	1,17	0.27	1,17	0.28	1,17	0.12
P X D	1,17	1,17	0.09	1,17	0.02	1,17	X.XX
P X E	1,17	1,17	7.49	1,17	5.81	1,17	4.35
D X E	1,17	1,17	0.20	1,17	0.24	1,17	X.XX
P X D X A	1,17	1,17	0.09	1,17	0.00	1,17	X.XX
P X E X A	1,17	1,17	4.96	1,17	5.33	1,17	2.49
D X E X A	1,17	1,17	0.01	1,17	0.01	1,17	X.XX
P X D X E	1,17	1,17	0.05	1,17	0.26	1,17	X.XX
P X D X E X A	1,17	1,17	0.04	1,17	0.03	1,17	X.XX

Table 5. Factor I discrimination stimulus, lateral difference analysis. Codes are the same as in Table 4.

*p<.01

<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>BM</u>	<u>Rdf</u>	<u>RM</u>	<u>Rdf</u>	<u>IM</u>
A(AGE)	1,17	1,17	2.36	1,17	2.89	1,17	2.22
P(PRECEDENCE)	1,17	1,17	0.00	1,17	0.17	1,17	0.01
D(DIFFICULTY)	1,17	1,17	0.37	1,17	2.76	1,17	X.XX
E(ELECTRODE)	4,68	2,33	10.47*	2,35	10.24*	1,17	6.04
P X A	1,17	1,17	0.14	1,17	0.02	1,17	0.08
D X A	1,17	1,17	2.25	1,17	0.17	1,17	X.XX
E X A	4,68	2,33	3.55	2,35	3.16	1,17	1.84
P X D	1,17	1,17	1.38	1,17	0.20	1,17	X.XX
P X E	4,68	2,33	6.25*	2,35	5.11	1,17	2.92
D X E	4,68	2,33	1.12	2,35	0.82	1,17	X.XX
P X D X A	1,17	1,17	0.06	1,17	1.16	1,17	X.XX
P X E X A	4,68	2,33	1.19	2,35	1.82	1,17	0.25
D X E X A	4,68	2,33	0.73	2,35	1.09	1,17	X.XX
P X D X E	4,68	2,33	2.53	2,35	4.33	1,17	X.XX
P X D X E X A	4,68	2,33	2.40	2,35	0.92	1,17	X.XX

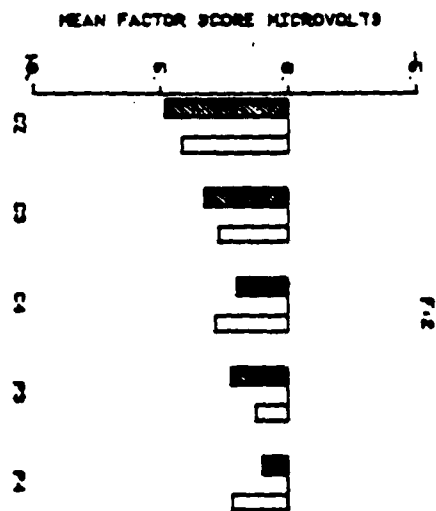
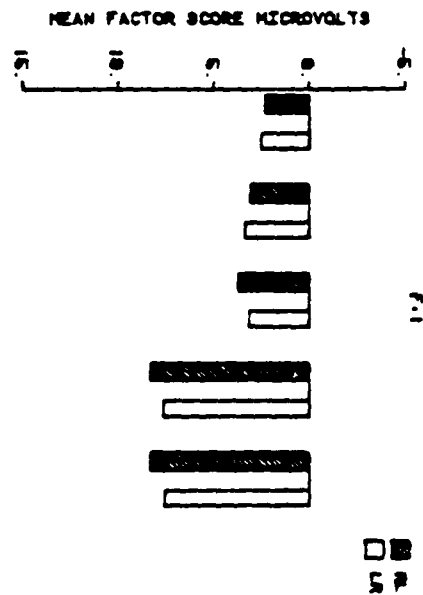
Table 6. Factor II discrimination stimulus, all electrode analysis. Codes are the same as in Table 4.

*p<.01

defined at the central electrodes, particularly for the children as seen in the cross subject averages (Figures 3 and 4). However, the age by electrode interaction did not reach statistical significance. At the parietal electrodes, the phasic positive component and Slow Wave overlapped, making it difficult to visualize each component separately. Table 6 showed that the main effect of electrode remained significant in the range match analysis, but did not reach statistical significance in the interval match analysis.

For the behavioral match, there was a significant stimulus precedence by electrode interaction ($F=6.25$, $p<.01$) for Factor II (Table 6). Figure 8 presents the same data as Figure 7 except that Figure 8 shows the data as a function of stimulus precedence with the data collapsed across stimulus difficulty and age. Factor II was larger over the left hemisphere (C3 and P3) for the RL than for the LR stimuli, whereas it was larger over the right hemisphere (C4 and P4) for the LR than for the RL stimuli (Figure 8). In other words, the phasic positivity in the 300 msec region was larger over the hemisphere contralateral to the ear receiving the lead stimulus. However, the precedence by electrode interaction was a relatively small effect; and, due to the overlap with Slow Wave, it could not be observed in the cross subject averages (Figures 3 and 4). The effect of stimulus precedence fell short of the .01 level of significance in the lateral difference score analysis

Figure 8. The mean factor scores (microvolts) as a function of electrode (CZ, C3, C4, P3, P4) and stimulus precedence (RL= right before left, LR= left before right) collapsed across stimulus difficulty and age, for all factors, for the discrimination stimulus. F:1= Factor I, F:2= Factor II, F:3= Factor III.



($F=7.25$, Table 7). This apparent discrepancy between the lateral difference analysis and the all-electrode analysis was probably due to the loss of degrees of freedom in the lateral difference analysis.

In the range match analysis, for Factor II, the stimulus precedence by electrode interaction, which was significant for the behavioral match analysis, dropped to a trend at $p<.05$, (Table 6). In the interval match analysis, the stimulus precedence by electrode interaction dropped further, to a p of $<.10$ (Table 6).

Factor II was larger for the hard than easy stimuli for the RL sequence, particularly in the right hemisphere, but there was little difference between the easy and hard stimuli for the LR sequence (Figure 9) in the range match lateral difference ANOVA ($F=13.22$, $p<.01$, Table 7). This precedence by difficulty interaction occurred only as a trend ($F=7.82$, $p<.05$) in the behavioral match analysis.

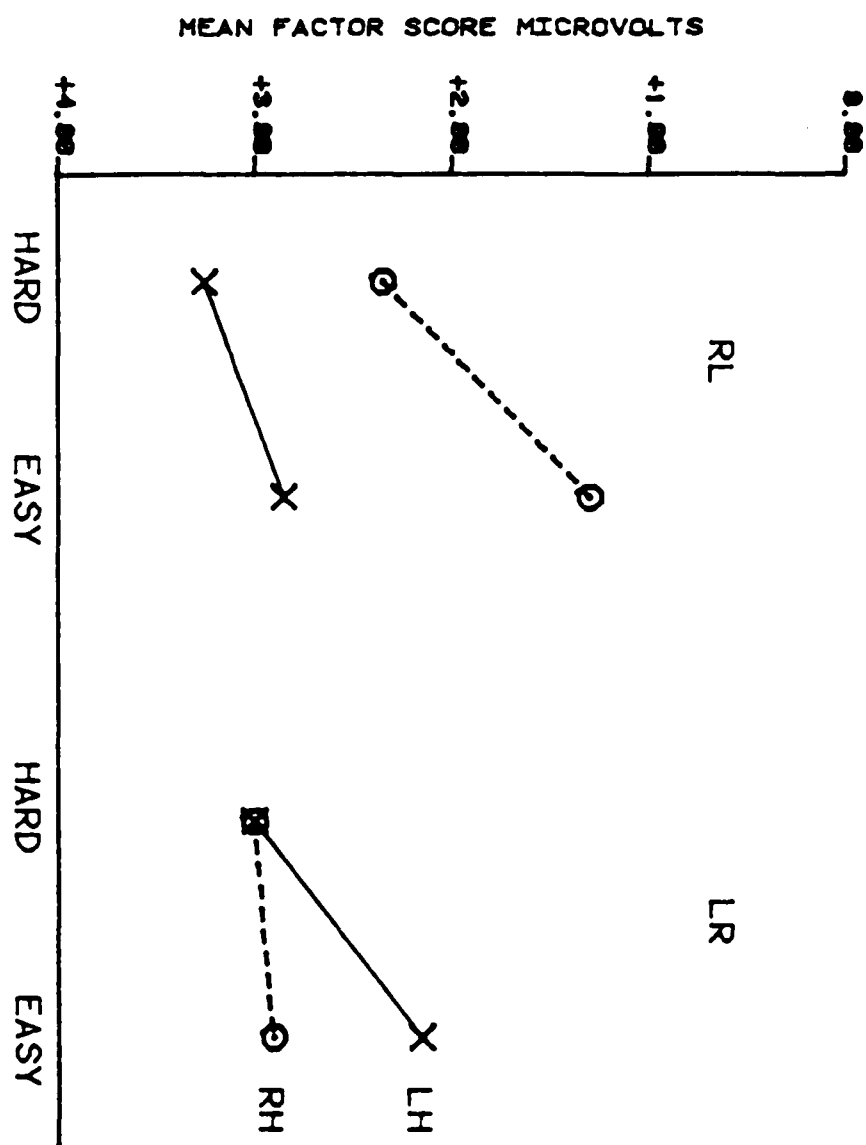
Factor III (Figure 6) was a biphasic component with an early negative limb followed by a later positive limb. The early negative limb extended from 100 to 300 msec, and it reached a maximum amplitude between 100 to 175 msec. The positive limb extended from 300 to 675 msec with a shallow peak at 480 msec. The main effect of electrode was not statistically significant ($F=3.25$, $p>.05$, Table 8) in any of the three matches. Figure 7 indicates that the negative limb of this factor seemed to be predominant in the adults;

<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>BM</u>	<u>Rdf</u>	<u>RM</u>	<u>Rdf</u>	<u>IM</u>
A(AGE)	1,17	1,17	1.23	1,17	1.14	1,17	0.72
P(PRECEDENCE)	1,17	1,17	7.25	1,17	6.03	1,17	4.39
D(DIFFICULTY)	1,17	1,17	0.01	1,17	0.02	1,17	X.XX
E(ELECTRODE)	1,17	1,17	1.28	1,17	1.12	1,17	1.33
P X A	1,17	1,17	1.27	1,17	1.77	1,17	0.06
D X A	1,17	1,17	0.01	1,17	0.06	1,17	X.XX
E X A	1,17	1,17	0.08	1,17	0.04	1,17	0.09
P X D	1,17	1,17	7.82	1,17	13.22*	1,17	X.XX
P X E	1,17	1,17	4.02	1,17	4.13	1,17	1.04
D X E	1,17	1,17	0.02	1,17	0.31	1,17	X.XX
P X D X A	1,17	1,17	5.33	1,17	2.79	1,17	X.XX
P X E X A	1,17	1,17	2.95	1,17	3.53	1,17	1.69
D X E X A	1,17	1,17	0.25	1,17	0.47	1,17	X.XX
P X D X E	1,17	1,17	0.25	1,17	0.41	1,17	X.XX
P X D X E X A	1,17	1,17	4.12	1,17	3.00	1,17	X.XX

Table 7. Factor II discrimination stimulus, lateral difference analysis. Codes are the same as in Table 4.

*p<.01

Figure 9. Mean Factor II (microvolts) as a function of stimulus precedence, stimulus difficulty and hemisphere, from the behavioral match analysis, for the discrimination stimulus. RL= right before left, LR= left before right, RH= right hemisphere, LH= left hemisphere.



<u>SOURCE</u>	<u>df</u>	Rdf	BM	Rdf	RM	Rdf	IM
A(AGE)	1,17	1,17	6.94	1,17	4.75	1,17	6.83
P(PRECEDENCE)	1,17	1,17	0.15	1,17	0.12	1,17	0.00
D(DIFFICULTY)	1,17	1,17	4.42	1,17	12.68*	1,17	X.XX
E(ELECTRODE)	4,68#	2,35	3.25	2,35	2.62	1,17	3.12
P X A	1,17	1,17	0.45	1,17	0.03	1,17	0.19
D X A	1,17	1,17	0.00	1,17	2.35	1,17	X.XX
E X A	4,68	2,35	0.27	2,35	0.31	1,17	0.73
P X D	1,17	1,17	0.01	1,17	2.73	1,17	X.XX
P X E	4,68	2,35	3.76	2,35	3.53	1,17	4.96
D X E	4,68	2,35	1.37	2,35	1.31	1,17	X.XX
P X D X A	1,17	1,17	1.13	1,17	0.38	1,17	X.XX
P X E X A	4,68	2,35	1.44	2,35	1.57	1,17	3.33
D X E X A	4,68	2,35	1.00	2,35	1.51	1,17	X.XX
P X D X E	4,68	2,35	0.88	2,35	0.81	1,17	X.XX
P X D X E X A	4,68	2,35	0.70	2,35	0.70	1,17	X.XX

Table 8. Factor III discrimination stimulus, all electrode analysis. Codes are the same as in Table 4.

*p<.01

whereas the positive limb seemed to be predominant in the children. The main effect of age for Factor III (Table 8) appeared as a trend ($F=6.94$, $p<.017$) in the behavioral match analysis but but did not approach significance in the range match and interval match analyses (Table 8). The negative limb characteristic of the adults appeared to be related to a negative process between 100 and 135 msec, prominent at the central electrodes (Figure 5). The positive limb characteristic of the children was not visible due its overlap with Slow Wave (Figure 5).

The lateral difference score analysis (Table 9) for Factor III revealed a significant main effect of stimulus precedence ($p<.01$) in all three matches. For the behavioral match, Factor III was most positive over the hemisphere contralateral to the lead stimulus (Figure 8). Inspection of the cross subject averages (Figure 3) shows that the positivity at 400 msec was larger in amplitude at C3 and P3 for the RL stimuli than for the LR stimuli. Although Figure 8 indicates that Factor III was larger over the right hemisphere for the LR stimuli, than for the RL stimuli, this small effect was not clear in the cross subject averages.

The data from the interval match analysis (main effect of precedence, lateral difference ANOVA, Table 9), however, are in part in conflict with the data from the behavioral match and range match analyses. Although Table 9 shows that the main effect of stimulus precedence was statistically

<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>BM</u>	<u>Rdf</u>	<u>RM</u>	<u>Rdf</u>	<u>IM</u>
A(AGE)	1,17	1,17	0.05	1,17	0.02	1,17	0.42
P(PRECEDENCE)	1,17	1,17	11.38*	1,17	9.62*	1,17	16.86*
D(DIFFICULTY)	1,17	1,17	0.48	1,17	1.25	1,17	X.XX
E(ELECTRODE)	1,17	1,17	0.13	1,17	0.34	1,17	0.00
P X A	1,17	1,17	2.87	1,17	2.75	1,17	12.06*
D X A	1,17	1,17	0.77	1,17	0.26	1,17	X.XX
E X A	1,17	1,17	0.22	1,17	0.10	1,17	0.02
P X D	1,17	1,17	1.58	1,17	1.37	1,17	X.XX
P X E	1,17	1,17	2.35	1,17	3.62	1,17	3.19
D X E	1,17	1,17	1.74	1,17	0.40	1,17	X.XX
P X D X A	1,17	1,17	0.14	1,17	0.15	1,17	X.XX
P X E X A	1,17	1,17	0.00	1,17	0.01	1,17	0.11
D X E X A	1,17	1,17	1.27	1,17	3.28	1,17	X.XX
P X D X E	1,17	1,17	0.90	1,17	1.14	1,17	X.XX
P X D X E X A	1,17	1,17	0.00	1,17	0.08	1,17	X.XX

Table 9. Factor III discrimination stimulus, lateral difference analysis. Codes are the same as in Table 4.

*p<.01

significant in the interval match, Factor III was most positive over the hemisphere contralateral to the lead stimulus in the RL condition, whereas for the LR condition, Factor III was most positive over the contralateral hemisphere at the parietal electrodes, but was most positive over the hemisphere ipsilateral to the lead stimulus at the central electrodes (Figure 10).

The data from the lateral difference ANOVA interval match analysis also indicate that there was a significant stimulus precedence by age interaction ($F=12.06$, $p<.01$, Table 9) for Factor III. Figure 11 shows that for the children, Factor III was more positive over the right hemisphere in the RL sequence and marginally more positive over the left hemisphere in the LR sequence. Adults showed a largest negative Factor III loading over the left hemisphere regardless of the stimulus sequence.

The range match analysis indicated that a main effect of stimulus difficulty emerged as a significant factor in the all electrode analysis ($F=12.68$, $p<.01$, Table 8). In response to the difficult condition (shorter t) Factor III was 0.09 uv, and in response to the easy condition (longer t) Factor III was 0.71 uv (Figure 12). Although this effect was statistically significant, the small size of the effect precluded identification in the cross subject averages.

Figure 10. Factor III (microvolts) as a function of electrode (C3, C4, P3, P4) and stimulus precedence to the discrimination stimulus in the interval match analysis. RL= right before left, LR= left before right.

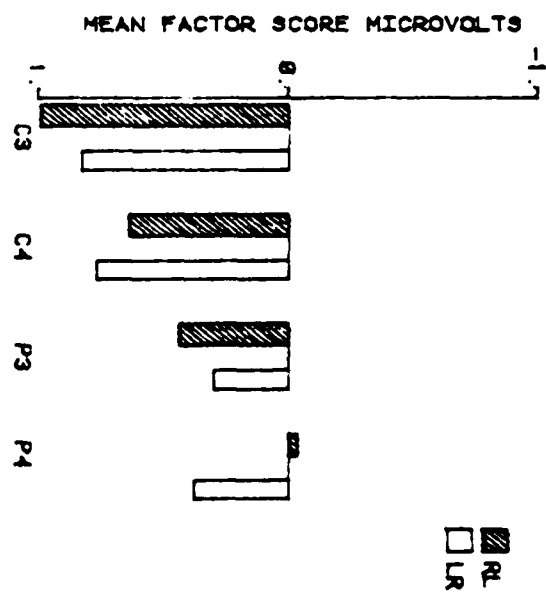


Figure 11. Mean Factor III (microvolts) as a function of stimulus precedence, hemisphere and age, from the interval match analysis, for the discrimination stimulus. RL= right before left, LR= left before right, RH= right hemisphere, LH= left hemisphere.

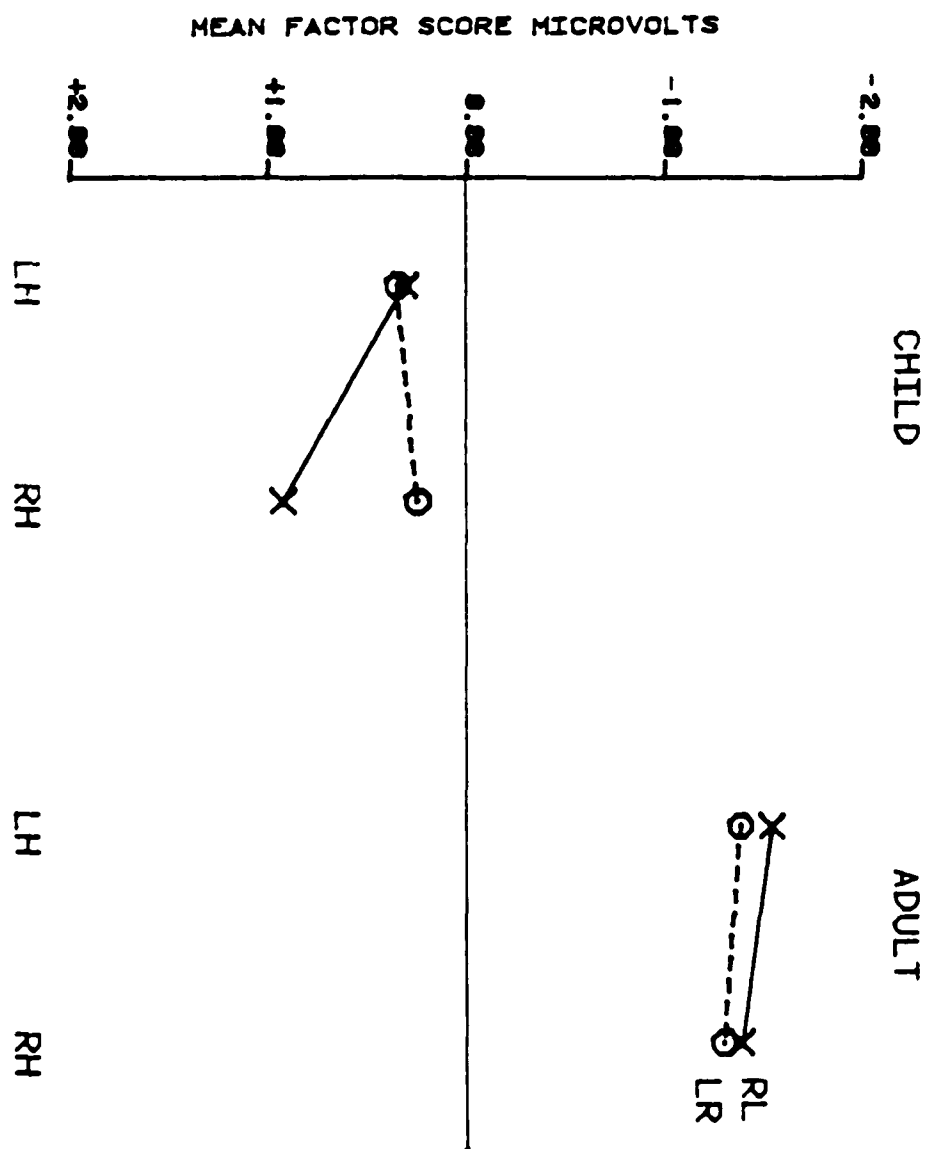
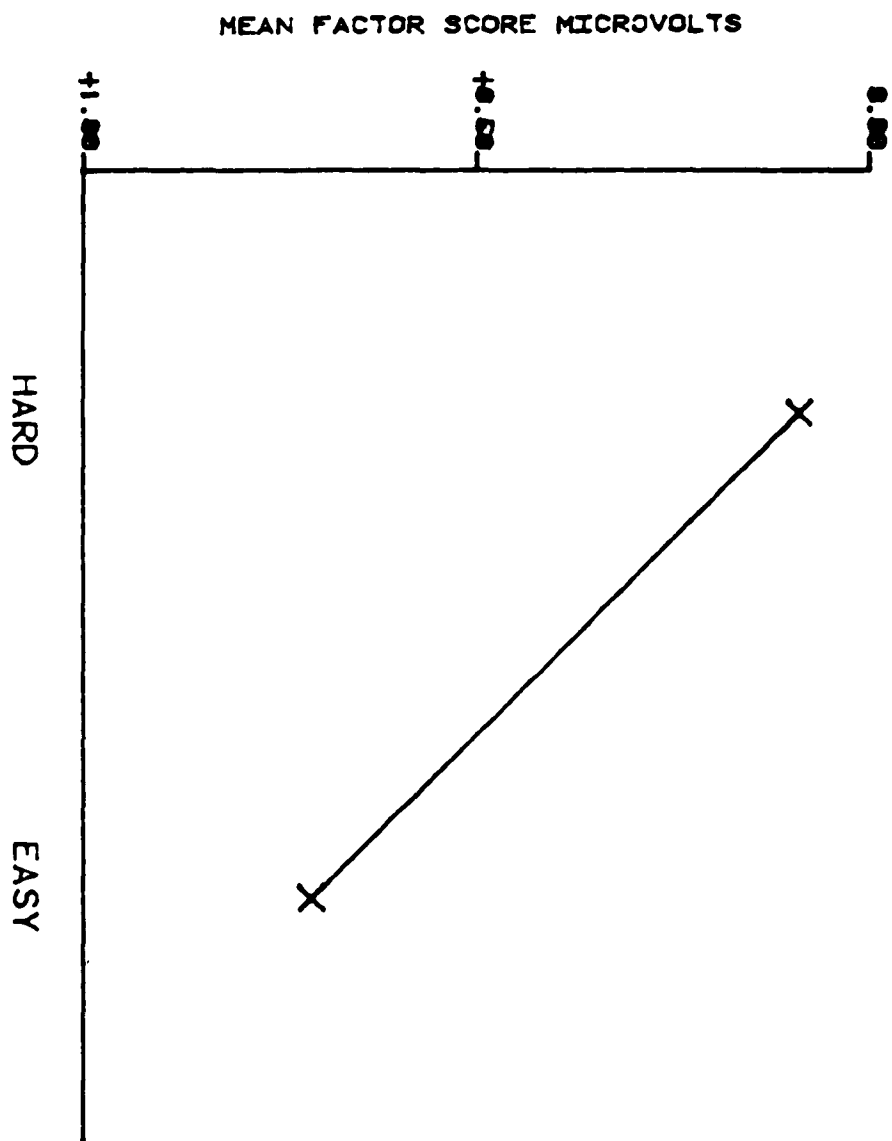


Figure 12. Mean Factor III (microvolts) as a function of stimulus difficulty, from the range match analysis, for the discrimination stimulus.



Feedback Stimulus Epoch (Referred to Feedback Baseline).

The lower half of Figure 5 shows the cross-subject averages to the feedback stimuli collapsed across stimulus precedence and stimulus difficulty. Figures 13 and 14 show the conventionally averaged cross subject ERP waveforms in response to the feedback stimulus for the behavioral match for children and adults, respectively. The format of these figures is the same as was used for the discrimination stimulus. At the central electrodes the adults showed a larger phasic positivity in the 300 msec region and a more well defined N100 component than the children did (Figure 5).

PCVA Analyses. Figure 15 shows the ERP basis waveforms obtained in response to the feedback stimuli. Four principal components, labeled F:1, F:2, F:3 and F:4.

Factor I was a long duration tonic positive component and is tentatively identified as Slow Wave. It had an onset latency of approximately 125 msec and a peak amplitude at 325 msec. It remained positive to the baseline 900 msec after stimulus onset. Figures 16 and 17 indicate that the feedback Slow Wave component was largest at C3 and smallest at CZ ($F=5.78$, $p<.01$) (Table 10). This effect was not visible in the cross subject average (Figure 5) due to overlap of Factor II with Slow Wave at CZ. Although the Slow Wave component appeared larger in the children than in

Figure 13. Conventional cross subject ERP averages for the children from all experimental conditions (rows: RL 75, RL 125, LR 75, LR 125) and all electrodes (columns: CZ, C3, C4, P3, P4) for the feedback stimulus. Abscissa the same as in Figure 3. Stimulus onset occurs at time 0.

CHILD
FEEDBACK

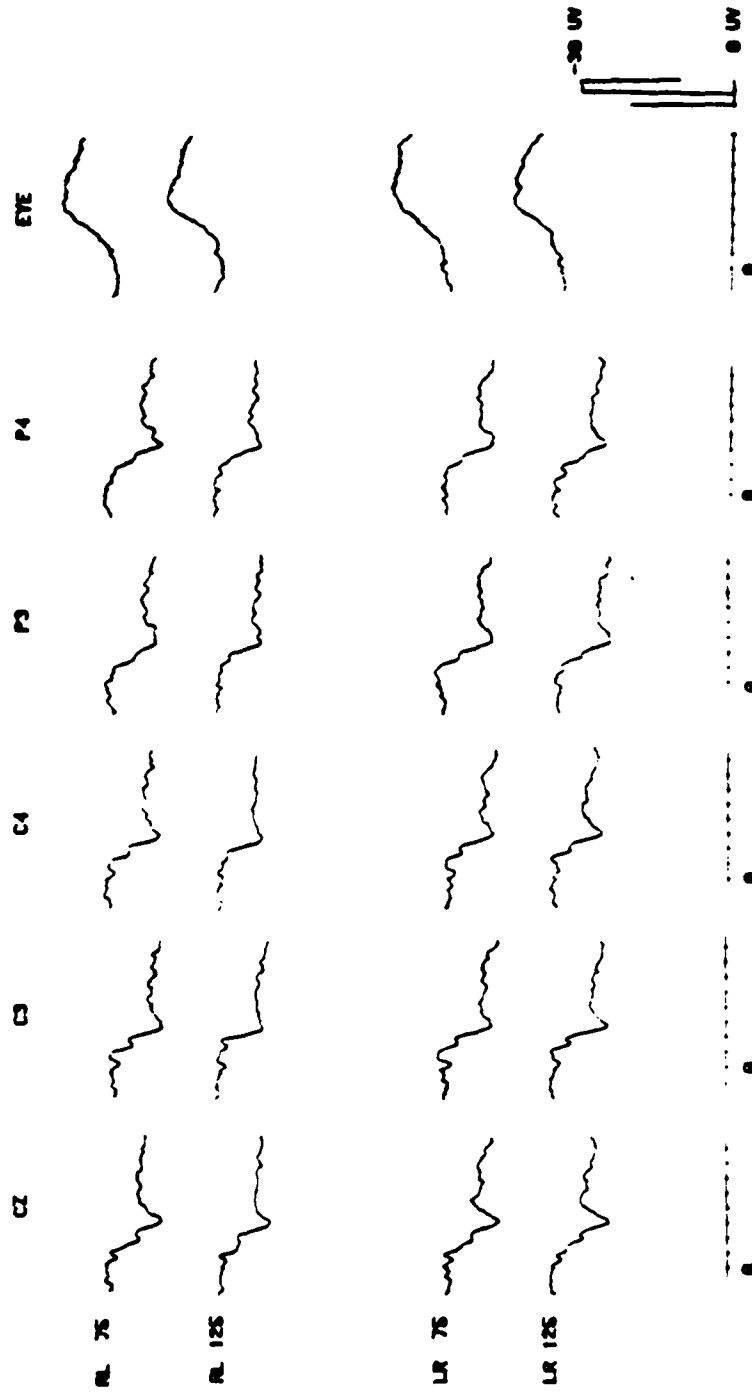


Figure 14. Conventional cross subject ERP averages for the adults from all experimental conditions (rows: RL 50, RL 75, LR 50, LR 75) and all electrodes (columns: CZ, C3, C4, P3, P4) for the feedback stimulus. Abscissa the same as in Figure 3. Stimulus onset occurs at time 0.

ADULT
FEEDBACK

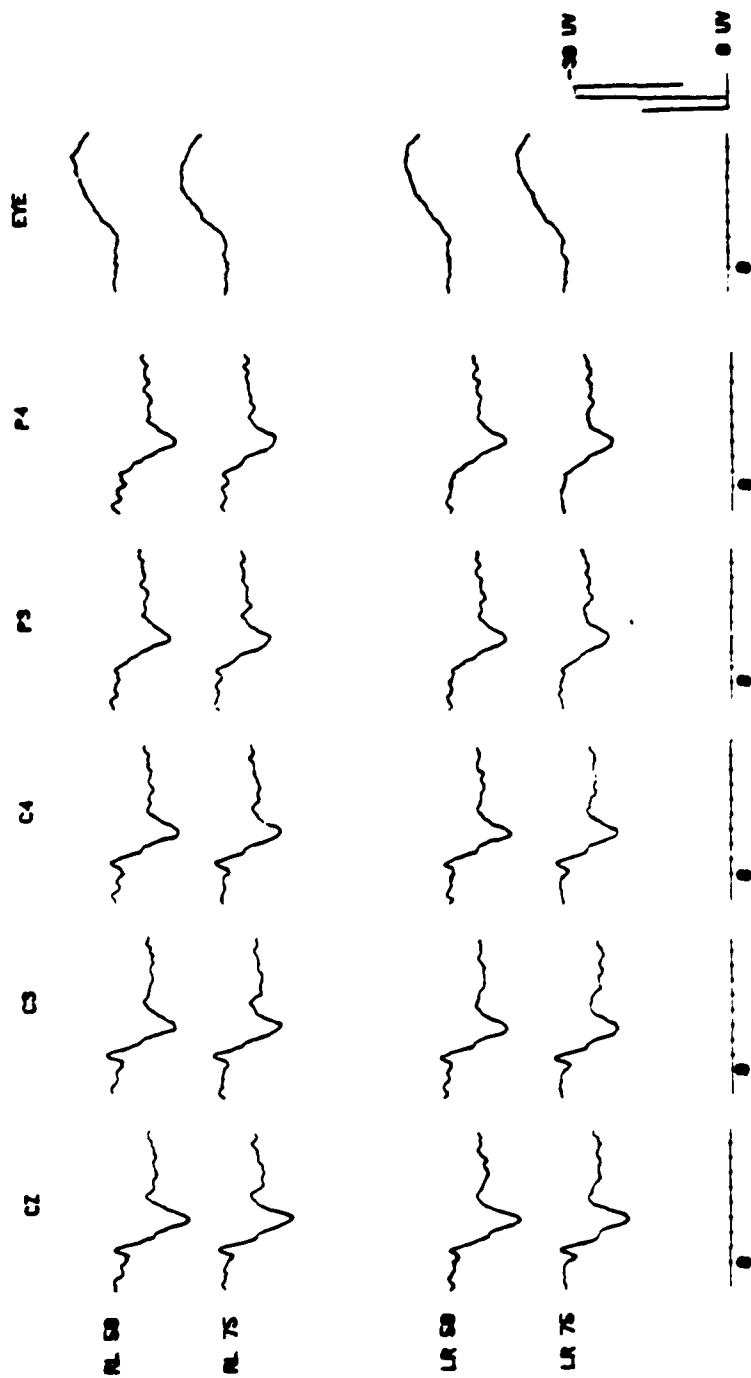


Figure 15. The basis waveforms (rotated factor loadings, microvolts) for children and adults, for all scalp electrodes, for all experimental conditions, for the feedback stimulus referred to the feedback stimulus baseline. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV. Stimulus onset occurs at time 0.

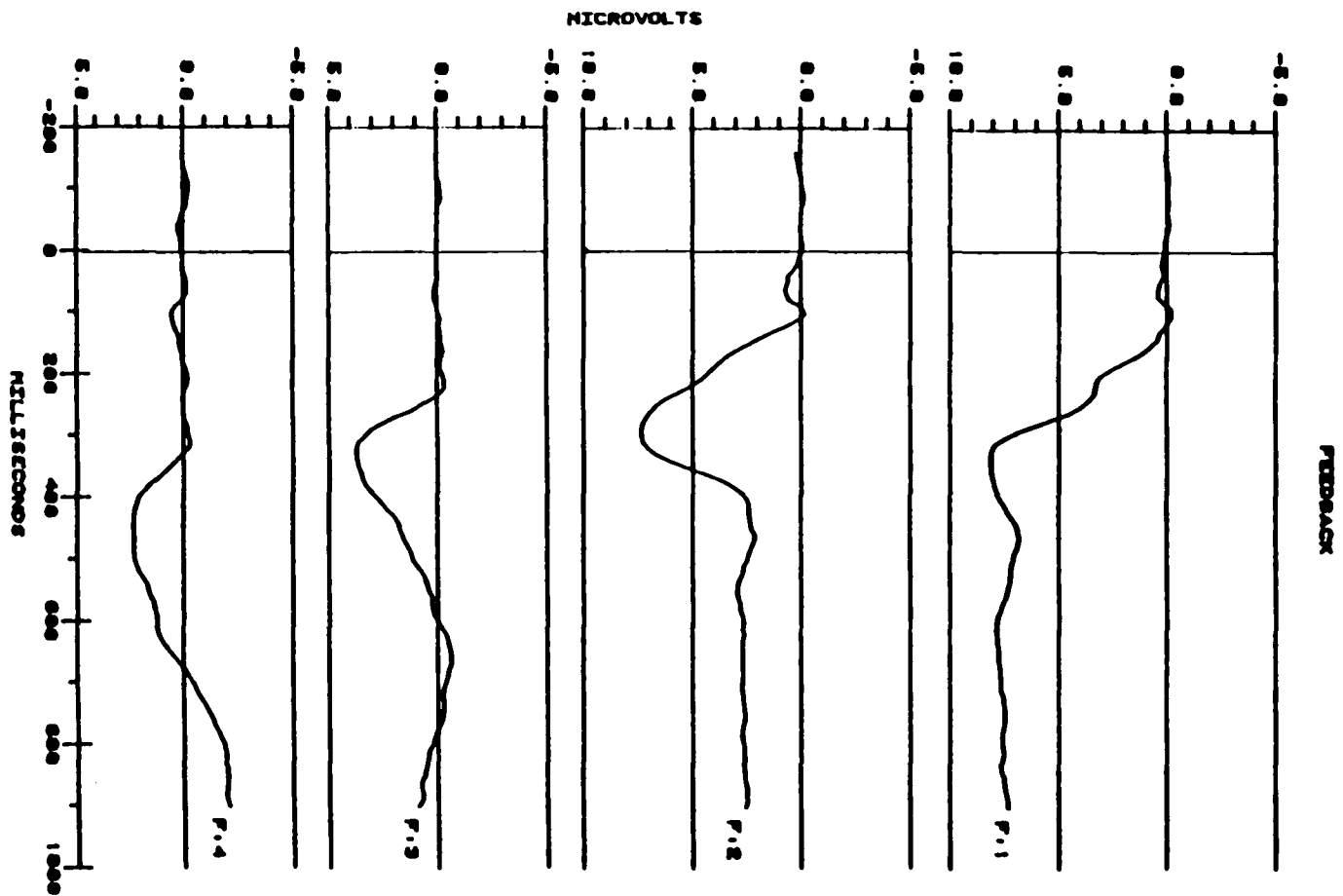


Figure 16. The mean factor scores (microvolts) as a function of electrode (CZ, C3, C4, P3, P4) and age collapsed across stimulus difficulty and stimulus precedence, for all factors, for the feedback stimulus referred to the feedback stimulus baseline. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV.

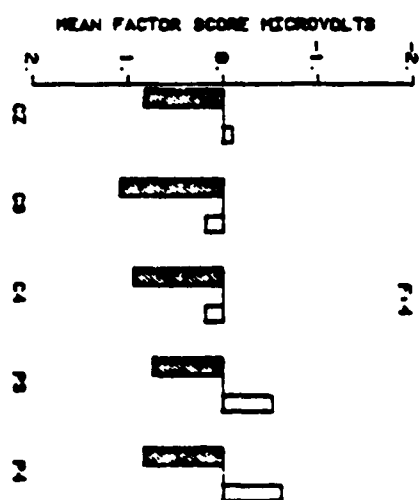
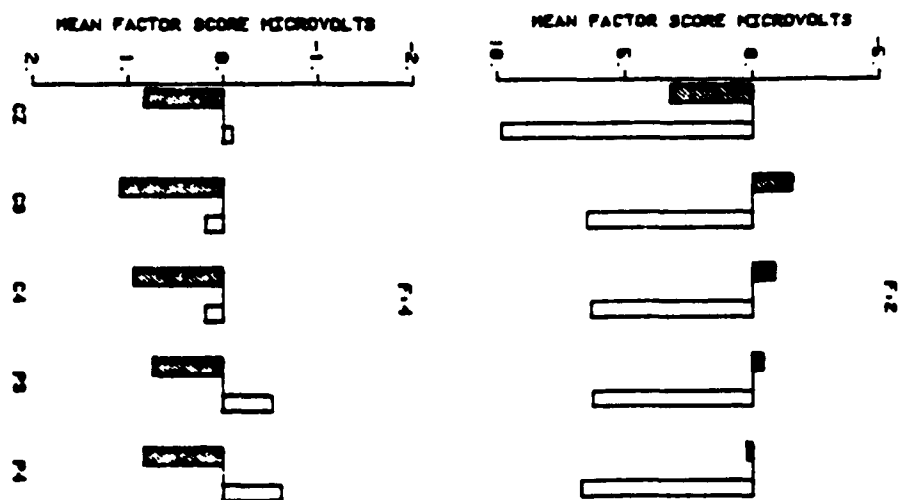
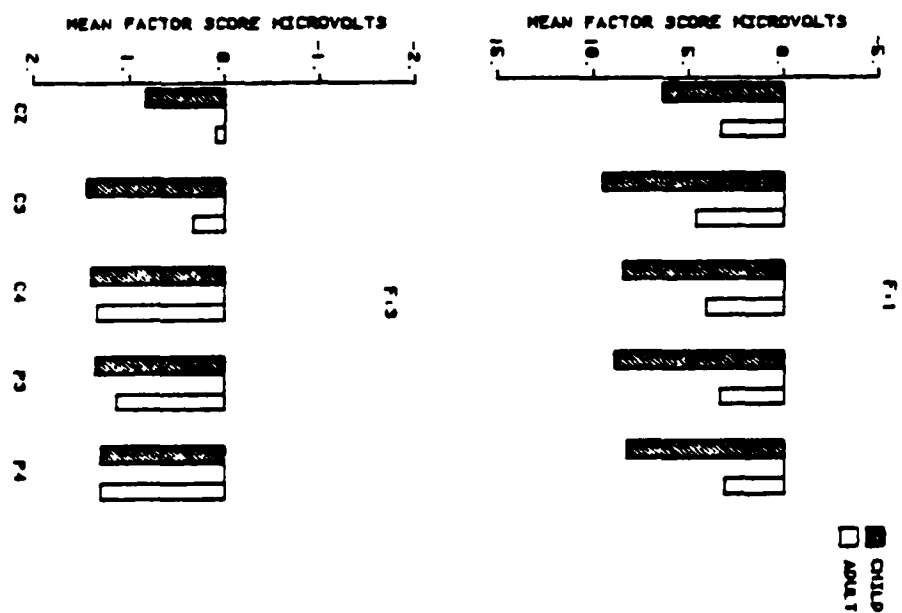
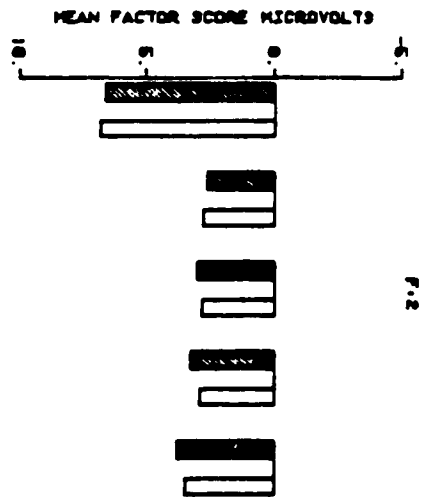
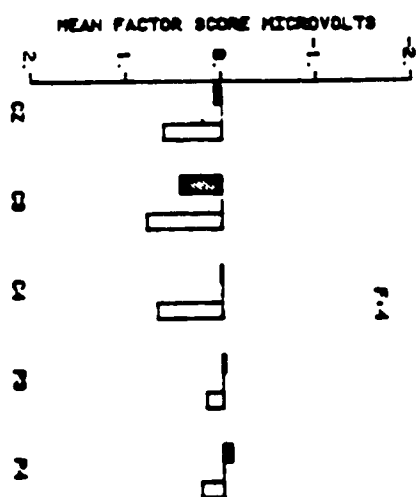
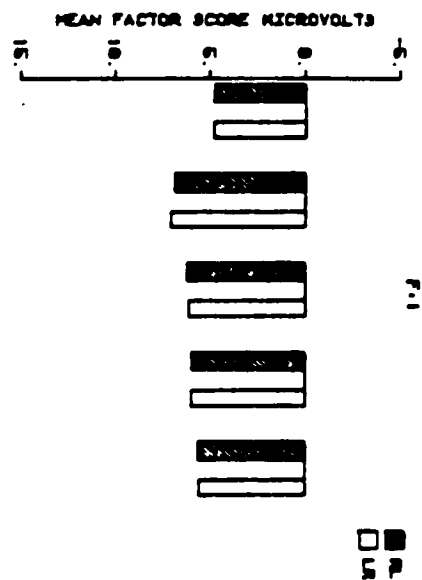
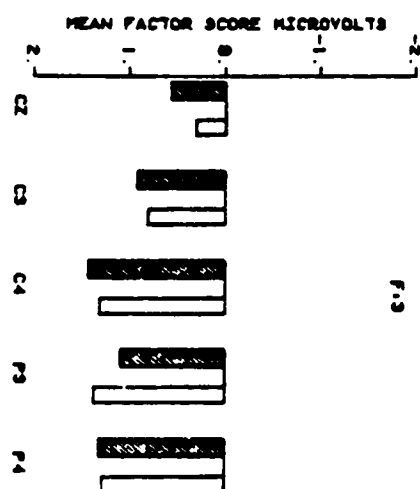


Figure 17. The mean factor scores (microvolts) as a function of electrode (C2, C3, C4, P3, P4) and stimulus precedence collapsed across stimulus difficulty and age, for all factors, for the feedback stimulus referred to the feedback stimulus baseline. RL= right before left, LR= left before right.



<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>F:1</u>	<u>Rdf</u>	<u>F:2</u>	<u>Rdf</u>	<u>F:3</u>	<u>Rdf</u>	<u>F:4</u>
A(AGE)	1,17	1,17	4.23	1,17	10.93*	1,17	0.09	1,17	1.53
P(PRECEDENCE)	1,17	1,17	0.01	1,17	0.04	1,17	0.00	1,17	2.52
D(DIFFICULTY)	1,17	1,17	0.45	1,17	0.16	1,17	2.03	1,17	0.21
E(ELECTRODE)	4,68	3,48	5.78*	2,41	19.42*	2,37	1.14	2,33	2.45
P X A	1,17	1,17	0.15	1,17	0.02	1,17	0.62	1,17	0.31
D X A	1,17	1,17	0.43	1,17	0.57	1,17	0.18	1,17	0.36
E X A	4,68	3,48	1.89	2,41	0.76	2,37	0.46	2,33	0.65
P X D	1,17	1,17	0.06	1,17	2.77	1,17	0.01	1,17	0.25
P X E	4,68	3,48	0.14	2,41	1.02	2,37	1.51	2,33	3.79
D X E	4,68	3,48	2.87	2,41	0.40	2,37	2.13	2,33	0.11
P X D X A	1,17	1,17	0.76	1,17	7.83	1,17	0.18	1,17	0.22
P X E X A	4,68	3,48	0.62	2,41	0.82	2,37	2.02	2,33	1.58
D X E X A	4,68	3,48	2.31	2,41	0.22	2,37	2.48	2,33	0.35
P X D X E	4,68	3,48	0.34	2,41	0.09	2,37	1.35	2,33	1.23
P X D X E X A	4,68	3,48	1.58	2,41	0.56	2,37	0.47	2,33	1.44

Table 10. Factors I, II, III and IV, all electrode analysis, behavioral match, feedback stimulus. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV. df= degrees of freedom, Rdf= reduced degrees of freedom.

*p<.01

the adults (Figure 16), this effect did not even reach the .05 level (Table 10). No differences emerged for Slow Wave as a function of experimental conditions for any of the matches.

Factor II was a phasic positive component followed by a sustained positivity. It had an onset latency of 125 msec and reached a peak amplitude at 300 msec. At 900 msec after the stimulus, the factor was positive to the baseline.

Figure 17 indicates that this phasic positivity was largest at CZ and smaller at lateral sites ($F=19.42$, $p<.01$, Table 10). It appeared similar in topography to the phasic positive component (Factor II) obtained to the discrimination stimulus. Factor II can be observed in the cross subject averages (Figures 5, 13 and 14) especially at the vertex electrode. The statistically significant main effect of electrode was also found in the range match and interval match analyses. The main effect of age ($F=10.93$, $p<.01$) was also significant (Table 10). Figure 16 shows that Factor II was larger in the adults than in the children, as can also be seen in the cross subject averages (Figure 5). The statistically significant main effect of age was also found in the range match and interval match analyses.

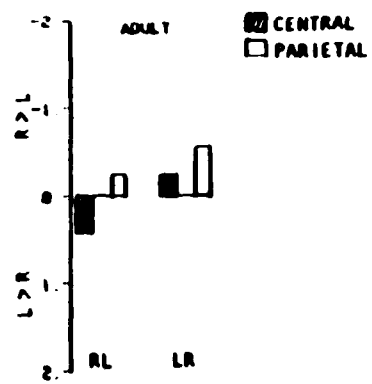
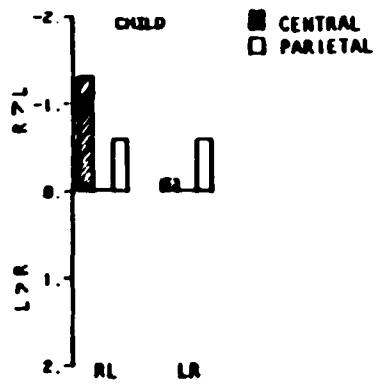
In the range match analysis, a significant stimulus precedence by electrode by age interaction with regard to the lateralization of Factor II emerged. This effect was present only as a trend in the behavioral and interval match

analyses. Figure 18 indicates that for the RL stimuli at the central electrodes, children and adults showed an opposite direction of asymmetry; whereas for all other conditions, the direction of asymmetry was the same for children and adults at both central and parietal sites.

Factor III was a phasic positive component (Figure 15). It had an onset latency of approximately 250 msec, reached a peak amplitude at about 325 msec and returned to the baseline 600 msec after stimulus onset. Figures 16 and 17 indicate that Factor III was smallest at C2, but the main effect of electrode was not statistically significant. This factor did not vary significantly in relation to any experimental variable (Table 10) and no differences emerged between its behavioral match, range match or interval match analyses.

Factor IV was a relatively late and shallow phasic positive and negative component (Figure 15). It had an onset latency of 325 msec, initially forming a positive plateau between 400 and 500 msec. The factor then crossed the baseline approximately 675 msec after the stimulus and remained negative to the baseline throughout the analysis epoch. Factor IV had its largest positive loading at C3 (Figures 16 and 17), but the main effect of electrode was not statistically significant ($F = 2.45$, $P > .05$, Table 10). It had a positive loading in the children and a negative loading in the adults (Figure 16). However, this effect of

Figure 18. Mean lateral difference Factor II (microvolts) as a function of stimulus precedence, electrode and age. RL= right before left, LR= left before right.



age did not even approach statistical significance (Table 10).

The all-electrode ANOVA for the behavioral match analysis (Table 10) indicated that a stimulus precedence by electrode interaction ($F=3.79$, $p<.05$) showed a trend for Factor IV to be largest over the hemisphere contralateral to the lead stimulus. A similar trend emerged for the range match analysis, but no trend emerged for the interval match analysis. The lateral difference score ANOVA (Table 11) indicated that for the behavioral match, the effect of stimulus precedence ($F=31.18$, $p<.01$) and a precedence by age interaction ($F=30.17$, $p<.01$) were statistically significant. Figure 19 shows the main effect of stimulus precedence in relation to Factor IV lateralization. In this plot, values for central and parietal electrodes are averaged. For stimuli presented in the RL sequence, Factor IV was more negative over the left hemisphere than over the right hemisphere; whereas for the LR stimuli Factor IV shows little difference in negativity over both hemispheres. Figure 20 shows that the main effect of stimulus precedence in Figure 19 was somewhat misleading. In fact, in the adults, Factor IV was negative for all stimuli, but more negative for the RL than LR stimuli with a greater negativity over the right than the left hemisphere for all stimuli; whereas for children, Factor IV was positive for all stimuli, but more positive for the RL than LR stimuli

<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>F:1</u>	<u>Rdf</u>	<u>F:2</u>	<u>Rdf</u>	<u>F:3</u>	<u>Rdf</u>	<u>F:4</u>
A(AGE)	1,17	1,17	0.29	1,17	0.69	1,17	0.79	1,17	0.62
P(PRECEDENCE)	1,17	1,17	0.25	1,17	0.37	1,17	0.99	1,17	31.18*
D(DIFFICULTY)	1,17	1,17	4.40	1,17	0.05	1,17	0.86	1,17	0.67
E(ELECTRODE)	1,17	1,17	1.00	1,17	0.28	1,17	3.23	1,17	2.98
P X A	1,17	1,17	0.67	1,17	1.21	1,17	0.32	1,17	30.17*
D X A	1,17	1,17	4.53	1,17	0.41	1,17	0.31	1,17	1.08
E X A	1,17	1,17	0.01	1,17	0.30	1,17	3.07	1,17	0.01
P X D	1,17	1,17	1.50	1,17	0.36	1,17	0.25	1,17	0.28
P X E	1,17	1,17	0.65	1,17	4.78	1,17	4.87	1,17	6.18
D X E	1,17	1,17	6.01	1,17	0.05	1,17	0.94	1,17	0.28
P X D X A	1,17	1,17	5.88	1,17	1.17	1,17	0.11	1,17	2.13
P X E X A	1,17	1,17	0.42	1,17	7.36	1,17	5.60	1,17	2.45
D X E X A	1,17	1,17	1.45	1,17	0.63	1,17	3.08	1,17	0.95
P X D X E	1,17	1,17	0.11	1,17	0.09	1,17	0.49	1,17	6.44
P X D X E X A	1,17	1,17	0.09	1,17	0.77	1,17	1.47	1,17	11.94*

Table 11. Factors I, II, III and IV, lateral difference analysis, behavioral match, feedback stimulus. Codes are the same as in Table 10.

*p<.01

Figure 19. Mean Factor IV (microvolts) as a function of stimulus precedence and hemisphere from the behavioral match analysis for the feedback stimulus referred to the feedback stimulus baseline. LR= left before right, RL= right before left, LH= left hemisphere, RH= right hemisphere.

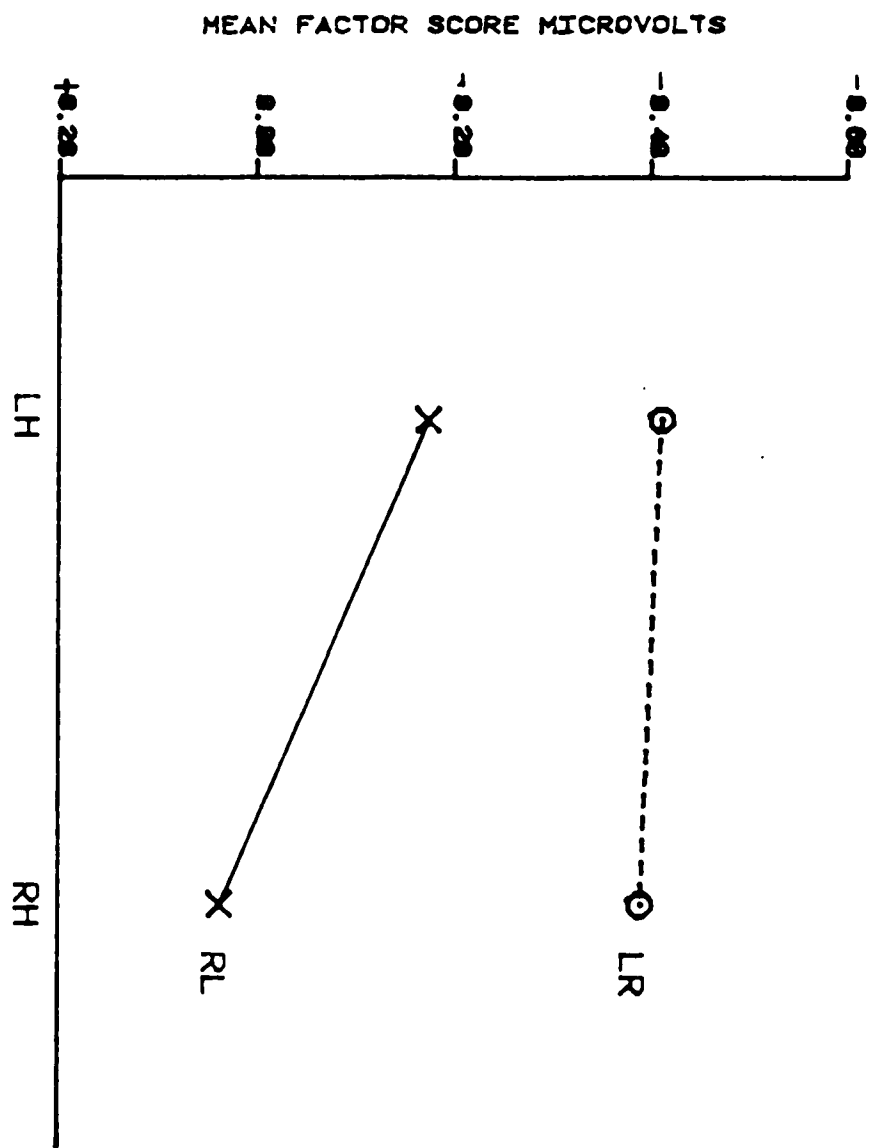
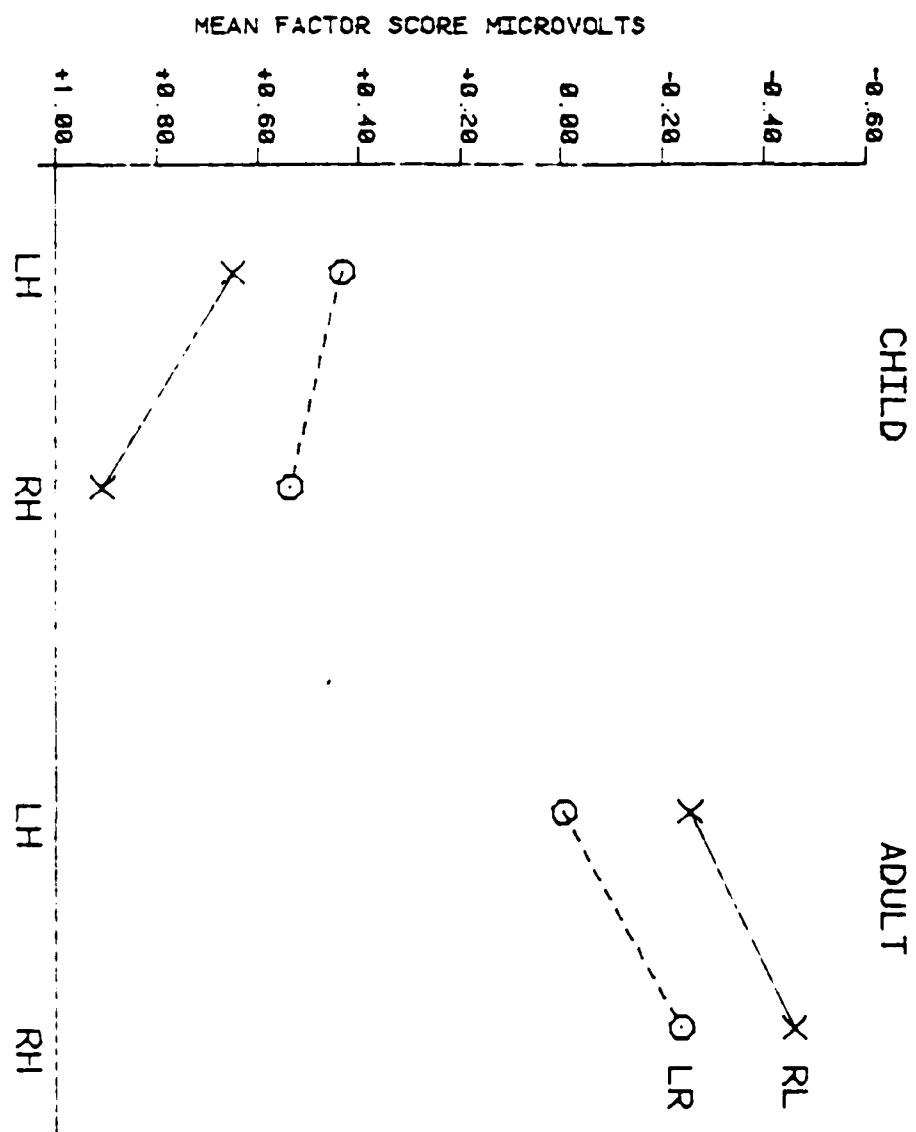


Figure 20. Mean Factor IV (microvolts) as a function of stimulus precedence, hemisphere and age from the behavioral match analysis for the feedback stimulus referred to the feedback stimulus baseline. LR= left before right, RL= right before left, LH= left hemisphere, RH= right hemisphere.



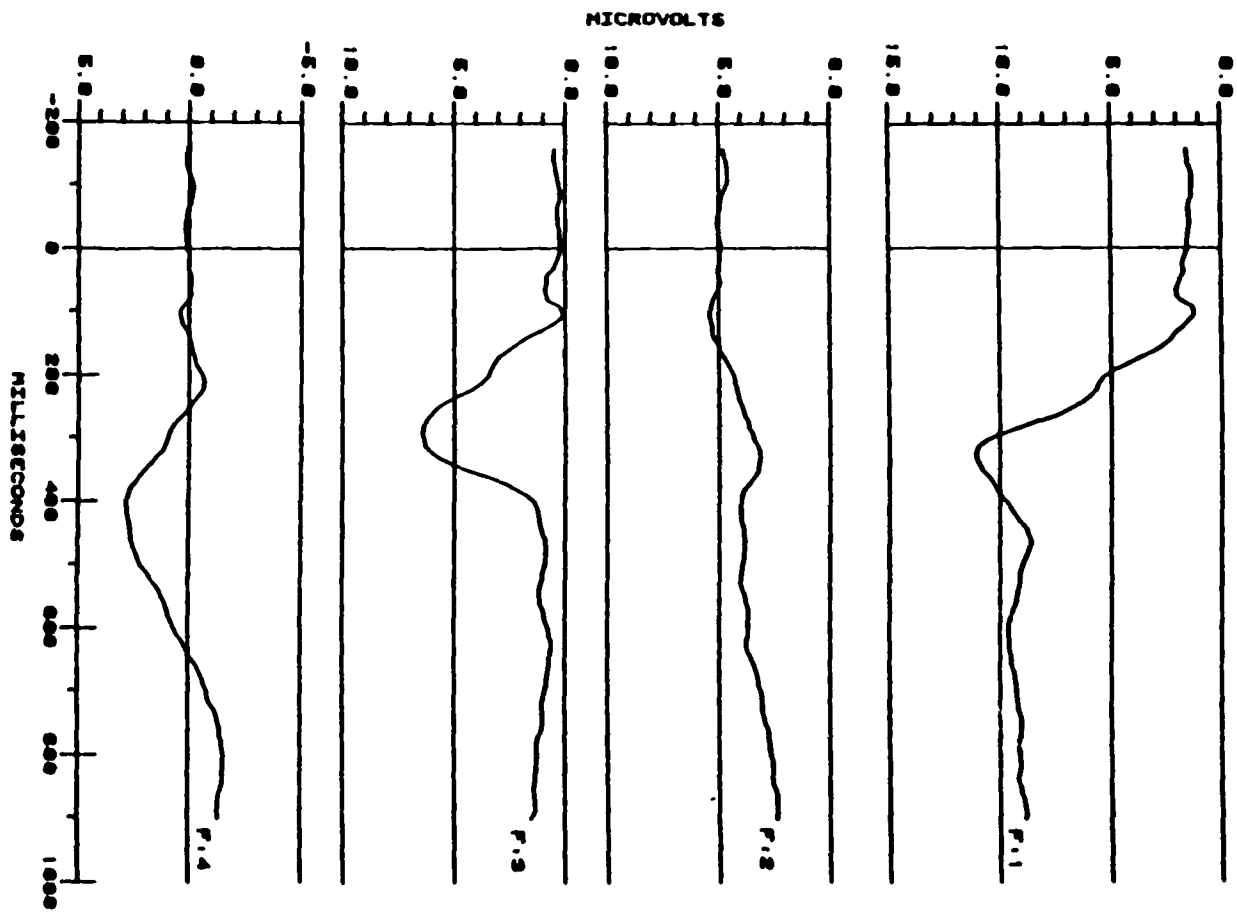
with a greater positivity over the right than left hemisphere for all stimuli. The small size of these effects precluded visualization in the cross subject averages.

In the range match analysis, the main effect of stimulus precedence and the precedence by age interaction were statistically significant. However, in the interval match analysis, the main effect of stimulus precedence and the precedence by age interaction failed to reach significance.

Feedback (Referred to Discrimination Stimulus Baseline).

Figure 21 shows the ERP basis waveforms in response to the feedback stimulus when the median baseline voltage from the preceeding discrimination stimulus was subtracted from each point along the feedback stimulus waveform. Four factors labeled F:1, F:2, F:3 and F:4 were obtained. Except for a shift in the prestimulus baseline these three factors were essentially the same as Factors I, II and IV in the previous analysis (Figure 15). The present analysis revealed the presence of a sustained DC shift (Factor II). For this sustained DC shift the main effect of electrode was significant ($F = 14.83$, $p < .01$) in the behavioral match analysis (Table 12). The main effect of electrode was not significant in either the range or interval match analyses. Factor II was distributed negative centrally and positive parietally for the behavioral match (Figure 22), however,

Figure 21. The basis waveforms (rotated factor loadings, microvolts) for the children and adults, for all scalp electrodes, for all experimental conditions for the feedback stimulus referred to the discrimination stimulus baseline. F:1= Factor 1, F:2= Factor II, F:3= Factor III, F:4=Factor IV. Stimulus onset occurs at time 0.



<u>SOURCE</u>	<u>df</u>	<u>Rdf</u>	<u>ALL</u>	<u>Rdf</u>	<u>LAT</u>
A(AGE)	1,17	1,17	1.38	1,17	16.66*
P(PRECEDENCE)	1,17	1,17	1.09	1,17	0.49
D(DIFFICULTY)	1,17	1,17	0.02	1,17	0.20
E(ELECTRODE)	4,68	3,45	14.83*	1,17	0.66
P X A	1,17	1,17	2.59	1,17	1.27
D X A	1,17	1,17	0.13	1,17	0.69
E X A	4,68	3,45	9.65*	1,17	3.39
P X D	1,17	1,17	0.17	1,17	0.03
P X E	4,68	3,45	0.61	1,17	0.08
D X E	4,68	3,45	0.30	1,17	0.20
P X D X A	1,17	1,17	1.04	1,17	0.00
P X E X A	4,68	3,45	1.63	1,17	4.23
D X E X A	4,68	3,45	0.49	1,17	2.26
P X D X E	4,68	3,45	0.68	1,17	0.08
P X D X E X A	4,68	3,45	1.25	1,17	0.59

Table 12. Factor II, feedback stimulus referred to discrimination stimulus baseline, behavioral match analysis. ALL= all electrode analysis, LAT= lateral difference analysis. df= degrees of freedom, Rdf= reduced degrees of freedom.

*p<.01

Figure 22. Mean Factor II (microvolts) as a function of electrode (CZ, C3, C4, P3, P4) and stimulus precedence from the behavioral match analysis collapsed across stimulus difficulty and age, for the feedback stimulus referred to the discrimination stimulus baseline. RL= right before left, LR= left before right.

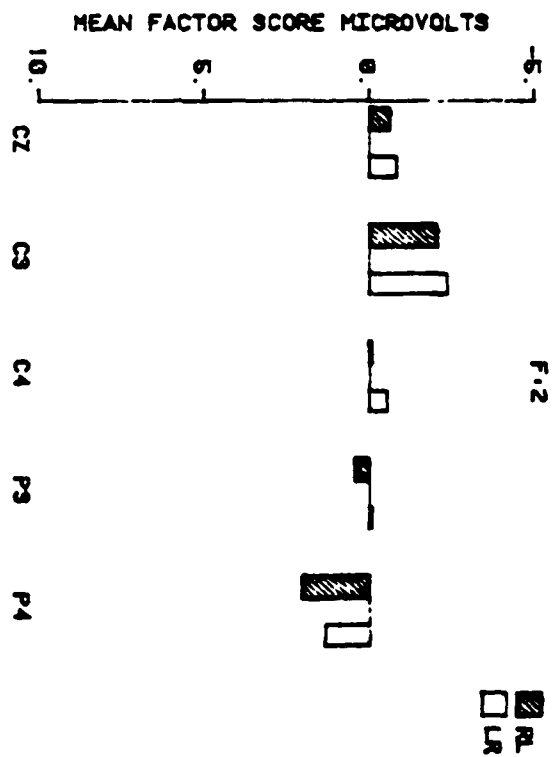


Figure 23 shows that the main effect of electrode was somewhat misleading. Factor II had a largest negative amplitude at CZ and C3 in the children, and was relatively small in amplitude (Figure 23) in the adults. This effect (electrode by age) was significant ($F=9.65$, $p<.01$, Table 12) for the behavioral match but not for the range and interval match analyses. Figure 24 indicates the negative shift in the baseline for the children at electrodes CZ and C3 and the positive or absent baseline shift elsewhere.

Factor II showed a significant main effect of age with respect to the behavioral match lateral difference analysis ($F=16.66$, $p<.01$, Table 12). Figure 23 shows that the response was more negative at the left hemisphere for the children, but showed no difference between hemispheres for the adults. This effect was not found in the range match and interval match analyses.

Eye Movement Control Analysis. Tables 13 and 14 indicate that despite instructions to the subject not to blink and despite rejection of trials containing excessive eye movement, some time-locked electrophysiological activity occurred at the eye channel. Table 13 shows the mean factor scores (microvolts) in response to the discrimination stimulus for each channel and subject group collapsed across levels of stimulus precedence and stimulus difficulty. For Slow Wave, there was a slight amount of activity at the

Figure 23. Mean Factor II (microvolts) as a function of electrode (CZ, C3, C4, P3, P4) and age from the behavioral match analysis collapsed across stimulus precedence and stimulus difficulty, for the feedback stimulus referred to the discrimination stimulus baseline.

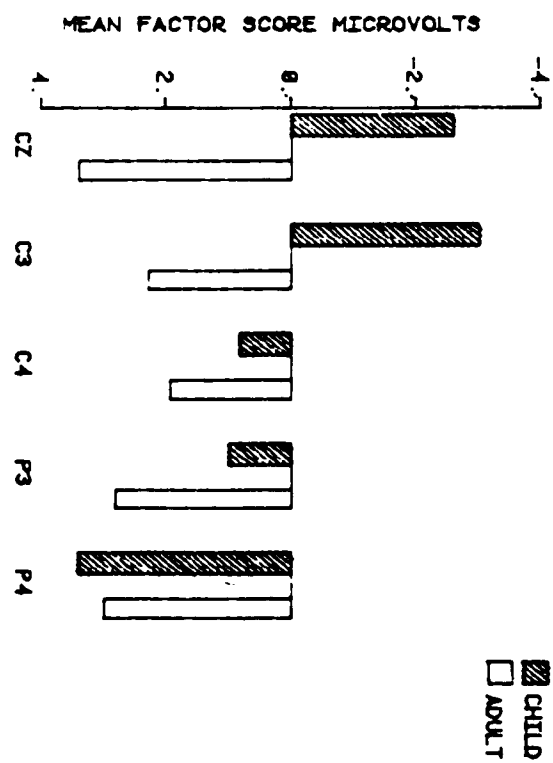
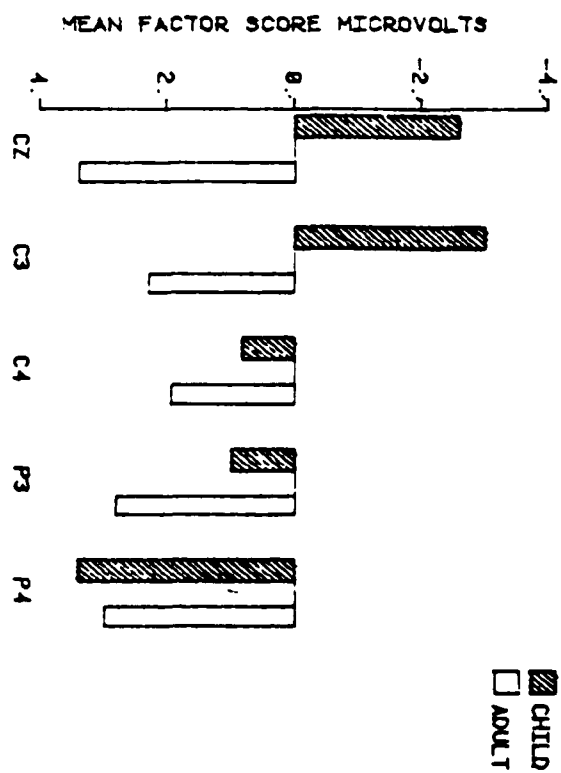


Figure 24. Mean Factor II (microvolts) as a function of electrode (CZ, C3, C4, P3, P4) and age to the feedback stimulus rererred to the discrimination stimulus baseline.



	EYE	CZ	C3	C4	P3	P4
F:1						
CHILD	-3.2	5.2	7.0	6.2	12.6	11.2
ADULT	-2.4	-0.5	-0.3	0.7	3.5	4.6
F:2						
CHILD	-1.5	4.4	2.5	1.4	0.5	-0.3
ADULT	0.8	5.0	3.9	3.8	3.6	4.0
F:3						
CHILD	-2.1	-5.9	0.1	0.4	-0.9	-0.9
ADULT	0.3	1.4	1.5	1.4	1.1	0.9

Table 13. Mean factor scores as a function of electrode (EYE, CZ, C3, C4, P3, P4) and age for the discrimination stimulus in the behavioral match. F:1= Factor I, F:2= Factor II, F:3= Factor III.

	EYE	CZ	C3	C4	P3	P4
F:1						
CHILD	-9.2	5.8	8.7	7.8	8.1	7.6
ADULT	-9.4	3.0	4.2	3.7	3.0	2.8
F:2						
CHILD	1.1	4.2	-0.4	0.2	0.6	1.3
ADULT	2.6	10.5	7.2	6.9	6.7	7.1
F:3						
CHILD	0.7	1.4	2.6	2.4	2.4	2.2
ADULT	2.4	0.1	0.6	1.6	1.3	1.4
F:4						
CHILD	-2.3	-1.0	-1.4	-1.2	-1.0	-1.1
ADULT	-0.2	-0.1	-0.3	0.1	0.5	0.6

Table 14. Mean factor scores as a function of electrode (EYE, CZ, C3, C4, P3, P4) and age for the feedback stimulus referred to the feedback stimulus baseline for the behavioral match. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV.

scalp electrodes that may be ocular in origin. However, it is doubtful that this activity significantly effected the findings for Slow Wave since the amplitude of the Slow Wave was approximately four times as large for the children than adults at the parietal electrodes, whereas the amplitude differential at the eye channel was considerably less. Table 13 also indicates that for Factor II in the children, there was a slight influence of ocular activity on observed amplitude at the scalp electrodes.

Table 14 shows that the mean factor scores in response to the feedback stimulus for each channel and subject group collapsed across stimulus precedence and difficulty. Of the four factor scores, only Factor I (Slow Wave) was larger in amplitude and inverted in polarity at the eye channel with regard to the scalp electrodes. However, close inspection of the table reveals that at each scalp electrode the Slow Wave amplitude was approximately twice as large for the children than for the adults. Yet there was no difference in amplitude of Factor I at the eye channel for the children and adults.

Separate Groups Analyses

The separate groups analysis was conducted to answer questions raised by the combined groups analysis. No attempt was made to present a complete systematic analysis of each group.

Discrimination Stimulus. Figures 25 and 26 shows the basis waveforms from the children and adults respectively in response to the discrimination stimulus. In the children (Figure 25) Slow Wave was the first component to emerge. It had an onset latency of about 150 msec and reached a peak at about 500 msec. Slow Wave was most positive at the parietal electrodes. No other significant effects were found. An early phasic positive component (Factor II) peaked at 300 msec and displayed a non-significant CZ maximum. This component showed no relation to experimental condition. A later phasic positive component (Factor III) showed a CZ maximum and formed a plateau between 350-425 msec. This latter component showed a significant precedence by electrode interaction in which the component was larger over the hemisphere contralateral than ipsilateral to the lead stimulus.

For the adults (Figure 26), Slow Wave was also the first component to emerge. It had an onset latency of about 250 msec and it reached a peak between 500-600 msec. Slow Wave

Figure 25. The basis waveforms (rotated factor loadings, microvolts) for the children, for all scalp electrodes, for all experimental conditions, for the discrimination stimulus. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV. Stimulus onset occurs at time 0.

CHILD DISCRIMINATION

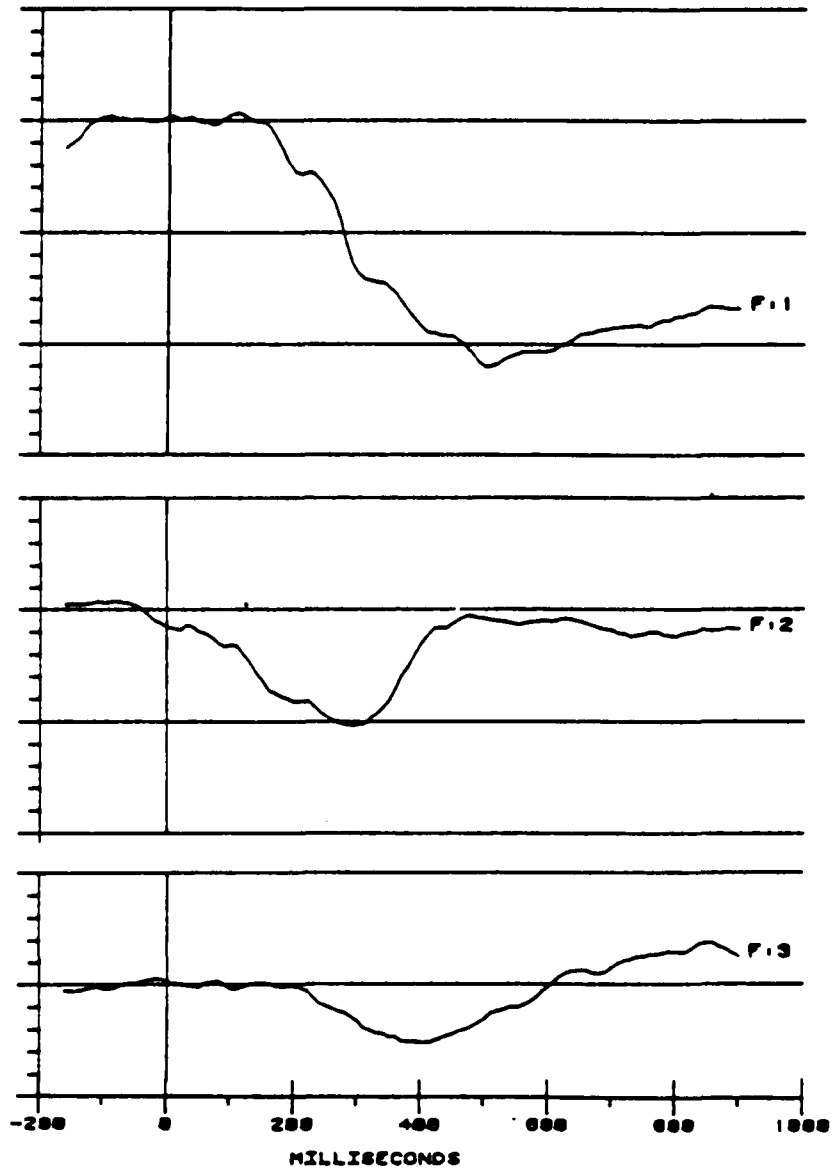
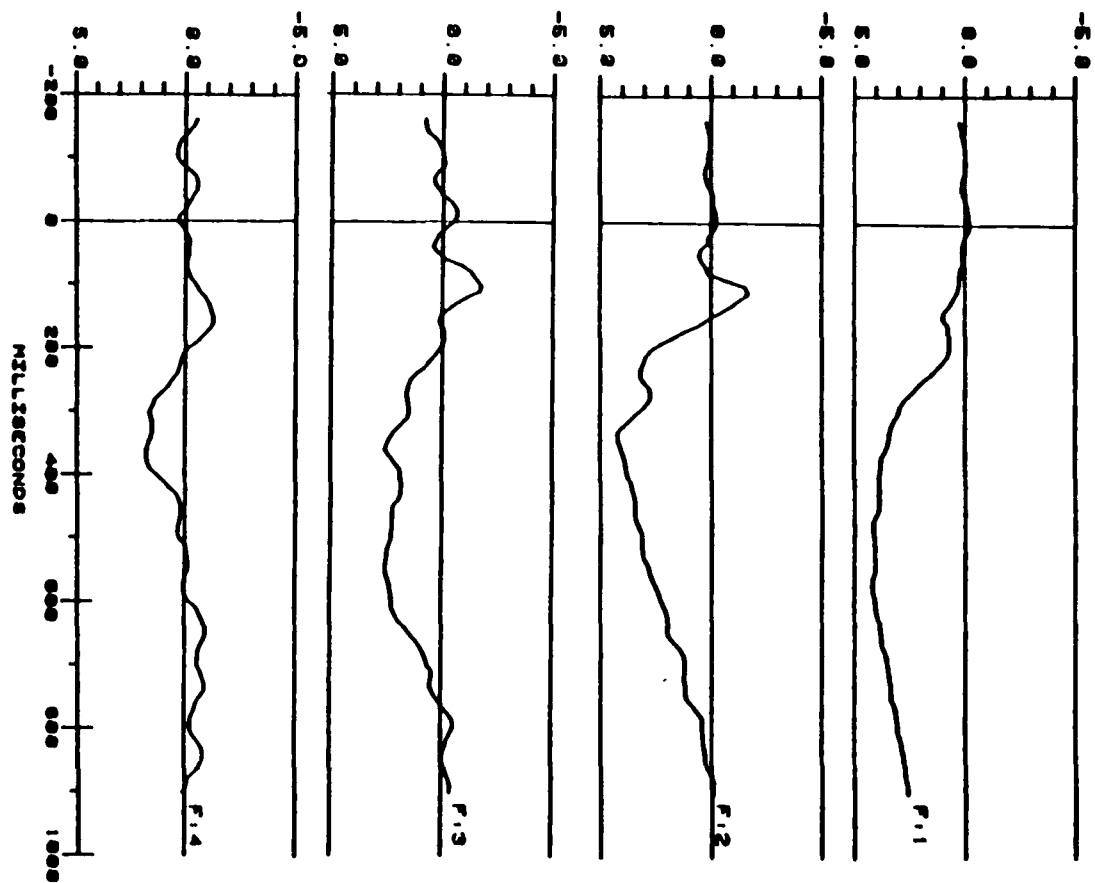


Figure 26. The basis waveforms (rotated factor loadings, microvolts) for the adults, for all scalp electrodes, for all experimental conditions, for the discrimination stimulus. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV. Stimulus onset occurs at time 0.

ADULT DISCRIMINATION



was most positive at parietal electrodes and most negative at CZ. No other significant findings occurred for Slow Wave. In addition to Slow Wave, three biphasic factors were found. Factors II, III and IV showed early negative processes (100-175 msec) which were followed by positive processes. Factor II showed a positive peak at 350 msec. There was a trend for Factor II to occur largest at CZ. A significant stimulus precedence by electrode interaction occurred with the largest response recorded over the hemisphere contralateral to the lead stimulus. A later phasic positive component (Factor III) peaked at 360 msec. Factor III showed no significant scalp distribution. Factor III was not related to any experimental condition. A final phasic positive component (Factor IV) reached a peak at 375 msec and had a CZ maximum. There was a trend for Factor IV to occur largest to the easy stimuli.

Feedback Stimulus. Figures 27 and 28 show the basis waveforms from the children and adults respectively to the feedback stimulus. These figures confirmed the existence of multiple positive components in each subject group. Each group showed a factor which corresponded to Slow Wave, P300E, P3b and Factor IV in the combined subjects analysis.

The data from the children (Figure 27) showed that Slow Wave was the first factor to emerge. Slow Wave had a peak latency of 300 msec and remained positive to the baseline

Figure 27. The basis waveforms (rotated factor loadings, microvolts) for the children, for all scalp electrodes, for all experimental conditions, for the feedback stimulus referred to the feedback stimulus baseline. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV. Stimulus onset occurs at time 0.

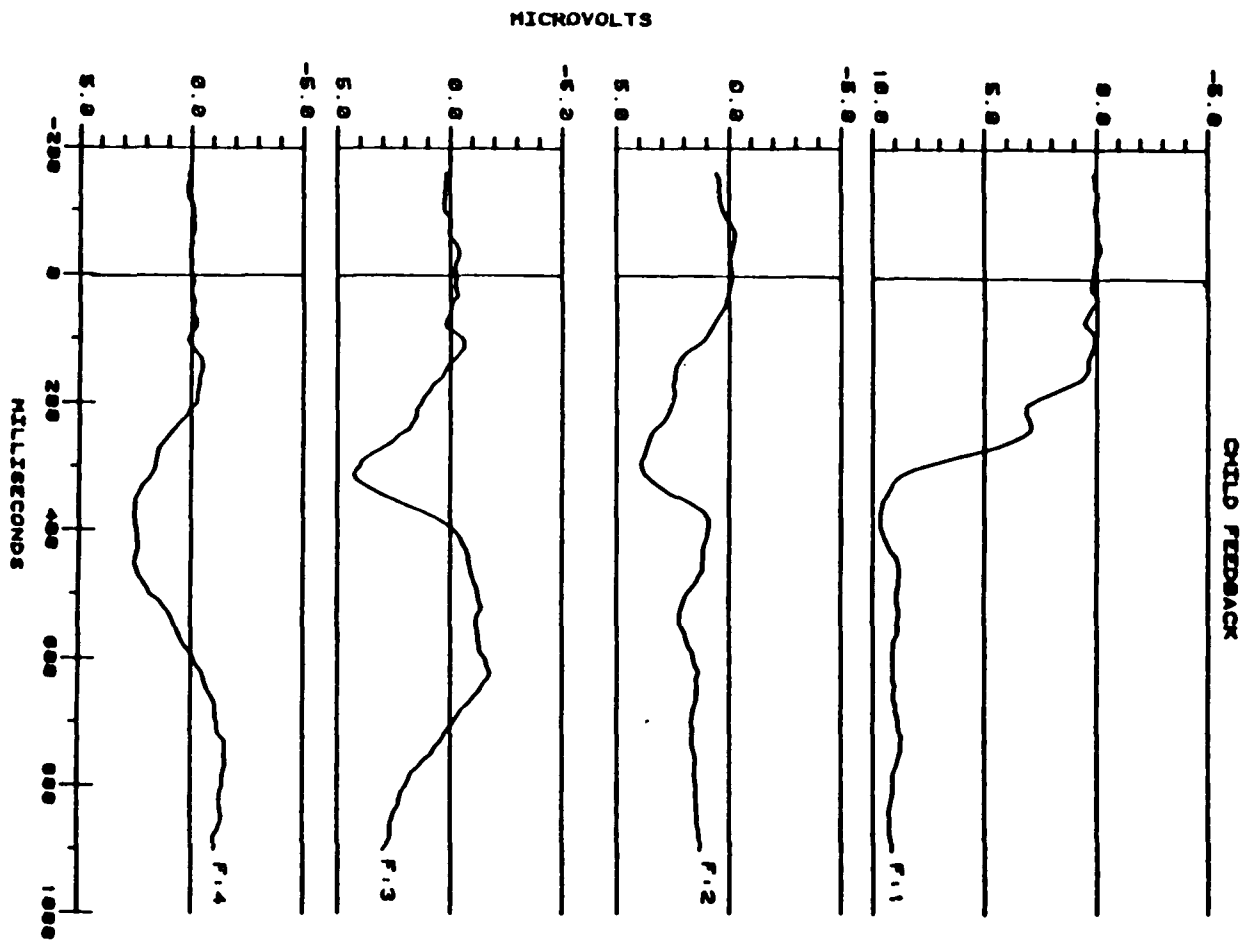
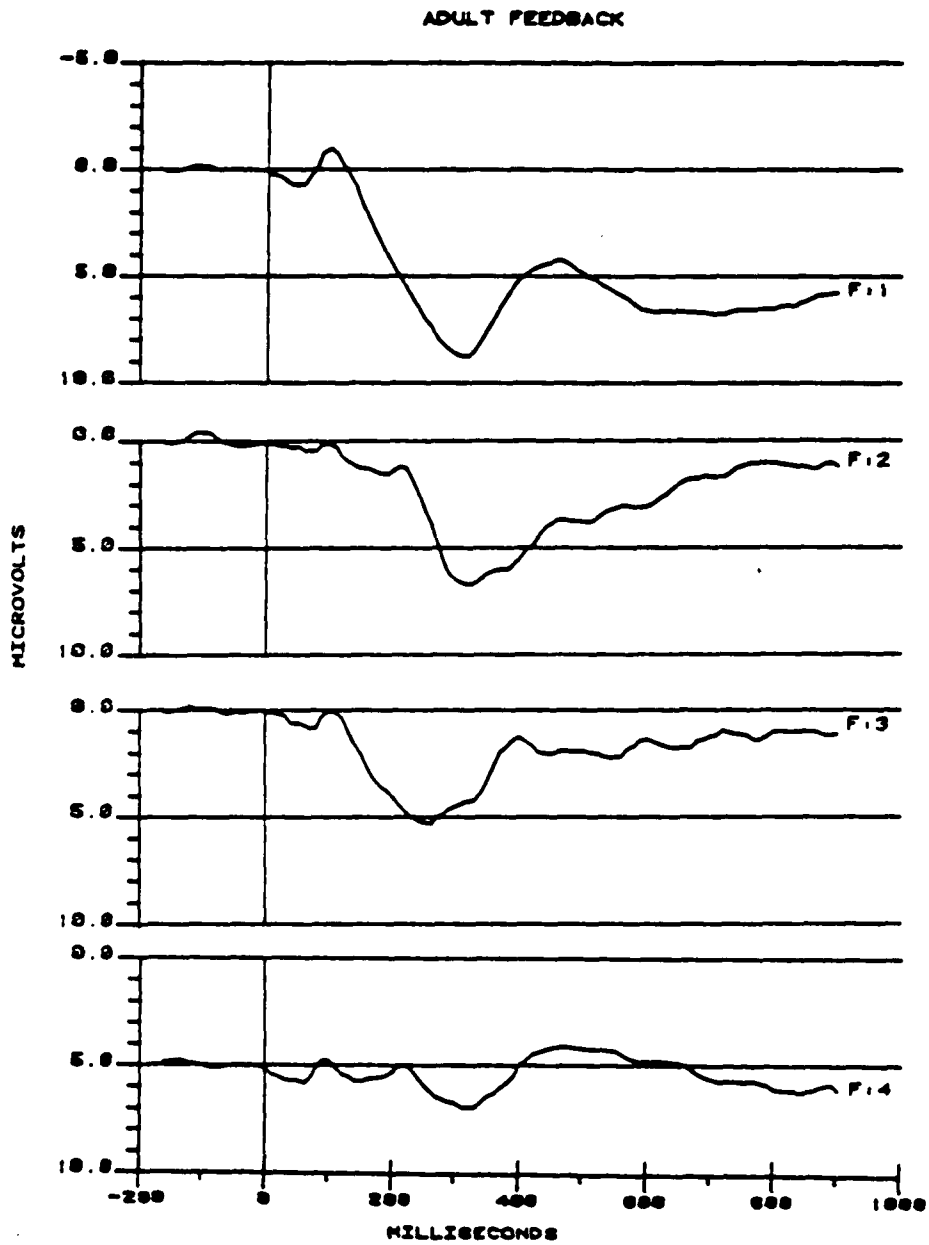


Figure 28. The basis waveforms (rotated factor loadings, microvolts) for the adults, for all scalp electrodes, for all experimental conditions, for the feedback stimulus referred to the feedback stimulus baseline. F:1= Factor I, F:2= Factor II, F:3= Factor III, F:4= Factor IV. Stimulus onset occurs at time 0.



throughout the epoch. Slow Wave was largest at the lateral electrodes and smallest at CZ. Factor II had a peak latency of 300 msec, was largest at CZ, but was not related to any other experimental condition. Factor III had a peak latency of approximately 315 msec, a non-significant scalp distribution and was not related to other experimental condition. Factor IV was a shallow phasic positive component (350-450 msec) followed by a phasic negativity. In addition, Factor IV was most positive over the hemisphere ipsilateral to the lead stimulus or most negative over the hemisphere contralateral to the lead stimulus.

Figure 28 shows that Slow Wave was also the first factor in the adult group. Slow Wave had a peak latency of about 300 msec and remained positive to the baseline throughout the analysis epoch. It had a non-significant parietal maximum. Factor II reached a positive peak at about 300 msec and had a non-significant parietal scalp distribution. Factor II was larger to the more difficult stimulus condition. Factor III was also a positive component, but it reached a peak at 265 msec, was largest at CZ and was not related to any other condition. Factor IV was a positive phasic component, with a trend for a CZ maximum. It was largest over the right hemisphere.

Correlational Analysis

Pearson product moment correlations across subjects were obtained between each ERP factor score and the following behavioral measures: 1) subject hit rate during each experimental condition, 2) age and 3) verbal IQ. In order to minimize the number of correlations performed ($N=156$), analyses were conducted only for the electrode which yielded the maximum factor score loading.

Discrimination Stimulus vs Hit Rate. For the children, a significant negative correlation ($r=-.80$, $p<.01$) between hit rate in the LR hard condition and the amplitude of Factor II emerged, the higher the hit rate, the smaller the amplitude.

Feedback Stimulus vs Hit Rate. No significant correlations emerged between the hit rate and amplitude of any component in response to the feedback stimulus.

TOF Threshold vs Factor Scores. There was a significant correlation ($r=.82$, $p<.01$) in the adults between the temporal order threshold for the RL stimuli and the amplitude of Factor II to the discrimination stimulus in the RL hard condition (greater threshold sensitivity associated with smaller amplitude of Factor II).

Age and IQ vs Factor Scores. No significant correlations emerged between age or IQ and the factor scores.

Correlation of Discrimination and Feedback ERPs. There was a significant positive correlation in the children ($r=.79$ LR hard, $p<.01$, and $r=.97$ LR easy $p<.01$) between the discrimination stimulus Factor II and the feedback stimulus Factor II. For the LR sequence, a larger Factor II amplitude to the discrimination stimulus was associated with a larger Factor II amplitude to the feedback stimulus.

Factor III of the discrimination stimulus and Factor IV of the feedback stimulus were similar in the basis waveform morphology, and they accounted for similar percentages of energy. Therefore, these two factors were correlated in the present analysis. For the children, there was a significant positive correlation ($r=.76$, $p<.01$ RL hard, and $r=.75$, $p<.01$ LR hard) between these Factors for the two epochs. For the more difficult discriminations, a larger Factor III in response to the discrimination stimulus was associated with a larger Factor IV to the feedback stimulus.

SUMMARY
DISCRIMINATION STIMULUS
ALL ELECTRODES

SOURCE	BEHAVIOR MATCH	RANGE MATCH	INTERVAL MATCH	DESCRIPTION	FIGURE
FACTOR I					
AGE	2.01	2.01	2.01	larger in children	7
ELECT	2.01	2.01	2.01	largest at parietal	7,8
(A X E)	2.05	2.05	7.10	larger LM in children larger RM in adults	7
FACTOR II					
ELECT	2.01	2.01	2.05	CZ maximum	7,8
P X E	2.10	2.05	7.10	larger over hemisphere contralateral to lead click	7
(PxExE)	2.10	2.05	NA	larger contra lead click and larger asymmetry in easy cond	9
FACTOR III					
DIFF	2.10	2.01	NA	more + easy less + hard	12
(P X E)	2.05	2.05	2.05	Table 16	
(PxExA)	7.10	7.10	2.10		
AGE	2.05	2.05	2.05	larger - adults larger + child	7

Table 15. Summary of significant findings for the discrimination stimulus, all electrode analysis in the behavioral, range and interval matches.

SUMMARY
DISCRIMINATION STIMULUS
LATERAL DIFFERENCE

SOURCE	BEHAVIOR MATCH	RANGE MATCH	INTERVAL MATCH	DESCRIPTION	FIGURE
FACTOR I					
AGE	<.01	<.01	<.05	larger LH children larger RH adults	7
FACTOR II					
P X D	<.05	<.01	NA	larger over hemisphere contralateral to lead click and larger asymmetry in easy condition	9
FACTOR III					
PREC	<.01	<.01	<.01	BM & RM larger + contralateral to lead click LM for RL larger + contralateral to lead click for LR larger + contralateral to lead click at parietal. more + ipsilateral at central electrodes	
P X A	>.10	>.10	<.01	children: more + RH for RL less difference for LR adults: more - LH	11

Table 16. Summary of significant findings for the discrimination stimulus, lateral difference analysis in the behavioral, range and interval matches.

SUMMARY
 FEEDBACK STIMULUS
 ALL ELECTRODES

SOURCE	BEHAVIOR MATCH	RANGE MATCH	INTERVAL MATCH	DESCRIPTION	FIGURE
FACTOR I					
ELECT	<.01	<.01	<.05	largest at C3	16, 17
AGE	>.10	7.10	7.10		16
FACTOR II					
ELECT	<.01	<.01	<.01	largest at CZ	16, 17
AGE	<.01	<.01	<.01	larger + in adults	16
FACTOR III					
FACTOR IV					
(PREC)	7.10	7.10	7.10		
(P X A)	7.10	7.10	7.10		
P X E	<.05	<.05	7.10	see Table 18	17

Table 17. Summary of significant findings for the feedback stimulus referred to the feedback stimulus baseline in the all electrode analysis for the behavioral, range and interval matches.

SUMMARY
 FEEDBACK STIMULUS
 LATERAL DIFFERENCE

SOURCE	BEHAVIOR	RANGE	INTERVAL	DESCRIPTION	FIGURE
	MATCH	MATCH	MATCH		
FACTOR I					
(AGE)	>.10	>.10	>.10		
(ELECT)	>.10	>.10	>.10		
FACTOR II					
(AGE)	>.10	>.10	>.10		
(ELECT)	>.10	>.10	>.10		
PxExA	<.05	<.01	<.05	RL: opposite direction of asymmetry for adults at central, not parietal LR: no difference at central and parietal, but adults show more asymmetry than children	
FACTOR III					
FACTOR IV					
PREC	<.01	<.01	>.10	RL more - over LH than RH LR = negativity both hemispheres	19
P X A	<.01	<.01	>.10	children: negative all stimuli, but more - for RL with greater - over RH for all stimuli adults: positive all stimuli, but more + for RL with greater + over RH for all stimuli	20

Table 18. Summary of significant findings for the feedback stimulus referred to the feedback stimulus baseline in the lateral difference analysis for the behavioral, range and interval matches.

DISCUSSION

Behavioral Data

The adults showed significantly greater sensitivity on the temporal order threshold task than the children. Previous studies of temporal order performance (Bakker, 1972) have indicated that older children (11 years) show better recall of temporal sequence than young children (6 years). The findings from the temporal order threshold task are supported by the data from the interval match analysis.

The behavioral data do not provide support for Mills and Rollman (1980) who reported superior temporal ordering ability in the left hemisphere. Although the adults showed an advantage in the temporal order threshold for the RL as opposed to the LR stimuli, the effect of stimulus precedence and the precedence by age interaction were not significant. The present data instead seem to support Hammond (1982) who suggested that with respect to temporal processing ability, each hemisphere probably processes information that is specifically directed towards it. Hammond (1982) further suggested that the two hemispheres may be efficient at processing different kinds of information due to a differential rate of information processing ability between them.

It would appear that the behavioral match analysis provided the optimal choice of stimulus parameters in order to obtain two levels of approximately equal difficulty for each group. In the behavioral and range match conditions, the longer Δt (easy condition) yielded a significantly higher hit rate than the shorter Δt (hard condition) indicating that the stimulus Δt s used in this study were appropriate for achieving two levels of stimulus difficulty. In the behavioral match analysis, there was no difficulty by age interaction, suggesting that the two subject groups were adequately matched for stimulus difficulty. However, in the range match analysis, the significant difficulty by age interaction reflects the fact that the adults showed a lower hit rate than the children in the difficult condition. The main effect of age in the interval match analysis reflected the fact that the children had a significantly lower accuracy level than the adults did at the 75 msec Δt .

ERP Results

The major findings of this study involved age and hemispheric differences in the ERP. These findings were obtained from a PCVA analysis of the ERP waveforms from all subjects in the behavioral match analysis. With few exceptions, these findings were consistent across all three types of matches.

The ERP in response to the discrimination stimulus was characterized by three principal component factors: 1) Slow Wave, 2) a phasic positivity in the 300 msec latency region (P350) and 3) N100/P450 (Figure 6). The ERP in response to the feedback stimulus was characterized by four principal component factors: 1) Slow Wave, 2) an early phasic positive component, 3) a later phasic positive component and 4) P450 (Figure 15).

Discrimination Stimulus

Factor I (Slow Wave). Factor I emerged as the first factor in all three analyses. Inspection of Factor I showed that the scalp distribution and morphology of the component strongly suggest that Factor I is Slow Wave. Slow Wave was first identified by Squires et al (1975) in response to attended but infrequently presented auditory stimuli and it has been characterized as a tonic, long duration component with a maximum positive amplitude at PZ and a maximum negative amplitude at FZ (Squires et al (1975); Squires, K, C, Donchin, Herning, and McCarthy, 1977; Friedman et al 1981a; Ruchkin, Sutton, Munson, Silver and Macar, 1981).

In the present study, two major findings emerged for Slow Wave in response to the discrimination stimulus: 1) it was substantially larger in the children than in the adults at all electrode placements, 2) there was a different

pattern of lateralization for Slow Wave in the children and adults. This was a relatively small effect. In the children, Slow Wave was largest over the left hemisphere, and in the adults, it was largest over the right hemisphere. In both groups, Slow Wave was most positive at the parietal electrodes. It was positive at all electrodes in the children, but was close to zero at the central electrodes in the adults. Due to an insufficient number of data channels, FZ was not recorded in the present study.

The functional role of Slow Wave is as yet somewhat unclear. However, several studies in adults (Ruchkin et al 1980b; Ruchkin, Sutton, Kietzman and Silver, 1980; and Sutton and Ruchkin, 1981) have demonstrated that Slow Wave amplitude is directly related to task difficulty, i.e., Slow Wave is larger the more difficult the task for the subject. In addition, Sutton, Ruchkin, Munson, Kietzman and Hammer (in preparation) have shown that Slow Wave is larger under conditions in which subjects are less confident in their decision. Due to its relatively long latency and duration it has been suggested that Slow Wave represents an ongoing evaluative process by the subject, and its amplitude reflects the degree of such processing.

Developmental data on Slow Wave is sparse. Few developmental studies have used experimental paradigms or analytic techniques that have permitted its adequate assessment. Friedman et al (1981a) reported one of the few

studies of Slow Wave in a group of adolescents aged 11-18 years. They reported the same scalp distribution for Slow Wave in adolescents as Squires et al (1975) did in adults. Within the adolescent age range, Slow Wave became less negative at FZ with increasing age. Friedman, Brown, Sutton and Putnam (in press) have indicated that the Slow Wave of children under twelve is considerably more positive than that of older children. This is consistent with the direction of the age related finding reported in this study.

While it may be tempting to suggest that the difference in amplitude of Slow Wave found in the present study between children and adults reflects a difference in task difficulty between the groups, evidence to support this suggestion is tenuous. Evidence against the task difficulty interpretation is derived from the fact that in the behavioral match analysis, the children and adults were matched for detection accuracy (presumably a measure of difficulty). Yet clear age differences in Slow Wave amplitude were found for the behavioral match analysis. In fact, data from the interval match analysis in which the hit rate for the children was about 10% less than the adults demonstrated that the difference in Slow Wave amplitude between the groups was no longer significant; whereas data from the range match analysis in which the adults performed at a 10% lower accuracy level than the children indicated that the direction of the Slow Wave age amplitude difference

(larger for children) was maintained. Additional evidence against the difficulty interpretation comes from the failure of the stimulus difficulty factor (Δt) in the behavioral match analysis to exert any influence (across groups) on Slow Wave amplitude. While there is no clear evidence to support a task difficulty interpretation of the Slow Wave amplitude difference between the children and adults, it is possible that the children had to exert greater effort to achieve the same level of performance as the adults, and this may have been reflected in the Slow Wave. It may be remembered that Friedman et al (in press) also reported larger Slow Wave in children than adults. They suggested that the larger Slow Wave in children may reflect a difference in mode of processing in that group. The present findings confirm their empirical observations, but do not shed any further light on the source of the difference between children and adults.

In addition to the difference in its amplitude between the children and adults, Slow Wave lateralized differently in response to the discrimination stimulus for the children and adults. In the children, Slow Wave was largest over the left hemisphere; in the adults, Slow Wave was largest over the right hemisphere. No previous studies, designed to deal with component overlap, in either children or adults have reported finding lateral differences for Slow Wave. In fact, the majority of studies using PCVA assessment of Slow

Wave were not specifically designed to assess lateralization of components. Kurtzberg et al (1979), however, reported that a late positive component (LPC) (unknown if P300 or Slow Wave or both) in response to detection of a visual target showed a shift in lateralization from the left hemisphere to the right hemisphere (parietal and temporal electrodes) from 10-13 years of age.

Marsh (1975) reported that the same late positive component alluded to earlier (500 msec latency) was significantly larger over the right than left hemisphere for young adults. Unfortunately, it is difficult to draw any firm conclusions or comparisons between Marsh's data and the present study as there is no way of knowing exactly which component Marsh's findings refer to since Slow Wave and P300 continue to overlap even at 500 msec.

Kutas and Hillyard (1980) have demonstrated that a late prolonged positivity in the 400 to 700 msec latency region (probably Slow Wave) was larger over the left than the right hemisphere in an experimental paradigm which required subjects to read words presented within the context of a sentence. The same component occurred with equal amplitude over both hemispheres in response to a warning stimulus and a single word repeated continuously. The authors suggested that the post-300 msec asymmetry might reflect an engagement of the language system of the left hemisphere or might reflect left hemisphere involvement in a more general

extraction of stimulus meaning. Kutas and Hillyard suggested that the tonic slow waves may be more revealing of hemispheric specialization than the more phasic ERPs.

Neville (1980) reported that a late positive component was larger over the right than the left hemisphere from 300 - 1000 msec after the onset of a visual spatial stimulus designed to engage the right hemisphere. There was a concurrent left visual field advantage. This is consistent with the findings for adults in the present study. On the other hand, a letter or verbal (left hemisphere) analogue of the spatial task demonstrated a larger positive voltage over the left rather than right hemisphere 200 msec after stimulus onset. Interestingly, in this case, no significant visual field advantage emerged. Neville (1980) suggested that the observed asymmetries might reflect a different time course of specialized processing for the two tasks.

In summary, the findings for adults in this study of larger Slow Wave over the right than left hemisphere is consistent with lateralized findings reported in the literature for non-linguistic tasks.

In the present findings Slow Wave was not only larger in children than in adults, but was differently lateralized in the two groups. Thus both sets of findings suggest that the children and adults process the task in a different way, although the nature of the processing differences is not clear. A number of studies have demonstrated that ERP

asymmetries of early and late components involve a larger amplitude response over the hemisphere ostensibly engaged in processing stimulus information (Kutas and Hillyard, 1980; Neville, 1980). However, the emergence of an ERP asymmetry has not been validated as a measure of cerebral lateralization of function. ERP asymmetries have been somewhat elusive. The literature contains negative as well as positive findings of asymmetries from studies designed to elicit ERP asymmetries. The Slow Wave asymmetry found in the present study was unexpected and cannot be interpreted in terms of our present knowledge. Although it may be tempting to use the present Slow Wave data to infer that children were processing the task predominantly in their left hemisphere, and the adults predominantly in their right hemisphere, supporting evidence for this inference is not available. However, speculation on the implications of the Slow Wave asymmetry found in this study is suggested below. Adults had a consistently higher hit rate during the behavioral match RL than LR conditions; whereas children had a consistently higher hit rate during the behavioral match LR than RL conditions. Although the differences in hit rate between LR and RL conditions as a function of age are not statistically significant, these data suggest that the adults had more difficulty with the LR stimuli (i.e., had a right hemisphere disadvantage) and the children had more difficulty with the RL stimuli (i.e., had a left hemisphere

disadvantage). It might make sense that Slow Wave Wave lateralized over the hemisphere opposite the ear which received the leading stimulus in the condition which was more difficult and required more processing by the subject i.e., the left hemisphere for the children and the right hemisphere for the adults. In other words, increased behavioral difficulty is associated with greater processing requirements and greater processing requirements means a larger ERP.

It should be pointed out that the rationale used above in the interpretation of the Slow Wave lateralization effect is unconventional. The general approach to interpreting ERP asymmetries has been that a larger amplitude response is indicative of increased processing, i.e., an advantage, not a disadvantage (Kutas and Hillyard, 1980; Neville, 1980). The interpretation of the Slow Wave asymmetry in the present study is that increased amplitude is associated with a processing disadvantage, and that decreased amplitude is associated with a processing advantage. A partial analogy to the present interpretation may be the relationship of alpha activity to hemispheric activation. Lower amplitude EEG activity (alpha blocking) is generally indicative of increased activation and increased processing load (Butler and Glass, 1976).

In terms of development, the present data suggest that in this task the children were more reliant on right

hemisphere than left hemisphere mechanisms; whereas the adults were more reliant on left hemisphere than right hemisphere mechanisms.

Factor II (P350). A phasic positive component, P350, reaching a peak at CZ approximately 350 msec after stimulus onset, emerged in response to the discrimination stimulus in the behavioral match. This component was largest over the hemisphere contralateral to the lead stimulus. The identity of this late positive component is uncertain. Numerous studies have reported that several late positive components exist in addition to the classical P300 component (Sutton et al, 1965) which is here referred to as P3b. These components include: 1) P3a, Squires et al (1975), 2) Courchesne's novelty P3 (Courchesne, 1978), 3) P300E and P300L (Ruchkin et al, 1981), but P300L is probably the same as P3b, 4) P400 (which may be identical with phasic Slow Wave) (Jenness, 1972; Stuss and Picton, 1978) and 5) P450 (Friedman et al, 1981b). It is not clear, however, the extent to which the various positivities represent unique components. Discussion of the late positive components in the present study will be reviewed in the context of their relationship to experimental condition and to previously identified late positive components.

The present P350 component displayed a maximum amplitude at CZ and a smaller amplitude at the lateral electrodes. The

CZ maximum for this component suggests that it belongs to the family of early phasic positive components P3a or P300E, which respectively have a central or centro-frontal scalp distribution (Squires et al, 1975; Ruchkin et al, 1981).

The latency of Factor II (350 msec) suggests that it occurs too late to be P3a (240 msec) or P300E (225-300 msec) but might be P3b. However, P3b has been shown to have a maximum amplitude at parietal electrodes (Squires et al, 1975) Therefore, according to the combined criteria of scalp distribution and latency, Factor II cannot be definitely identified as either P3a, P300E or P3b. Ruchkin et al, (1981) have indicated that "the failure of the combined criteria of polarity, latency, time course and scalp distribution to definitely identify components pose a genuine problem whose resolution may require extending our concepts of how components are to be defined".

Squires et al (1975) first identified the existence of multiple late positive components within the same ERP waveform. They indicated that an early P3a component (fronto-central scalp distribution, short latency (240 msec)) was elicited in response to ostensibly unattended infrequent stimuli. The amplitude of P3a was directly related to the relative frequency of occurrence of the stimulus. Snyder and Hillyard (1976) reported similar multiple positive (P3a and P3b) components with similar scalp distribution and latency. They suggested, however,

that the necessary condition to elicit a P3a was the deviation of a stimulus from a repetitive background.

Ruchkin et al (1981) reported a phasic positive component (P300E, 225-300 msec latency, central-frontal distribution) in response to a feedback stimulus which conveyed either confirming or disconfirming information regarding a preceeding discrimination. Despite the fact that the P300E component shared the latency and scalp distribution criteria of P3a, P300E was obtained under conditions of active attention and was therefore tentatively differentiated from P3a. The relationship of Factor II in the present study to P300E is unclear since although Factor II was obtained under conditions of active attention, it was obtained in response to a discrimination stimulus, whereas P300E was reported as a response to a feedback stimulus.

P3b or the classical P300 component (300+ msec latency, PZ maximum) was first reported by Sutton, Braren, Zubin and John (1965) in response to infrequently presented but actively attended stimuli. P300 has also become known as P3b after Squires et al (1975) reported finding two late phasic positive components in response to the same stimulus. Amongst the experimental variables known to effect P3b or P300, stimulus difficulty, stimulus probability, and task relevancy remain the most potent (Sutton et al, 1965; Tueting, Sutton and Zubin, 1971; Sutton and Ruchkin, 1981; Kutas, McCarthy and Donchin (1977)). On this basis, it is

possible albeit questionable, that Factor II can be identified as P3b.

The amplitude of P3b is known to be inversely related to stimulus probability (Tueting et al, 1971) i.e., P300 is larger to less frequent stimuli. In the present study, however, the probability of all stimulus conditions were equal (25%) and the sequence of presentation completely random. However, the difference in level of accuracy between easy and hard conditions could have created a difference in amplitude due to the uncontrolled difference in probability of being correct. It is unlikely that stimulus probability played any role in the precedence by electrode interaction of Factor II because the finding was across the easy and hard condition. However, the issues of task difficulty, task relevancy and stimulus value may be pertinent to the significant Factor II findings and may aid in identification of the phasic positive component.

The behavioral match analysis indicated that a precedence by difficulty (P X D) interaction occurred as a trend with regard to the lateralization of Factor II, i.e., the lateralization of Factor II was more marked for the easy stimuli. However, this effect was significant in the range match analysis. The difference between these two analyses is most likely that the range match analysis included a Δt which increased the difference in discriminability between the easy and hard conditions for the adults relative to the

behavioral match. Factor II was larger for the more difficult stimulus condition than for the easy stimulus condition, but this difference did not reach statistical significance. This suggests that Factor II is unlike P3b since it is not related to equivocation in the same direction as reported by Sutton and Ruchkin (1981).

Factor II may not be an endogenous P3-like component, but an exogenous P2 component with an unusually long latency. The present study indicated that the phasic positive component was largest over the hemisphere contralateral to the lead stimulus. Andreassi et al, (1975) have demonstrated that the sensory evoked potential (N2 and P2 measured peak to baseline) is largest over the hemisphere contralateral to a sensory stimulus. Similarly, Botte (1974) reported that the temporal N1-P2 (peak to peak) component was significantly larger at the left than the right in response to dichotic clicks when the right click preceeded the left click. However, no studies have demonstrated a larger response of the contralateral hemisphere for endogenous components, but Krynicki (1976) has indicated that the late positive component is larger and more complex in waveform over the hemisphere presumably engaged in processing stimulus information, i.e., the hemisphere which is more accurate under the given task condition.

The present study leaves unclear whether Factor II is more closely related to an exogenous P2 component or an

endogenous P3 component. However, data on Factor III (the biphasic factor) in response to the discrimination stimulus revealed several findings potentially bearing on this question. Factor III is composed in part of a late positivity in the vicinity of 450 msec. In the range match analysis, a main effect of stimulus difficulty occurred in which a larger positive component was obtained in response to the easy than the difficult stimuli i.e., consistent with Ruchkin and Sutton (1978). This finding suggests that the positive portion of Factor III may represent a P3b type component, and that the positivity of Factor II might be an earlier positive component i.e., an earlier P300 or a P2. PCVA of the data from the children and adults separately suggested that the negative portion of the biphasic factor was present only in the adults, whereas the positive portion was shared by both groups. Therefore, separate PCVAs were conducted on the data from the children and adults in an attempt to clarify the identity of Factor II.

The data from the children and adults analyzed separately showed that each age group showed a component that displayed a significant precedence by electrode interaction in which a late phasic positive component was largest over the hemisphere contralateral to the lead stimulus (presumably equivalent to Factor II above). In both groups, the phasic positivity was largest at CZ. In the children, this component reached a peak at approximately 400

msec, whereas in the adults the component reached a peak at about 330 msec. In addition, the data from the adults revealed the presence of a later phasic positivity (375 msec, CZ maximum) that was responsive to stimulus difficulty in the manner described by Sutton and Ruchkin (1981) for P3b.

The data from the children and adults analyzed separately in addition to the data from the combined groups are difficult to interpret parsimoniously. If it is valid to match and identify components from separate groups according to the combined criteria of scalp topography and relationship to experimental variation, then the children and adults each showed a phasic positive component with a CZ maximum that demonstrated a significant precedence by electrode interaction. The peak latencies of these components were 330 msec in the adults and 400 msec in the children. Courchesne (1977, 1978) has demonstrated that a P2 maximal P3 component decreases significantly in latency from age 7 to 25. (Courchesne (1978) reported no significant changes in amplitude or latency for P2 over the same period of time). The two positive components obtained in the separate PCVAs, which showed the precedence by electrode interaction for the children and adults could have formed a single component (Factor II, Figure 6) in the combined PCVA.

If the preceding interpretation is valid (i.e., the late positive component (Factor II, Figure 6) is an

endogenous component), it leaves three problems unanswered: 1) why did the component have a CZ maximum? 2) why was the component unrelated to stimulus difficulty? 3) why did the component lateralize? Ruchkin et al (1981) have commented on the inadequacy of the existing criteria used to define ERP components. For instance, Sutton et al (in press) have demonstrated a late P3b-like, component, with a CZ maximum, occurring in response to stimulus detection in a two interval forced-choice paradigm. However, it is difficult to identify Factor II (Figure 6) as P3b when it was unrelated to stimulus difficulty, while a later occurring phasic positivity (positive limb of Factor III, Figure 6) was significantly related to stimulus difficulty in the manner described by Sutton and Ruchkin (1981). Even if Factor II is identified as an exogenous component and Factor III as P3b, a third problem remains, i.e., a P3b-like component was found to be lateralized (i.e., Factor III). The evidence to date has not been convincing that P3b lateralizes over either hemisphere (Friedman et al, 1975; Galambos et al, 1975, see Introduction). The more immediate problem however, is how to interpret the precedence by electrode interaction of Factor II. If Factor II is an exogenous component, then the precedence by electrode interaction can be interpreted as a dominance effect of the contralateral sensory pathways (Rosenzweig and Rosenblith, 1950; Botte, 1974; Andreassi et al, 1975). However, if

Factor II is classified as an exogenous component, then the late phasic positivity found in the children (400 msec latency) would also be P2. This is unlikely since at least one other phasic positive component preceded it by 100 msec.

An alternate interpretation of the precedence by electrode interaction of Factor II will be suggested. Several recent studies (Homberg, Grunewald and Grunewald-Zuberbier 1980), have indicated that target stimuli and stimuli which have been assigned a value or incentive for a subject generally yield a P300 component with a larger amplitude than a non-target stimulus or an identical stimulus with less value assigned to it i.e., money. This interpretation received support from Halgren, N. K. Squires, Wilson, Rohrbaugh, Babb and Crandall (1980) and Wood, Allison, Goff, Williamson, and Spencer (1980) who suggested that the P3b component may originate within the limbic system. In the present study, the lead stimulus of each click pair was essentially designated as a target for the subject to attend, i.e., at which ear did the stimulus come first? It has already been shown that unilateral sensory stimulation yields greater activation of the crossed (contralateral) sensory pathways.

Sutton and coworkers have indicated that P300 probably indexes or reflects a post decision evaluation or confirmation by a subject. Friedman has suggested the term

"closure" in reference to the psychologic correlates of P300. It may seem reasonable then that the lead stimulus which has been assigned as a target yielded a larger late positive component over the hemisphere contralateral to the ear stimulated first since the stimulus had greater value for the subject. It remains unclear why stimulus difficulty did not exert any effect.

In summary, Factor II (Figure 6) is probably an endogenous component due to its relatively long latency, and its central maximal scalp distribution is not inconsistent with the CZ maximal scalp distribution reported by Sutton et al (in press) for what was apparently P3b.

Factor III (N100/P450). Factor III has been in part discussed above since its identification might bear on the identification of Factor II. Here, other aspects of Factor III are discussed. Factor III in response to the discrimination stimulus is a biphasic component characterized by an early negative limb (100-300 msec) followed by a later positive limb (300-675 msec). The negative limb was more dominant in the adults than children and is maximal at CZ, (Figure 5), while the positive limb of Factor III was more dominant in children (Figure 7). The main effect of age fell just short of significance but there was a significant main effect of stimulus precedence with regard to the lateralization of Factor III in the behavioral

match, range match and interval match analyses. Factor III was more positive over the hemisphere contralateral to the lead stimulus in both the behavioral and range match analyses. However, in the interval match analysis for the children, Factor III was more positive over the hemisphere ipsilateral to the lead stimulus; whereas for the adults, Factor III was more negative over the left hemisphere regardless of stimulus precedence. The discrepancy between the interval match findings and the behavioral and range match findings cannot be explained on the basis of the present data. The interval match analysis was more difficult for the children than for the adults, but it is not clear why this should shift lateralization as a function of precedence.

Interpretation of a biphasic factor is difficult because it is hard to determine if the different experimental conditions and groups contribute separately to each phase of the factor, or if the different conditions and groups contribute to both phases of the factor. The data from the separate PCVAs of the children and adults suggested that the negative phase of Factor III (Figure 6) was characteristic of the adults, whereas the positive limb was characteristic of both children and adults. The data suggests that the negative limb was more developed in the adults than in the children. However, it did not emerge as a separate factor in the adult PCVA. In addition, the difference between

adults and children reached a confidence level of .017, and inspection of Factor III in Figure 7 indicated that there was virtually no overlap of the groups.

The identity of the negative limb of Factor III is uncertain. At least three negative components within the latency region of 60-300 msec have been identified which may correspond to the negative limb of Factor III: 1) N100, 2) Nd (processing negativity) and 3) Na.

The N100 component of the ERP has a peak latency of 80-120 msec and a frontal-central scalp distribution and is observed in response to auditory stimulation (Hillyard, Picton and Regan, 1978; Hink, Fenton, Pfefferbaum, Tinklenberg and Kopell, 1978; Hansen and Hillyard, 1980). It is an exogenous component of the ERP. N100 has been shown to be sensitive to stimulus repetition rate, i.e., the response to a second stimulus is reduced in amplitude as the interval between paired or multiple stimuli is decreased (Davis, Mast, Yoshie and Zerlin, 1966; Nelson and Lassman, 1968). N100 has also been shown to be related to selective attention, i.e., the amplitude of the component is selectively increased when a stimulus is delivered via an input channel which must be selectively attended (Hillyard, Hink, Schwent and Picton, 1973; Schwent, Hillyard, and Galambos, 1976; Schwent, Snyder and Hillyard, 1976; Hillyard et al, 1978; Hink et al, 1978; Hillyard, 1981). Hillyard and coworkers have suggested that the N100 component of the ERP

might be related to a peripheral gating stimulus selection set mechanism.

Nd (Hansen and Hillyard, 1980) or processing negativity (Naatanen and Michie, 1979) is an endogenous negative component with an onset latency as early as 60 msec and a duration as long as 700 msec. Hansen and Hillyard (1980) demonstrated that in response to auditory stimulation, the onset latency of Nd increased and its amplitude decreased as the discriminability of the eliciting stimuli decreased. Hansen and Hillyard suggested that Nd is related to additional processing of stimuli within a relevant channel. Hillyard et al (1978) and Naatanen and Michie (1979) have suggested that Nd is responsible for the selective attention enhancement effect reported for N100, due to temporal and spatal overlap of the two components.

Na is a negative component with an onset latency of 130 msec in response to visual stimulation. It is related to stimulus complexity and difficulty, perhaps to pattern recognition (Ritter, 1981). If a visual stimulus is masked or made more complex, the onset latency, peak latency and duration of the Na component increases. However, Na has not been reported for auditory stimulation. So that it is unlikely that the negative limb of Factor III is related to it.

At about 100 msec a negative component is seen in the cross subject waveform averages which was largest at the

central electrodes. This component would appear to be an N100 component. However, the basis waveforms (Figure 6) indicated that Factor III included a sustained negativity between 100-300 msec which is largest at the central Presumably N100 did not differ as a function of experimental conditions and therefore did not emerge as a factor in the PCVA analysis. electrodes (Figure 7). The duration of the negativity would suggest that it may be an Nd component. Hansen and Hillyard (1980) showed that Nd was not visible in the conventional cross subject averages, but emerged in difference waveforms. Both Hillyard et al, 1978; and Naatanen and Michie, 1979; suggested that both components occur and overlap in the same waveform. It is therefore likely that the negativity in the present study is a combination of N100 and Nd.

Factor III (Figure 6) was related to stimulus difficulty in the range match all-electrode analysis, and to stimulus precedence and precedence by age in the lateral difference ANOVA in all three matches. The cross subject averages (Figure 5) and the basis waveform distribution (Figure 7) strongly suggest that the negative process was more developed in the adults than the children. This finding cannot be related to the literature as no studies relevant to ERPs in relation to development have been reported for Nd. There have been a few studies which investigated N100 in relationship to age.

Factor III showed a main effect of stimulus difficulty in the range match all-electrode ANOVA. It was more positive for the easy than for the difficult suggesting that the main effect of difficulty involved to some extent the positive limb of Factor III. Although Factor III had a maximum loading at the central electrodes (Figure 8) it was previously suggested that the positive phase of Factor III behaves like P3b, due to the manner in which it relates to stimulus difficulty (see Discussion section Factor II).

There is, however, a problem with identifying the positive limb of Factor III with P3b. In the lateral difference ANOVA (Table 9) there was a significant main effect of stimulus precedence across all three matches, and there was a precedence by age interaction in the interval match analysis. Factor III was more positive over the hemisphere contralateral to the lead stimulus (Figure 8). This effect would also suggest that the laterality effect to some extent involved the positive limb of Factor III or P3b as had been previously suggested. However, lateralization effects for P3b have not been demonstrated in the literature. If the positive limb of Factor III is P3b, then the lateralization effect could be interpreted in terms of the concept of stimulus value, as proposed earlier.

The data from the range match analysis support the findings from the behavioral match analysis in reference to Factor III lateralization. The data from the interval match

analysis showed that for the RL stimuli Factor III was more positive over the hemisphere contralateral to the lead stimulus, whereas for the LR stimuli Factor III was more positive over the contralateral hemisphere only at the parietal electrodes. The discrepancy between analyses is probably related to the differences in difficulty between the groups at the 75 msec Δt .

The data from the precedence by age interaction (Table 9, Interval match) complicate the notion that the lateralization effects for Factor III arise only from the positive limb of Factor III. Factor III was more positive over the right hemisphere in the RL sequence, and marginally more positive over the left hemisphere for stimuli in the LR sequence (Figure 11). The adults showed a more negative Factor III loading over the left hemisphere regardless of stimulus sequence. Although the data from the interval match reflect different levels of difficulty, these data raise the question of a potential involvement of the negative limb of Factor III in the lateralization effect. If this is the case, then interpretation of the lateralization effect becomes extremely difficult due to ambiguity of the phase of the factor involved in the effect.

Feedback Stimulus

Factor I (Slow Wave). The all-electrode and lateral difference score ANOVAs for the behavioral, range and interval matches for the feedback stimulus indicated Slow Wave was the first factor to emerge. The only statistically significant effect for Slow Wave, however, was a main effect of electrode with the largest amplitude at C3. This finding was in contrast with the finding for Slow Wave to the discrimination stimulus where Slow Wave was largest at the parietal electrodes. Ruchkin et al (1981) reported a similar shift in the topography of Slow Wave in comparison of a detection paradigm with a guessing paradigm. For example, when a subject detected the presence of a stimulus, a PZ maximum Slow Wave occurred; however, when an identical stimulus confirmed or disconfirmed a subject's guess, a CZ maximum Slow Wave occurred. It would seem that the feedback role was responsible for the shift in the Slow Wave topography. When the feedback stimulus was referred to the discrimination stimulus, the effect of electrode was not significant. This would suggest that part or all of the central maximal Slow Wave was due to the effect of a resident negativity.

The major findings for Slow Wave in the present study were found in response to the discrimination stimulus and not the feedback stimulus. This finding would seem to support Sutton and Ruchkin's (1981) finding that Slow Wave is related to further processing on the part of the subject,

since the discrimination stimulus required considerably more information processing and effort by the subject than did the feedback stimulus.

~~Factors~~ II, III and IV. Three late phasic positive components in the 300-500 msec latency range emerged in response to the feedback stimulus (Factor II, III and IV) (Figure 15). Despite this, multiple positive peaks could not be visualized in the cross subject averages. This is probably due to the temporal and spatial overlap of the components. The combined criteria of scalp distribution and latency suggest that Factor II might be P300E and that Factor III might be P3b (see below). The identity of Factor IV is unclear.

The data from the separate PCVAs of the children and adults confirmed the existence of multiple positive components in each group. The children and adults each showed a factor that corresponded to Slow Wave, P300E, P3b and Factor IV in the combined subjects analysis.

Factor II (Figure 15) had a peak latency of 300 msec and reached a maximum amplitude at CZ, suggesting that it was P300E. It was significantly larger in the adults than the children, as could be seen in the cross subject averages (Figure 5). Factor II (Figure 27) in the children, was most likely P300E. It had a peak latency of 300 msec, was largest at CZ, but was not related to any other experimental

condition. Factor III (Figure 28), in the adults, was most likely P300E. It had a peak latency of about 265 msec, was largest at CZ and also was not related to any other experimental condition. In addition, Factor III of the adults was larger than Factor II of the children, supporting the age effect in the all-subject analysis.

No previous study has compared ERP differences between children and adults to a feedback stimulus. However, Courchesne (1978) has demonstrated that a PZ maximal P300 component in response to a discrimination stimulus was larger in children than in adults. It is unlikely, however, that the Factor II (Figure 15) component reported here and the P300 component reported by Courchesne (1978) refer to the same component since there are differences in scalp topography and in the nature of the eliciting event. Little is known about P300E. Ruchkin et al (1981) demonstrated that P300E is larger as an evoked as opposed to an emitted potential, but it is not clear how this would relate to the age effect reported here. Several of the late phasic positivities have been shown to be related to stimulus probability (Squires et al, 1975). However, the probability of being correct was the same in the children and adults in the behavioral match analysis. The difference in amplitude of Factor II between the children and adults may reflect a greater ability of the adults to make use of the information provided by the feedback stimulus.

Factor III (Figure 15) had a peak latency of 325 msec and reached a peak amplitude at the central and parietal electrodes suggesting that it is P3b. Factor III did not vary significantly in relation to experimental conditions; but appeared larger to the more difficult stimulus condition. (The main effect of stimulus difficulty did not reach statistical significance, $p=.173$). Factor III (Figure 27) in the children is most likely P3b. It had a peak latency of about 315 msec, a central-parietal distribution and was not related to experimental condition. In the adults, Factor II is most likely P3b (Figure 28). This had a peak latency of about 300 msec and had a parietal scalp distribution. In addition, Factor II was larger to the more difficult stimuli. Campbell, Courchesne, Picton & Squires (1979) demonstrated a similar effect but attributed the larger response to the fact that the more difficult feedback stimulus occurred less frequently.

Factor IV (Figure 15) formed a shallow phasic positivity between 400-500 msec, then crossed the baseline at about 675 msec and remained negative to the baseline throughout the remaining analysis epoch. It appeared largest at C3 but the effect of electrode was not significant. Factor IV showed a significant main effect of stimulus precedence in the lateral difference ANOVA. Figure 19 shows that for the RL stimuli, Factor IV was more negative over the left hemisphere than over the right hemisphere; whereas for the

LR stimuli Factor IV was equally negative over both hemispheres. However, a significant stimulus precedence by age interaction for Factor IV in the lateral difference ANOVA (Figure 20) showed that these findings masked a further effect. For the children, Factor IV was positive for all stimuli, but more positive for the RL stimuli with a greater positivity over the right hemisphere for all stimuli; whereas, for the adults, Factor IV was negative for all stimuli, but more negative for the RL stimuli with a greater negativity over the right hemisphere for all stimuli.

Although this effect was small, it may be related to the difference in detection accuracy between the groups as a function of stimulus precedence (Table 3), i.e., the children had greater difficulty with the RL stimuli and the adults greater difficulty with the LR stimuli in the behavioral match. It is possible that the feedback stimulus to the more difficult condition resulted in a waveform with increased positivity.

Feedback Stimulus Referred to Discrimination Stimulus Baseline

When the feedback stimulus was referred to the discrimination stimulus baseline, a slow DC shift emerged (Factor II, Figure 21). This DC shift was negative at the

central electrodes and positive at the parietal electrodes. The shift was maximally negative for the children at CZ and C3 and positive or absent elsewhere. In addition, the DC shift was significantly more negative over the left hemisphere for the children; whereas it was of equal amplitude over both hemispheres for the adults.

Previous investigation by Rohrbaugh, Syndulko & Lindsley (1976) has identified two distinct negative baseline shifts in a CNV paradigm over a four second time base. An initial negative component occurs 500 msec after a warning stimulus. This shift is maximal at FZ, reduced in amplitude at CZ, and absent or positive at PZ. In contrast, a later negative component occurs 1.5 sec prior to an imperative stimulus. This later component has a CZ maximum with a reduced amplitude at FZ and PZ. The later negativity is significantly larger over the hemisphere contralateral to the responding hand. In addition, there is a significant negative correlation between reaction time and the late CNV component amplitude suggesting that the late component reflects a process of response preparation.

In the present study, the fixation light and discrimination stimulus served as warning stimuli in an analogy to a CNV paradigm, whereas the offset of the fixation light served as an imperative stimulus for the subject to respond. The feedback stimulus was delivered two seconds after the offset of the fixation light. The

lateralization of the DC shift over the left hemisphere in the children (all right handed), and the CZ maximum suggest that the DC shift obtained in the present study is the later negativity reported by Rohrbaugh et al (1976). It is not clear why the DC shift did not lateralize in the adults (also right handed).

Finally, Picton, Campbell, Baribeau-Braun and Proulx (1978) have demonstrated that when subjects are required to attend to a prolonged sequence of auditory stimuli, a sustained cortical negativity accompanies the ERPs until the subjects detect a target, after which the negativity subsides. This tonic shift is twice as large at frontal compared to parietal scalp. Picton et al suggested that the increased negativity might be related to increased cortical activity of thalamocortical or corticocortical projections; however, they also indicated that the function of the CNV is not well understood. It is possible that the baseline shift in the present study is related to the negativity described by Picton et al (1978).

Conclusions

Discrimination Stimulus

The present study has demonstrated that in response to dichotic click stimuli of equal sensation level and

perceptual difficulty that require a discrimination of temporal sequence, Slow Wave was larger in children than adults. In addition, Slow Wave was larger over the left than right hemisphere in children, and was larger over the right than left hemisphere in the adults. It was suggested that Slow Wave was largest over the hemisphere which received the lead stimulus in the condition which yielded the lowest accuracy level. It was not clear how to interpret the difference in amplitude of Slow Wave between the children and adults.

The P350 component in response to the discrimination stimulus was largest over the hemisphere contralateral to the ear which received the lead click. It was suggested that the asymmetry may reflect the fact that the lead stimulus was designated as a target event since target stimuli are known to result in late positive components with increased amplitude. This asymmetry would seem to support Babkoff's model of temporal order processing which predicted a largest amplitude response over the hemisphere in which a lateralization judgment was made. However, it has not been established that detection of the lead stimulus is sufficient for temporal order perception.

The N100/P450 (biphasic) factor is difficult to evaluate since one cannot be certain as to which phase of the factor the findings apply. The biphasic factor was largest to the easier stimulus condition suggesting that it responded as a

P3b component. In addition, for the children, the biphasic factor was more positive over the right than left hemisphere in the RL sequence and marginally more positive over the left than right hemisphere in the LR sequence. The adults showed a largest negative loading over the left hemisphere regardless of the stimulus sequence.

Feedback Stimulus

Slow Wave showed a more central scalp topography to the feedback stimulus than to the discrimination stimulus (which showed a parietal topography). This finding confirmed a similar effect found by Ruchkin et al (1981). The shift in topography may be related to differential processing requirements of the two tasks.

P300 was larger in the adults than in the children. It was suggested that the adults may extract more information from the feedback stimulus than the children.

P450 showed a complex interaction of stimulus precedence, age and hemisphere that remains to be clearly interpreted.

Finally, a DC baseline shift occurred between the discrimination and feedback stimuli. This baseline shift may have been related to the subjects' manual response.

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