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Probe Event-Related Potentials During Language Processing in Children: A Comparison of Resource Allocation and Stimulus Set Models of Attention

by

Albert John Johnstone

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Psychology

in the

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of the

UNIVERSITY OF CALIFORNIA

San Francisco

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Probe Event-Related Potentials During Language Processing in Children: A Comparison of Resource Allocation and Stimulus Set Models of Attention

Albert John Johnstone

University of California, San Francisco

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iii. ABSTRACT

Regional brain activity during complex tasks can be "probed" by recording ERPs to brief repeated task-irrelevant stimuli. The ERPs vary as a function of the concurrent task. The mechanisms by which the concurrent task modifies the response to the probe stimulus were investigated in the present study.

Since probe stimuli are irrelevant to the primary task at least some of the ERP modulation was thought to be due to selective attention. Two models of selective attention mechanisms predicted opposite results when the degree of competition between probe stimuli and the primary task was varied. In this study, auditory and visual sensory modalities were defined as channels and responses to probe stimuli presented to the two channels were compared as a function of stimulus channel of the concurrent language task. The tasks were silent reading (visual channel) and listening to text (auditory channel). This approach allowed inferences concerning whether probe responses reflect actual competition for neuronal subsystems, or filtering mechanisms operating on the basis of stimulus set. Attenuation of responses to stimuli in the same modality as the task was predicted by the "resource allocation" model and the opposite was predicted by the "stimulus set" model.

Broad peripheral flashes and tone-pips were presented alternately at one-second intervals during the tasks. A

control condition requiring direct monitoring of probe stimuli was included ("probe-attend"). Fifteen 10-12 year old boys served as subjects. A priori predictions were made regarding ERP components known to be affected by attention: auditory N100, recorded at the vertex, and visual P100, recorded in the parietal region, referred to linked ears. It was found that the auditory N100 peak was significantly smaller in listening than reading or probe-attend and that the visual P100 peak was significantly smaller in reading than in listening or probe-attend. No significant latency differences were found among tasks for either probe modality. It was concluded that a resource allocation model most adequately explained the task-dependent attenuation of ERP components studied. Possible effects of masking were considered and rejected. The predictions of the stimulus set model were clearly disconfirmed.

I. INTRODUCTION

The application of sophisticated new technologies in the neurosciences to the study of specific detailed models of mental functioning holds great promise for advances in understanding brain-behavior relationships. For example, recent developments in the measurement and analysis of brain electrical activity provide a means for examining neurophysiological events which accompany human information-processing.

Two strategies for the use of event-related potentials in the investigation of brain mechanisms underlying cognitive processes are available. One approach requires subjects to cognitively process briefly presented stimuli. An alternative approach involves presentation of irrelevant stimuli during the concurrent performance of a task. Responses to the task-irrelevant stimuli are modified by on-going brain activity and are "probes" of regional brain processing. Donchin et al. (1977) state "The more direct strategy adopted by most investigators is somewhat weak because the choice of differential tasks is dictated by the requirement that they provide distinct stimuli for eliciting ERPs. The probe strategy permits the choice of tasks which are continuous in time and with a potential for substantially loading the hemispheres" (pg. 236). Hillyard et al. (1978) concur with Gibson (1966), Neisser (1976) and Donchin et al. that a "satisfactory theory of human

perception can hardly be established by experiments in which subjects are exposed to stimuli so simple that they are irrelevant to the conduct of normal life.." (Hillyard et al., 1978, pg. 226).

The present study was designed to investigate mechanisms underlying brain electrical potentials elicited by background "probe" stimuli during complex information-processing. Specifically, responses to probe stimuli were examined where the degree of competition between probe stimuli and the primary task for neuronal systems was varied. This approach allowed inferences concerning whether probe responses are a function of actual competition for neuronal subsystems, or whether responses reflect the presence of filtering mechanisms operating on the basis of stimulus set. In this study, auditory and visual sensory modalities were defined as channels and responses to probe stimuli presented to the two channels were compared as a function of stimulus channel of the concurrent language task.

In the following review, I first discuss literature on the use of probe-ERPs with emphasis on how changes in ERP components have been interpreted. Second, after a brief review of the extensive behavioral and electrophysiological literature on selective attention, two alternative models for probe-ERP modulation will be outlined. It will be argued that although most probe-ERP studies presume that responses

are modulated as a result of competition for specific neuronal aggregates ("resource model"), an extensive literature on ERPs and selective attention suggests the presence of gating mechanisms operating on the basis of stimulus set ("stimulus set" model). Gating mechanisms may operate at many levels of the nervous system and may act as filters to protect against overload or increase the signal to noise ratio. It is proposed that a comparison of within vs. between channel effects* is essential in resolving which of these models most accurately represents the mechanisms underlying responses to probe stimuli.

II. LITERATURE REVIEW

A) Use of Probe-ERPs

The probe-ERP technique has been used in a variety of experimental situations. In general, modulation of probe responses has been examined as a function of how active a region is predicted to be. The types of studies which have used probe-ERPs can be grouped as primarily concerned with 1) selective attention, 2) functional differences between the cerebral hemispheres, and 3) language processing. These categories represent different approaches to making predictions about regional activity. These categories are

*The terms within- and between-channel are used interchangably with same- and cross-channel (or modality) or intra- and inter-channel.

clearly related, yet the particular issues emphasized and specific methods employed in these types of probe studies are sufficiently different to consider them under these general headings. As will be evident from the following review, there are also considerable differences among studies within each category.

1) Attention

There are a number of early evoked potential experiments which used the basic probe method (i.e., presenting task-irrelevant sensory stimuli during performance of a complex task), in studies of attention, but did not use the concept or the term "probe" stimulus. Task involvement was considered merely as a distraction, and no quantitative analyses were performed to evaluate how the amplitude or latency of specific event-related potential components changed according to the type of task being performed. In fact, many of these studies were carried out prior to the availability of averaging computers and rely on visual inspection of superimposed single trial tracings. Since these studies have been reviewed in Tecce, 1970, only those studies most directly relevant to the current use of probe-ERPs will be considered here.

In an early evoked potential study, Guerrero-Figueroa & Heath (1964) electrically stimulated centromedian thalamic nuclei and obtained single trial recordings from hippocampal

electrodes during relaxation and mental arithmetic in a schizophrenic (catatonic) male. They noted no change in the amplitude of peaks occuring less than 200 msec after suprathreshold stimulation but report attenuation of a large "secondary component" (surface positive) occuring between 300-500 msec after stimulation during solution of an arithmetic problem. Averaged responses to auditory stimuli (80 db, at a rate of 1/15 sec) were also obtained from the mesencephalic reticular formation in the same patient during mental calculation and rest. In this situation, both early and late components were attenuated during the task compared to rest. With combined auditory and visual stimuli, attenuation was obtained from both the mesencephalic reticular formation and from visual cortex during mental arithmetic. No statistical evaluation of these results was presented.

However, Rodin, Zacharopoulos, Beckett & Frohman (1964) noted no change in the scalp-recorded visual evoked response during mental calculations compared to passive stimulation. Recordings were made from occipital-parietal bipolar scalp montages in a group of 10 schizophrenic patients. Again, no quantitative analyses were carried out.

Ervin & Mark (1964) reported task-related attenuation of responses in 24 patients treated for intractable pain. Responses evoked in the medial thalamus by regularly presented mild tapping stimuli were reduced during mental

arithmetic compared to counting stimuli. Ciganek (1964) reported a similar finding in a single subject using OZ-PZ scalp responses to paired flash stimuli. Responses obtained to the second member of the pair appeared to be larger when subjects counted stimuli compared to solving an arithmetic problem. No comparison of the two flashes in the pair was reported as a function of task engagement. Hernandez-Peon informally reported decreased amplitude of single-trial flash evoked potentials recorded from indwelling electrodes in the optic radiations during arithmetic computations and conversation in several patients (reviewed in Hernandez-Peon, 1966).

Eason, Aiken, White, & Lichtenstein (1964) report a series of experiments using various "distracting" tasks while subjects watched a flash stimulus at a distance of approximately 3 feet. The stimulus repetition rate varied between subjects and/or experimental runs, but was on the order of 4-7 flashes/second. An occipital electrode was placed 1 inch above the inion and 1 inch to the right of midline, with ipsilateral ear reference. Certain runs were done on only one subject although as many as 7 subjects were used in some runs. Subjects were either the authors themselves or associated lab personnel. A general trend was noted for active task conditions including visual, auditory, and kinesthetic imagery, memorizing, digit recall, mental arithmetic, lifting a weight, and squeezing a dynamometer to show higher response amplitudes (no specific peaks were

measured) than during relaxation conditions. This study included no statistical tests so that the significance and reliability of these results are unclear. Further, the use of non-naive subjects may have contributed substantially to the effects reported (Tecce, 1970).

Gross, Begleiter, Tobin, & Kissin (1965) studied the auditory evoked response to clicks in 11 subjects while reading compared to counting stimuli. Clicks were presented at 90 db every 1.55 second. Recordings were obtained from an electrode placed between C3 and T3 referenced to linked ears. The type of reading material used was not stated. Four peak-to-trough amplitudes were examined: P30-N60, N60-P100, P100-N160, and N160-P220. All four amplitude values were significantly larger during counting stimuli than during reading (t-tests uncorrected for multiple tests). No significant latency effects were found. However, it is not clear from the data presented how these measures correspond to the commonly reported vertex-maximum N100 component which presumably would be easily measured with this type of stimulus and recording procedure. Comparison with other studies is thus problematic.

Spehlman (1965) attempted to "shift attention over wider ranges than those that might be expected to result from experimental procedures" by engaging subjects in complex tasks. Although only brief consideration was given to these findings and no quantitative analyses were

performed, no clear change in visual evoked potentials recorded from the occiput to ear reference was found during listening to text compared to passive stimulation.

Shevrin & Rennick (1967) presented tactile stimuli during performance of duration estimation, mental arithmetic, and free association tasks with twelve pairs of twins. The stimulus was a mild, repetitive tap to the right index finger delivered by an automatically regulated stylus. Recordings were made from left and right parietal electrodes referenced to FPz. Apparently only contralateral responses were evaluated. Trough-to-peak measures between approximately N50 and P110 showed significantly larger excursions during estimation of interstimulus intervals than either mental arithmetic or free association conditions. In addition, the latency of a late positive peak significantly increased from approximately 500 msec in the arithmetic and free association conditions to 670 msec in the duration estimation task.

Tecce (1970) informally reported some findings on visual evoked potentials recorded during letter discrimination compared to visual fixation. A photostimulator was placed six inches from the fixation point for both conditions. An increase in visual evoked potential amplitude was noted but recording configurations and component specificity were not discussed.

Gerbrandt, Spinelli, & Pribram (1970) studied visual

attention in the monkey in a series of four experiments. The first peak of striate cortex responses to direct electrical probe stimulation (approx. 1 mA) of the lateral geniculate body was found to be larger when the monkeys engaged in visual search than when the stimulus field was limited by placing the animal in an enclosed box. It is important to note that the nature of the probe stimulus was non-physiological and quite different from the sensory stimuli used in other probe studies. These investigators also examined "recovery cycles" as a way of indexing level of cortical activation. Slower recovery (return to the size of the previous response) was anticipated when a region was activated as a function of either visual attention or direct electrical stimulation. A slower rate of recovery was observed when inferotemporal cortex was simultaneously stimulated. However, this slower recovery was not slowed further when the animals were allowed to search the visual field concurrently with direct stimulation. Thus there appears to be a summation of effects for inferotemporal stimulation and visual attention resulting in "saturation" of the recovery cycle: Monkeys appear to have been too visually alert in certain conditions for inferotemporal stimulation to have had any additional effect on recovery time.

Hink and Hillyard (1976) employed auditory probe stimuli during selective listening to dichotic speech messages. Synthesized phonemes sounding like the vowel "ah"

were superimposed at random intervals in passages of text. Auditory ERPs to the superimposed stimuli were recorded from vertex and sites lateral to C3 and C4, referenced to right ear, as 10 subjects listened to competing stories presented to each ear simultaneously. Subjects were instructed to monitor these meaningful, connected speech passages and were tested for comprehension and recall. Complex effects of masking and attention were found. In brief, substantial enhancement of P1-N1 and N1-P2 amplitudes were found when subjects were instructed to attend to the channel (ear) in which the probe stimuli were presented. The mean asymmetry of ERP response between attended and non-attended channels in the attention conditions was nearly twice that found during stimulation without instruction for comprehension. Unfortunately, no components later than 200 msec. were evaluated. Thus, both the Gerbrandt, et al. study and the Hink & Hillyard study report increased amplitude of the within-channel probe response with increased attention. These results are compatible with a filter model or selective excitation of a particular channel.

Woods & Hillyard (1976) employed a similar procedure in a study of attention on early ERP components generated subcortically. Rapid clicks (rather than the synthesized phonemes used by Hink & Hillyard, 1976) were embedded in competing passages and delivered to both ears simultaneously. Brainstem evoked responses during attention conditions were compared to a passive stimulation condition.

No effects of selective attention were found for any auditory component originating subcortically (Waves I-VII). The authors point out the possibility of a frequency-specific mechanism attenuating speech frequencies, accounting for the perceptual effects of attenuation of the message in the non-attended ear, with no accompanying change in the brainstem response to higher frequency clicks. Further discussion of filtering mechanisms may be found below in the section on selective attention studies, under "Filter and Stimulus Set Models".

2) Hemispheric Asymmetries

Galin and Ellis (1975) used the probe-ERP procedure with humans in a study of hemisphere specialization. They presented visual stimuli at 3 sec. intervals as six subjects performed visually guided tasks: writing and block design. They noted a positive relation between task dependence of EEG alpha asymmetry and ERP power asymmetry in the 100-350 msec. range at temporal and parietal leads, referenced to vertex. The relation between alpha power and peak-trough measures at temporal derivations was particularly striking. Alpha asymmetry was positively correlated with the asymmetry of the temporal ERP "early wave" (approx. 100-140 msec.), $r=.79$ ($p<.05$); whereas a negative but non-significant correlation was found for the asymmetry of the temporal "late wave" (approx. 250-280 msec.), $r=-.43$. The difference in signs of correlation with alpha implies that these

components were inversely asymmetrical. The functional significance of this finding is not clear and was not addressed by Galin and Ellis. The finding of parallels between EEG alpha asymmetry and ERP asymmetry was interpreted as evidence that both of these indices reflect hemisphere specialization for the cognitive tasks employed. This study was particularly useful in that it established that performance of these tasks was accompanied by differential activation of particular brain regions on the basis of EEG findings and then showed that the probe-ERP was similarly task-dependent. No other study using probe-ERPs has demonstrated that an area is active by techniques other than probe-ERPs, and compared probe responses to other measures, i.e., validating that the probe response is sensitive to regional activity. Unfortunately, only EEG alpha asymmetry vs. ERP asymmetry was quantitatively analyzed.

Mayes and Beaumont (1977) attempted a replication of Galin & Ellis. However, the recording procedures and dependent measures were not comparable to those employed by Galin and Ellis. Bipolar recordings, O1-P3 and O1-P4, were used. No control over eye movements was maintained, nor was EEG alpha analyzed. Therefore the experiment does not constitute a replication of Galin & Ellis (1975). They report no systematic hemispheric differences to visual probe stimuli presented during writing and block design tasks. They did find task differences in probe-ERPs bilaterally:

the writing task yielded greater amplitude for the N1-P2 component than did the blocks task.

A second study by Beaumont and Mayes (1977) modified the previous recording procedures and analyses. The electrode montage was changed so that 10 subjects had C3 and C4 recorded to vertex reference and another 10 subjects had P3 and P4 referenced to vertex. Peak amplitudes and latencies were used as dependent variables. The method of stimulus presentation was also changed from two flashing light sources placed on either side of the subject to an illuminated screen placed 10 cm in front of the subject. Different tasks were used: Subjects were required to analyze auditory and spatial properties of individual letters embedded in familiar nursery rhymes. Again, no task by hemisphere interactions were found, although considerable asymmetries were found independent of task, particularly in the latency of later peaks. In addition, higher amplitude was found for the spatial task bilaterally at parietal leads on the 320 msec. peak and longer latency for the verbal task on the 386 msec. peak, confirming that the probe-ERPs were sensitive to some difference between tasks. There is little evidence to suggest that these tasks would elicit differential hemispheric engagement. Use of these type of stimuli also does not make use of the power of the probe method; this could have been a study of responses to these stimuli as task-relevant.

Shucard, et al. have used paired auditory probe stimuli (tone-pips) during listening to music and listening to text conditions in several studies. Shucard, et al. (1977) found higher temporal ERP P1-N1-P2 excursions (referenced to the vertex) on the left side during listening to text, and relatively higher on the right side during listening to music with a group of 12 subjects. When interpreting these results, it is important to keep in mind that bipolar recordings reflect a voltage difference between electrodes. Thus, when a large signal is subtracted from a small signal, the resulting waveform is inverted in polarity compared to when a small signal is subtracted from a larger one. Both text and music listening yielded smaller responses than did a control condition requiring simple monitoring of occasional click stimuli. The interpretation of the asymmetry is complex because the auditory response is largest at the vertex. The increased net response over the hemisphere presumed to be engaged was explained as due to greater voltage differences between the "active" site and the larger amplitude response at the vertex "reference". A smaller response was found over the presumed unengaged side because of greater similarity (i.e., higher amplitude and thus less voltage difference) compared to the vertex. They also found task-dependent asymmetry in amplitude decrement from the first to the second tone-pip: less decrement (reflecting slower recovery, i.e., both responses indicating relatively high levels of activation) in the hemisphere

believed to be more engaged by the task. This finding is consistent with the findings of Gerbrandt et al. (above) who reported that the time needed for recovery was generally greater in "high attentive" states. However, the experimental situations were so different that such a comparison may not be warranted. Shucard, et al. (1981) replicated and extended these findings using a linked mastoid reference with a group of 16 subjects. They found significantly smaller responses from the hemisphere thought to be most involved in the on-going task, confirming the previous interpretation of the apparently "reversed" asymmetry when they used a vertex reference. No reports on recovery cycles were included in this study. It is worthwhile noting that Galin & Ellis also used a vertex reference but with visual probe stimuli, and reported asymmetries in the opposite direction, i.e. smaller responses over the hemisphere engaged by the task. This could be explained if the vertex response were larger than the other leads in the auditory modality but smaller in the visual modality. Another possibility is that vertex responses may have been attenuated in the Galin & Ellis study due to the use of motor tasks.

Shucard, et al. do consider two alternative mechanisms for modulation of probe responses. They suggest that in the engaged hemisphere fewer neurons may be available to respond to probe stimuli, essentially invoking a limited resource model as an explanation for probe-ERPs. Alternatively, they

suggest that the activated hemisphere would better anticipate a sequential relationship resulting in less orienting to the second member of the pair.

Thomas & Shucard (1982) explicitly examined the effects of instructional set on probe-ERPs. Recordings were made from T3 and T4 referenced to the vertex from 12 subjects. Again, tone-pips were superimposed on music, however in one condition subjects were instructed to attend to the probe stimuli and ignore the music and in one condition attend to the music and ignore the probe stimuli. In the probe-attend condition, subjects were required to press a microswitch after silently counting sequences of two, three, or four tone-pairs. In the music-attend condition, subjects pressed a microswitch after detecting the occurrence of a specific recurring melody. Significantly different asymmetries were found between the two conditions for particular peak-trough measures. Within the probe-attend condition, left temporal N1-P2 responses were relatively larger than over the right temporal. There are certain differences in the details of the results in the 1977 and 1982 studies, which make it unclear just what components are reliably affected with this procedure, if any: the greatest asymmetry was seen with tone 1, N1-P2, whereas in their previous work they reported larger hemisphere differences to tone 2. For the music condition, P2-N2 was greater on the right at $p < .06$. This finding is also not strictly consistent with those reported by Shucard et al. (1977) who found the same direction

hemisphere difference for the music condition at $p<.005$ for overall P1-N1-P2 excursion. These authors conclude from the present findings that differential hemispheric processing is not solely a function of the physical characteristics of the probe stimuli. It is not clear whether these findings attributed to endogenous factors are due to attentional differences or the subject's cognitive approach to processing the stimuli. Although some inconsistencies are found across experiments and interpretations are complicated by the use of the vertex reference, the results reported by Shucard et al. generally indicate smaller response amplitudes (for the peaks measured) as a function of predicted hemisphere engagement.

Rasmussen, Allen, & Tarte (1977) carried out an experiment using Shucard's basic paired stimulus procedure, except using visual probe stimuli with a 150 msec interstimulus interval and an interpair interval of 2 sec. Recordings were made from C3 and C4 referenced to ipsilateral ear. The dependent measure was the amplitude difference between a prominent negative peak at approximately 120 msec following the first flash and the analogous peak following the second flash of the pair. Differences in hemispheric asymmetries in this measure were found as a function of carrying out a mental arithmetic task vs. a simple visual vigilance task. They found reduced left hemisphere ERP amplitude during arithmetic as compared to vigilance tasks, consistent with their hypothesis of left

hemisphere processing of arithmetic computations. However, their use of a compound dependent measure makes it difficult to assess the extent to which these findings represent a recovery cycle phenomenon as opposed to overall reduction in amplitude over the left sided leads.

3) Language Processing

Papanicolaou has utilized the probe-ERP paradigm in a study of language processing. Papanicolaou (1977, 1980) presented visual probe stimuli in the central field of vision while subjects performed different types of auditory discriminations (acoustic, phonetic, and semantic) on a constant set of linguistic material. Recordings were made from F7, F8, T3, T4, and midway between T3 and P3 on the left and midway between T4 and P4 on the right. Papanicolaou has analyzed these data for differences between the three experimental conditions and a control condition where subjects were instructed to ignore the auditory material and attend only to the flash stimuli. No significant difference between hemispheres was found for the control condition in contrast to the commonly reported finding of larger right-sided responses to visual stimuli (i.e. Davis & Wada, 1973). Papanicolaou does report significant hemisphere differences (right > left for P1-N1, P1 referring to a positivity at a mean of 92 msec., and N1 to a negativity at a mean of 133 msec.) for the phonetic and semantic conditions across lead pairs. For each lead, the ratios of P1-N1 in each of the

experimental conditions to the control condition were statistically analyzed. Significant attenuation of responses was found only for the phonetic condition at the left frontal placement. No significant enhancement effects were found. Unfortunately, the ratios were not transformed prior to analysis so that the data presented are difficult to interpret. For example, a ratio of 2.00 (double the control condition response) would be considered as 1.00 greater than no change whereas a ratio of .5 (half the control condition response) would be considered as only .5 less than no change. In fact, these hypothetical values should be considered as equidistant from no change in opposite directions. Enhancement effects would appear larger than attenuation effects in this type of analysis. Papanicolaou devotes considerable discussion to the idea of "bilateral divergence", that is, attenuation over one hemisphere and enhancement over the other. His conclusion that moduation of probe responses cannot be due to simple rejection of stimuli (i.e. a stimulus set model) because of the finding of bilateral divergence cannot be inferred based on the data presented. Another serious flaw in this study is that recordings were made from each hemisphere separately. The three available amplifiers were dedicated to recording from frontal, temporal, and tempero-parietal derivations over one hemisphere. However, since the hypotheses and conclusions are related primarily to differences between hemispheres, a more appropriate strategy would have been to record from

both hemispheres at the same time. Thus, for methodological reasons, the findings reported by Papanicoloau in regard to hemisphere differences in language processing must be considered tentative until confirmed. reasons.

4) Conclusion

As is evident from the above comprehensive review, there are many differences among studies which have used the basic probe-ERP procedure. Both animal and human subjects have been employed, stimuli have been presented singly and in pairs, visual stimuli have been presented foveally and peripherally, and recordings have been made from scalp and indwelling electrodes. There is no generally accepted procedure for the recording and analysis of probe-ERPs, as is true with evoked potentials in general. The examination of recovery effects using paired probe stimuli has been carried out in several studies although it is not clear that this procedure is critical to the experimental effects reported.

It is curious that two sets of literature exist: studies carried out prior to 1970, several of which have included intracranial recording and which have been reviewed by Tecce, 1970, and studies carried out since 1970 which rely exclusively on scalp recordings and with few exceptions (i.e., Rasmussen, et al., 1977) do not acknowledge the earlier literature.

The several early studies which have used indwelling electrodes with patient populations uniformly report attenuation of responses as a function of task engagement. These studies are seriously hampered by the lack of averaging techniques, reliance on qualitative analyses, and the use of small numbers of patients with widely varying disorders. However, the effects appear to be quite large: several studies reporting positive findings show figures which indicate greater than 50% attenuation during the performance of some tasks.

Several studies reported prior to 1970 used scalp electrodes. The majority of these studies have found attenuation of responses as a function of task engagement, however two studies report enhancement of responses (Eason, et al., 1964; Tecce, 1970). These latter two studies attribute enhancement effects to unspecified arousal factors rather than selection based on stimulus set, reviewed below. It appears that these enhancement effects are not due to bipolar recording, as is the case with the experiments reported by Shucard, et al., but may be due to the use of non-naive subjects.

The studies carried out after 1970 generally report attenuation of particular peaks as a function of task involvement. These studies have typically examined components at latencies longer than 50 msec. An exception was the study by Woods & Hillyard which measured early

components generated sub-cortically. These investigators report no modulation of brainstem responses due to attention toward the probe stimuli. Guerrero-Figueroa & Heath did find changes in recordings of early components from the mesencephalic reticular formation. However, these early results were not quantified and were obtained from only one schizophrenic patient.

The studies reported by Shucard et al., show modulation of specific peak-trough measures of probe-ERP responses due to task performance. Most other probe studies similarly indicate modulation of particular components, although not always according to a priori predictions (i.e., Mayes & Beaumont, 1977). Many of these studies have methodological disadvantages as discussed above. Nevertheless, using a variety of task conditions, stimulation procedures, recording configurations, subject populations, and measurement techniques, these studies converge on the finding of attenuation of responses to probe stimuli during performance of complex tasks. The mechanism of this attenuation has only been hinted at in the literature. The present study will investigate this issue in terms of theories of selective attention, reviewed below.

As indicated above, there are many differences among studies which employ the probe-ERP paradigm, making it difficult to draw any general conclusions across studies. One apparent common finding is that modulation of responses

to probe stimuli does tend to occur for the P1-N1 component(s) of the ERP. General conclusions regarding single vs. paired stimuli, peripheral vs. foveal presentation of visual stimuli, and interaction of sensory modality of the probe stimulus with the primary modality of the complex tasks are not warranted based on the current literature.

B) Studies of Selective Attention.

Since the behavioral and electrophysiological literature on selective attention is extensive and has been the subject of numerous reviews (Kahneman, 1973; Naatanen, 1975; Posner, 1975; Norman & Bobrow, 1975; Shiffrin, 1976; Broadbent, 1977; Skinner & Yingling, 1977; Picton, et al., 1978; Hillyard et al. , 1978; Kinsbourne & Hicks, 1978; Hillyard & Picton, 1979; Naatanen & Michie, 1979; Wickens, 1980; Navon & Gopher, 1980), only those studies and concepts most directly relevant to the present study will be reviewed here. Emphasis will be placed on 1) filter models, such as the classic early behavioral work of Broadbent and the ERP studies by Hillyard, et al., 2) studies which conceptualized sensory modalities as "channels" in examining selective attention, and 3) behavioral literature on resource allocation models of attention.

1) Filter and Stimulus Set Models

Broadbent (1952; reviewed in Broadbent, 1958) first provided evidence that filtering of sensory input may underly selective attention. He employed a dichotic listening paradigm where different auditory stimuli are presented simutaneously to both ears. The finding that subjects tended to recall information predominantly from one channel (ear) rather than a little from each led to a theory based on channel selection. Broadbent originally supposed that unattended channels were registered in short term memory but were blocked by a selective filter from further processing.

This interpretation was strongly supported by electrophysiological findings in the cat (Hernandez-Peon; 1956). Hernandez-Peon recorded evoked potentials from the cochlear nucleus while animals were presented with visual, olfactory, and somatic stimuli and while animals were relaxed. The cochlear response was decreased as a function of attention and was interpreted as blocked or filtered. Subsequent experiments cast doubt on both the completeness of the interpretation by Broadbent and the validity of the experimental findings of Hernandez-Peon. Behavioral studies in humans (Moray, 1959; Treisman, 1961) showed that words of special importance such as the person's name are detected when presented on the non-attended channel, indicating that these messages are not completely filtered. Hernandez-Peon's study was criticized by Horn (1965) and Worden (1966) on the grounds that the effective stimulus was reduced in the

"attention" conditions due to position of the pinna and contraction of the middle ear muscles. Interest in the stimulus filter model waned following these qualifications and criticisms. Nevertheless, Naatanen (1975) still regarded the study of a selective filtering mechanisms as being "still a basic one in the field as it was some 20 years ago when EP research on human attention was started " (Naatanen & Michie, 1979, pg. 85). He maintained that this question must be addressed before postulating further processes, such as late selection (i.e., Deutsch & Deutsch, 1963).

The idea of stimulus filtering at the periphery has been supported by well-controlled animal studies carried out by Oatman (1971, 1976) and Oatman & Anderson (1977, 1980). These investigators conclude that the olivocochlear bundle (OCB) inhibits auditory input during attentive behavior toward a visual stimulus in the cat. They controlled for effective stimulus amplitude by cutting the tendons of the stapedius and tensor tympani muscles, and by delivering tones through sound tubes held in place at the entrance to the external auditory meatus with a bracket. Simultaneous recordings were made from the round window (cochlear microphonics) and the cochlear nucleus. Suppression of auditory input at the cochlear nucleus was shown using tone-bursts as well as frequency-following.

Lukas (1980) has demonstrated a similar cross-modal

effect in humans at the level of the inferior colliculus. Eight subjects were presented with rapid tone-pips under two conditions: 1) maintaining visual fixation while listening to tone-pip stimuli and 2) mentally counting a projected target letter from an array of five letters while ignoring tone-pips. Tone-pip and letter stimuli were presented asynchronously. Auditory stimuli were presented binaurally with 10 usec rise-fall time at a rate of 10/sec. Letter stimuli were presented for a duration of 100 msec at a rate of 2/sec. A clear reduction in amplitude and increase in latency was found for Wave V of the auditory brainstem potential during visual attention, suggesting a subcortical gating mechanism. No results were reported for Wave II (cochlear nucleus) so it it not possible to make a direct comparison with the results reported by Oatman.

The work of Yingling & Skinner (1976, 1977) implicates central thalamic mechanisms in the gating of sensory stimuli. In a series of studies on cats, these investigators found strong evidence for gating in each of the three main sensory modalities. Gating was modality-specific when discrete regions of nucleus reticularis thalami were stimulated. Generalized gating (both visual and auditory) was found when the inferior thalamic peduncle was cooled to 10° C. These gating mechanisms were shown to specifically involve the action of nucleus reticularis which was shown to be modulated jointly by frontal cortex (selectively

excitatory) and the mesencephalic reticular formation (non-selectively inhibitory). Thus, although there are problems of interpretation of studies which report filtering at the periphery, gating mechanisms have been conclusively shown to be represented centrally. These results are very difficult to confirm in human subjects because of technical problems in making thalamic recordings.

The stimulus filtering model was generally supported by the extensive work by Hillyard's group. However, these investigators found no effects of attention on very early components generated in the afferent auditory pathways (Picton et al., 1971; Picton & Hillyard, 1974). The general paradigm employed presentation of tone-pips with attention directed to one ear (channel) vs. the other. Responses to target stimuli in the attended ear were larger in N100 amplitude than to the same stimuli in the same ear when the other ear was attended. The magnitude of the enhancement was found to depend on stimulus rate and intensity. In a comprehensive review of their work, Hillyard & Picton (1979) conclude: "the electrophysiological evidence reviewed above suggests that there are two distinct modes of stimulus selection, associated with the N1 and P3 waves respectively. These selective processes seem to correspond roughly with Broadbent's (1970) stimulus set and response set modes of attention.... The effects of selective attention upon the N1 wave are most easily demonstrated at high rates of stimulation and at relatively low intensities. This suggests

that N1 indexes a selection process that is brought to bear only when high input rates make it necessary, and then only in an "attenuating" manner, having less effect upon higher intensity stimuli" (pg. 51). Further, no effect of attention was found for components earlier than N1. Hillyard & Picton suggest that there is a filter which operates at a fairly high cortical level, beyond the primary receiving areas. In fact, the results reported suggest that gating is occuring above the level of the medial geniculate and below the generator of N100.

Hansen & Hillyard (1980; see also Hansen, 1981) have provided evidence that N100 modulation is not the result of gating processes. Two experiments in the auditory modality were undertaken. The first experiment involved manipulation of the degree of stimulus contrast between channels. The second study utilized a within vs. between-channel comparison in order to evaluate the extent of processing in non-attended channels.

In the first study, recordings were made from FPz, Fz, Cz, and Pz, referenced to the right mastoid, with 12 adult subjects. Recordings were made first while subjects were instructed to ignore the stimuli and read a book. In the first "ignore" run, standard 300 hz. stimuli were presented at 1 sec. intervals. In a second "ignore" run, randomized high and low tone (400 hz. separation) were presented. Six attention runs followed, with each subject presented with

two consecutive runs with each of three frequency differences between tones: 50 hz, 100 hz., and 400 hz. separation. Low tones were always at 300 hz. Subjects received different orders of presentation of the different frequency separation conditions. The task was to attend to either the high or the low tones, and to press a button when longer duration tones were detected. Standard duration for tones was 51 msec. Longer duration stimuli (102 msec) were presented on 20% of the trials (Bernoulli sequence). Attention effects were analyzed by subtracting ERP waveforms recorded to the shorter duration stimuli when unattended from the same stimuli when attended, point by point. These difference waves showed a broad negativity, termed Nd, due to "processing negativity" during attention conditions. The broad negativity was apparently composed of an early (100-300 msec) and late (300-400 msec) component, although a principal component analysis was not carried out. Larger frequency separation produced earlier Nd waves than smaller frequency separation. The later phase of the Nd appeared to be more frontally distributed than the earlier component. This later component was also more frontally distributed than the N100 evoked during the reading condition (only 1/sec. stimulation condition was analyzed), although waveforms recorded during the reading condition were not shown. The N100 and Nd were different in terms of distribution over time, with the N100 showing a faster rise and fall. On the basis of the sustained character of the

Nd, and the relatively long latency of this wave, it was considered to be endogenous; that is, a non-obligatory response to stimulation. Previously reported enhancement by attention of the N100 was interpreted by these authors as being due to the superimposition of Nd, suggesting that the N100 modulation is not the result of simple gating based on stimulus set, but rather the result of sustained cognitive processing of the stimuli. Of particular interest to the present study, the N100 during reading was found to have different phase relations at different electrode sites. The rising phase was found to be more posteriorly distributed than the falling phase. The authors conclude "Apparently, this exogenous component too does not arise from a unitary generator source." (Hansen & Hillyard, 1980; pg. 287). This study thus calls into question the nature of the modulation of N100 as an indicator of attentive processes. It is not clear whether N100 modulation is due to gating or the superimposition of a "processing negativity" (see also Naatanen, 1982, for a recent review of this controversy).

In a second study (Hansen, 1981), the degree of processing of non-relevant stimuli was examined. In this experiment, three groups of subjects (each n=8) were assigned to different listening task conditions. In each condition, subjects were to react to short duration target stimuli when they were presented in a designated pitch (low vs. high) and/or spatial location (right vs. left). The duration discrimination was difficult for all groups. In one

group the pitch was easily discriminable but the location discrimination was difficult, in the second group, pitch was difficult and location easy, and in the third group both discriminations were easy. ERPs to stimuli which shared or did not share pitch or location attributes of the target were examined. It was hypothesized that if the difference between standard and target was the same to the attended and non-attended sets of stimuli then parallel, non-interacting processing of both classes of stimuli would be supported. Alternatively, if ERP measures of "processing" of non-attended stimulus attributes was not observed, heirarchical processing would be implicated. It was found that failure to share the same level of cue (pitch and/or location) as the designated target tone resulted in attenuation of the "processing negativity" or Nd components. This was noted independently of whether pitch or location discrimination was easy or difficult. These results suggest that processing of stimuli is terminated when the most easily analyzable cue indicating target is detected. Early selection is thus based on analysis of as little information as possible, providing a mechanism for achieving an "economy of processing." The idea of "processing negativity" is most compatible with the resource allocation model.

The present study was designed to evaluate these issues by using the visual and auditory sensory modalities as channels. This maximizes the possibilty of selection based on stimulus set by providing a relatively easy dimension of

stimulus discriminability. Further, a statistical technique (PCA) was employed which may dissociate components overlapping in time on the basis of functional properties.

2) Sensory Modality as "Channel" in Selective Attention Studies

Spong, et al. (1965) studied short-term attentiveness to visual and auditory stimuli presented alternately. Thirteen subjects were instructed to respond to stimuli in one modality and ignore stimuli in the other modality. Three modes of response were compared: vigilance/reaction time to occasional weak stimuli in the given modality, key-pressing after each stimulus in a given modality, and counting stimuli in the given modality. Recordings were obtained from O2, midway between C6 and T4 (i.e., medial to T4) and vertex, referenced to A1. The vigilance and key press conditions both showed enhancement of N1-P2-N2 excursion in the attended modality compared to the same modality in the ignore condition. Data from the counting condition were less consistent. These results also support the idea of stimulus filtering. However, the regular alternation of stimuli presented leaves open the possibility that enhancement of the evoked response was due to generalized anticipatory arousal. This criticism was addressed in similar studies carried out by Naatanen (1967).

Naatanen (1967) carried out a series of experiments in

a cross-modal selective attention study. Three experiments were performed using simple click and flash stimuli. In the first experiment , clicks were designated as irrelevant and 12 male subjects were instructed to react to the second member of a pair of flashes. Clicks were presented either during the time between flashes, presumably a period of high visual attention, and after the second flash, during a relaxation period. Click stimuli were presented either one or two seconds after the warning flash stimulus and either 3, 4, or 5 sec. after the flash requiring a response. No evoked potentials to flash stimuli were obtained.

Fourteen dependent measures of amplitude, latency, and duration were submitted to ANOVA. Although the nomenclature used by Naatanen is rather awkward and mean latencies for each peak are not given, it appears that the principal finding was an increase in the auditory vertex-A1 "P50-N100" peak-to-peak amplitude during the high visual attention period compared to relaxation. Similar findings are reported for the T3-A1 montage. Naatanen interprets these results as representing non-specific attention effects because they were evident on auditory responses during visual attention. He states that "this is probably due to the activation of the reticular formation or non-specific thalamic nuclei with widespread facilitatory effects on the cortex and on the synaptic transmissions of all afferent sensory pathways" (pg. 94). It appears likely that changes in the N1 were confounded with the contingent negative variation which is

elicited in situations requiring that a motor response be held in readiness. The CNV has a widespread scalp distribution and is relatively modality non-specific (cf. Donchin et al., 1978).

Naatanen's second experiment with 5 male subjects involved presentation of visual and auditory stimuli in randomized order with varying interstimulus intervals. One modality at a time was made relevant by requiring subjects to react to occasional weak stimuli in the relevant modality. No significant differences were found in responses to clicks that were relevant vs. irrelevant. Significant effects were found in the visual modality but were attributed to the fact that only half of the recorded evoked potentials could be scored for latencies and amplitudes and thus the much reduced N produced unreliable statistical effects. Further, Naatanen points out that there were probably uncontrolled differences in ocular fixation when the stimulus was relevant vs. irrelevant.

In a third experiment, only the auditory modality was used in order to "avoid difficulties in controlling peripheral conditions". In this case 50 weak and 50 strong clicks were presented regularly at one-second intervals. In one run, weak clicks were designated as relevant, requiring a response and in a second run the reverse was true. Considerably larger responses were found to relevant clicks (either weak or strong) in the same subjects who showed no

effect when stimuli were presented in a randomized order with varying ISIs. It was concluded that selective attention modulation of evoked potentials is largely secondary to non-specific anticipatory and preparatory arousal and activation preceding relevant stimuli.

Schecter & Buchsbaum (1973) required 24 subjects to discriminate and react to different intensities of simple auditory or visual stimuli presented at a rate of 1/sec. Evoked potentials were recorded from vertex-A1 and peak-trough amplitudes from P1-N1 and N1-P2 were scored. It was found that the P1-N1 visual component was larger in visual than auditory vigilance. The P1-N1 auditory component was larger in auditory than visual vigilance. Hillyard & Picton (1978) criticize this study for failing to control for eye position and blinking, as well as for including several other conditions in addition to the vigilance tasks in the data analysis. The only statistical test comparing tasks which is presented is for an overall main effect of conditions. The additional conditions included a no instructions condition, counting stimuli, and a distraction condition (mental subtraction of serial sevens) which could have strongly effected the statistical tests.

Neuerberg & Hillyard (cited in Hillyard & Picton, 1978) also carried out a cross-modal attention study. Random sequences of tones and wide-field low-intensity flashes were presented with varying ISI's at a rapid rate with equal

probability of occurences for the auditory and visual stimuli. Subjects attended to one modality at a time and pressed a lever when occasional stimuli at higher intensity (flash) or pitch (tones) were detected. Vertex and midline occipital responses referenced to A2 were obtained and N1, P1-N1, and N1-P2 amplitudes were measured. For auditory EPs, a large enhancement (approx. 30%) was found for these measures during auditory attention whereas no modulation was found for visual EPs, either at the vertex or the occiput during visual attention. The authors suggest that since visual attention can be directed with peripheral mechanisms (direction of gaze, accomodation of lens), there is less central influence on visual attention.

In brief, a number of evoked potential studies have conceptualized sensory modality as "channel" and have examined the effects of directing attention toward and away from sensory channels. The most severe criticism of these studies has come from Naatanen who showed that the use of regular ISI's results in non-specific preparatory arousal which complicates interpretation of attention effects. Other methodological differences among studies include rate of stimulus presentation, control over eye movements and ocular fixation, and type of statistical treatment of the data. The present study is not subject to the criticism of Naatanen (above) in that attention is not directed toward and away from simple sensory stimuli. Although visual and auditory stimuli were presented alternatively at regular

intervals, both types of stimuli are task-irrelevant. These stimuli are not alternately relevant and irrelevant.

There have also been a number of relevant behavioral studies on cross-modal attention. Studies carried out by Segal & Fusella (1970; 1971), Treisman & Davies (1973); Nilsson, et al. (1977); and Wickens (1980) are of particular interest to the present study because they all show that there is more interference within-modality than between-modality.

Segal & Fusella (1970) studied the effect of self-generated imagery in different modalities on performance of detection tasks in the the same or different modalities. They found that the ability to detect stimuli in the same modality as the imaging was worse than when the detection task and imaging task were in different modalities. Segal & Fusella (1971) confirmed this result and interpreted the effect as due to modality-specific attentional channels. They suggest that there is also a general influence of "central" attention in explaining the effect of familiarity of the item imagined.

Treisman & Davies (1973) found that recall and discrimination performance was improved when words were presented simultaneously in visual and auditory modes, using both sensory channels, as compared with presentation of both words in the auditory modality or both in the visual modality. This suggests that the sensory modalities may be

considered as parallel input channels in a communication-theory sense. They conclude that there is a modality-specific perceptual capacity which cannot be reallocated to inputs in another modality. Wickens (1980) confirmed this result using serial subtraction presented in visual and auditory modality during a concurrent visual-manual tracking task. Greater decrement in tracking performance was found during visually presented arithmetic. He considers modality of encoding as a "dedicated processor".

Nilsson, Ohlsson, & Ronnberg (1977) investigated capacity differences in the storage of auditory and visual input. Results support the idea of modality-specific channels. They contrasted two opposing models as explanations for the finding that auditory sequential memory is superior to visual sequential memory ("the modality effect"). The two models are referred to as one- and two-store theories. The one-store theory is process-oriented and assumes that there is one primary input channel which processes information in a way that favors auditory input. The two-store theory is storage-oriented and suggests that a larger capacity of the auditory as opposed to the visual store is responsible for the auditory superiority.

These investigators carried out a series of experiments comparing one and two store theories. The experiments involved presentation of word lists in visual and auditory modalities for subsequent recall. A larger auditory modality

superiority was found in cases where subjects were not told in advance about the length of the lists. This result was interpreted as favoring the two-store theory since encoding strategies could not be developed on the basis of a particular amount of material to be stored. Subjects simply had to store as much as they could or change strategies based on changing subjective probability estimates. However, a modality effect was still evident when subjects were informed of the length of the list in advance, supporting a one-store theory. These findings were compared in an experiment where mixed lists were used so that subjects must presumably use both stores. In addition, different proportions of auditory and visual items were presented. It was hypothesized that results favoring each theory could be accommodated by a model which postulates both modality-specific stores and a central processor, which manipulates these stores. According to this model, the modality effect will increase as the number of items in the auditory store decreases, given that the limit of the visual store was reached. It was found that recall level reaches an asymptote in the visual modality with a short string of words (i.e., three) while for the auditory store the capacity is larger and recall performance is enhanced. It was proposed that the central processor is dedicated to processing information in both stores but more processing can be carried out on the auditory store since it is larger. Thus, the auditory superiority is postulated to be a

function of both storage and processing. These results are in agreement with Segal & Fusella, Treisman & Davies and Wickens in support the idea of modality-specific channels. This is relevant to the present study which involves both registration (short-term storage) of background sensory input presented through these two input channels while a presumed central processor (in this case a language processor, such as Wernicke's Area) is engaged in visual or auditory language processing.

3) Resource Allocation Models of Attention

Kahneman (1973) has emphasized the concept of limited capacity central processing in explaining selective attention. He claims that the effectiveness of rejection of irrelevant stimuli depends on the amount of capacity demanded by the primary task. Kahneman's model postulates that resources are drawn from a common pool. The model is used to explain interference between two tasks performed simultaneously. According to the single limited-capacity resource pool theory, interference between tasks occurs when their combined resource demand exceeds available capacity. Available resources are not constant, however, and can be increased with increasing arousal (undefined). Two tasks (or more) may be performed without performance decrement as long as spare capacity is not exhausted.

Kahneman (1973) makes the distinction between

structural models and capacity models. "Structural interference between related tasks suggests the image of antagonistic interactions among neural structures, such that a high degree of activation of one structure tends to reduce the levels of activity in others. This mode of organization is prevalent in the nervous system, where it appears in both sensory analysis and in the control of motor output." Effort interference results from two tasks which share capacity but do not share common mechanisms of perception or response. The structural type of interference certainly confounds comparison of effort interference between tasks; it is not possible to predict degree of interference based solely on competing demands for effort or capacity. Similarly, task difficulty must confound studies of structural interference. Kahneman suggests retention of the term "structural interference" for situations involving "strong interactions between similar tasks" and the term "capacity interference" where difficulty is the main determinant of outcome.

Norman & Bobrow (1975) present the influential concept of data-limited and resource-limited processes. They point out that when two or more tasks are performed simultaneously, presumably sharing resources, they may both interfere with one another, neither may interfere with the other, or one may interfere with the other without any interference from the second process to the first. If a given task is "data-limited" (i.e. threshold detection), performance is determined largely by the quality of the

data; increasing processing resources for the task has little effect. Conversely, when the task overloads the subject with an excess of processing demands, performance is said to be resource-limited. They introduce the notion of performance operating characteristics (POCs), which are indicators of the effect on performance on a given task of a second task performed simultaneously. By analyzing the slope of joint performance functions, it is possible to infer whether processes are data-limited or resource-limited (pg. 51). They urge caution in concluding that one process is independent of others (i.e., that the tasks do not require processing resources from the same limited capacity source) unless the entire range of the performance-resource function for the given tasks is examined. The choice of complex language tasks in the present study should not result in data-limited processing.

Navon & Gopher (1979) also rely on performance operating characteristics in their discussion of economy in human information processing. However, they suggest that to get a complete picture of how two tasks are time-shared, various subject-task parameters (e.g., practice) and task preferences must be examined. Interference effects can be presented as a family of POCs. Indeed, they suggest that the main problem with Kahneman's model is a strict reliance on a single resource pool. They argue for a multiple resource model which can integrate "structural" and "effort" interference effects by assuming that discrete channels or

units have their own capacities. Different tasks may require specific resources in particular proportions.

Kinsbourne & Hicks (1978) and Friedman & Polson (1981) similarly reject the idea of a single capacity system and cast multiple resources in neurological terms rather than using computer-based analogies. Kinsbourne & Hicks state that interference effects should be examined in terms of known characteristics of localization of function in the brain. Interference effects are interpreted as reflecting "functional cerebral distance". Tasks which interfere with one-another are said to share a "highly-linked neuronal space [network] of limited extent." These investigators suggest that "control of the right hand, right foot, rightward gaze and voice form one functionally close cluster, and left arm, left leg, and leftward gaze form another" (pg. 349). In general, the within-hemisphere systems are considered to be less distant than between-hemisphere systems and as such are more susceptible to interference effects. In contrast to Kahneman's model, no distinction is made between structural and effort interference.

Friedman and Polson (1981) also regard the two hemispheres as relatively independent resource systems. They view cerebral specialization as a special case of a multiple resources model of limited-capacity information processing. Of particular importance to the present study, they suggest

that the probe-ERP results of Shucard et al. (1977, 1981) provide corroborating evidence that the amplitude of the evoked response "may reflect the amount of resources being used by each hemisphere during tasks that vary in difficulty and can therefore be assumed to require different amounts of resources." The difficulty dimension referred to is the comparison of the baseline condition to the verbal and musical conditions.

4) Conclusion

Three areas of the selective attention literature have been briefly reviewed. One main conclusion is that the idea of stimulus filtering has occupied a prominent position in the history of this field. The early work of Hernandez-Peon was originally criticized for failure to control for peripheral factors. However, more recent studies by Oatman & Anderson, Lukas, and Yingling & Skinner, have revived interest in the filtering model. Hillyard's studies also appeared to support the filtering models based on analysis of N100 modulation with attention. The currently prevailing views seem to have shifted, however, from viewing N100 modulation as a result of gating to the view that superimposition of other components, which may represent cortical processing, accounts for the changes in N100. The superimposition theory has been extensively reviewed by Naatanen (1982). It may be hypothesized that both of these mechanisms operate in different situations, the nature of

the task demands perhaps being a crucial factor. When simple identification of target stimuli is the task, filtering mechanisms may operate, whereas when in-depth analysis of multiple stimulus dimensions is required, as in the Hansen & Hillyard study, on-going cortical activity, reflected by "processing negativity" may play a superordinate role.

The interpretation of sensory modalities as channels has been supported by evoked potentials to a limited extent. The limitations are due largely to methodology, as discussed by Naatanen (above). There is however, a substantial behavioral literature which also suggests that sensory channels are meaningful psychological entities. There generally appears to be more interference in dual processing within a sensory channel than between channels. These findings are the basis for examining within and between channel interactions in the present study.

Finally, there is an emerging literature on the limits of the capacity of information-processing systems. This literature stems largely from the work of Kahneman (1973) on attention and effort, and is now a dominant model in behavioral studies of attention. This model is also increasingly employed in interpreting the results of ERP studies of attention and is consistent with the idea of "processing negativity." The notion of a central pool of resources has been modified by several authors, notably

Navon & Gopher, to include the possibilty of multiple processing resources, each with limited capacity. There is an interesting suggestion from the cross-modal studies reviewed above that both dedicated sub-processors and a central processor may be operative in complex information-processing.

III. RATIONALE AND HYPOTHESES

A) Overview

The review of probe-ERP studies in general suggests that areas presumed to be "active" show less response to probe stimuli. However, none of these studies has directly examined the mechanism of changes in probe-ERP responses as a function of the concurrent task performed by the subject. Attenuation of responses could be due to gating or filtering of probe stimuli based on stimulus set, or alternatively might reflect an actual decrease in available processing resources.

We can test these alternatives experimentally by comparing responses recorded during situations favorable to selection based on stimulus set, i.e., task and probe stimuli in different modalities, with responses recorded during resource-limited situations, i.e., task and probe stimulus competing because they are within the same modality. The general hypotheses tested in the present study are as follows:

B) General Model:

Hypothesis 1: (Based on Resource Model) Given one modality of probe stimulus, if two concurrent tasks differ in their modality of presentation, then the probe response will be smaller when the probe stimuli and ongoing task are in the same modality. This will occur due to competition

for subsystems within-modality. Direct attention to the probe stimuli will result in the largest response in each modality since there is no competition for processing resources. These effects will be best measured on selected components, which in turn will be best measured with specific recording configurations (see below).

Alternative Hypothesis 1; (Based on Filter or Set Model); Responses to probe stimuli in the modality different from the primary language task will be relatively smaller due to recognition of these stimuli early in the processing sequence as irrelevant based on stimulus set. Gating will reduce sensory input in the unselected modality.

These hypotheses were tested on data collected as part of a large study of developmental dyslexia. The subjects used in the present study participated as a normal comparison group. Probe-ERPs were recorded as potential discriminators of normal and dyslexic boys. The tasks studied here include listening-to-text, reading, and attention to probe stimuli. The language tasks differ in modality of presentation but presumably share some common features in that they both involve receptive language comprehension. The use of language tasks will provide a naturalistic task load which is likely to result in resource-limited rather than data-limited performance, as discussed by Norman & Bobrow (1975). This approach has generally not been employed in previous evoked potential

studies of selective attention where attention has typically been directed toward simple sensory stimuli rather than a complex task such as language processing.

For this thesis, recordings from these particular task conditions and electrode configurations were studied solely with regard to the mechanism of probe-ERPs. The data obtained in the large-scale dyslexia study included other tasks, electrode sites, performance data, and spectral analysis of the EEG frequency domain, and subsequently will be used to explore a variety of subject and task dimensions.

For a priori tests, specific montages and components have been selected. For both visual and auditory probe responses, only the components which have previously been measured in probe studies and which have been shown to be related to the attention models of interest were examined, namely, the visual P100 and the auditory N100. For the visual modality, a P4-linked ears montage was employed for two reasons. First, Mountcastle (1978) and Wurtz, et al. (1982) have shown that posterior parietal cortex plays a major role in visual attention in the monkey. Other regions are implicated in attention but perform functions that are not dissociable from guidance of eye movement, i.e. superior colliculus, frontal eye fields. Secondly, there is a substantial clinical literature on neglect syndromes which points to specialized right parietal mechanisms in directing attention (e.g., Heilman, 1978). In addition, the visual

P100 component is probably generated in adjacent peri-striate cortex (Jefferys & Axford, 1972a,b) and is relatively easily measured at P4-linked ears. For auditory probes, the vertex-linked ears montage was used. This configuration was chosen because the amplitude of N100 is maximum at the vertex, and so much of the previous work on auditory attention has used this procedure successfully.

C) Specific Predictions (Note that predictions below are stated in terms of the resource model; the gating model would predict the opposite outcomes).

1. The P100 visual ERP component (or peak) recorded with parietal-linked ears montage will be smaller (tested with matched-pair t-test) in the reading task than in the listening task.

2. The N100 auditory ERP component (or peak) recorded with vertex-linked ears montage will be smaller in the listening task than in the reading task (matched pair t-test).

3. In both 1. and 2. above, the response in the cross-modal situation (non-shared channel) will appear more similar to the same component in the probe-attend condition than to the response in the within-mode (share) condition. This can be tested by comparing difference scores between each of the two language tasks and the probe-attend condition.

IV. METHOD

A) SUBJECTS

Subjects were recruited through schools and by newspaper advertisements soliciting participants in a research study involving brain-wave recording. All subjects were paid $20/day for their participation. Recordings were made from 15 caucasian, right-handed, middle-class, 10-12 year old males. Subjects were carefully screened for neurological, sensory, and emotional problems to facilitate later comparisons with other groups. An extensive history was taken from parents, including pregnancy and perinatal complications, medical, social, and academic problems. Children with histories of emotional disorders, hyperactivity, or birth stress were excluded. Neurological screening was carried out based on the method of Touwen and Prechtl (1970), including cranial nerves, muscle strength and symmetry, deep tendon reflexes, superficial reflexes, five categories of motor functioning (balance, tremor, associated movements, abnormal movements, sequencing), and perceptual-motor performance including double simultaneous touch, two point localization on fingers, graphesthesia, and imitation of gestures. Exclusion criteria were moderate disabilities in three or more motor categories, or a consistent pattern of disability in the sensory-perceptual area. No child with major neurological signs, such as clearly impaired motor coordination, seizures, etc., was

included. Pure-tone audiometry and visual acuity examinations were performed. Exclusion criteria, except for one minor exception (below) were as follows: for vision, acuity poorer than 20/30 in each eye corrected; strabismus; horizontal heterophoria greater than 6; vertical heterophoria greater than 1; refractive error greater than 1.5 diopters for myopia, hyperopia or astigmatism; accommodation amplitude less than 10 diopters (near point = 10 cm.); any abnormalities in health screening, history of eye surgery, etc. Pure tone audiometric thresholds were no greater than 20 dB below 0 (HL) at any frequency between 500 and 6000 Hz; in addition, no difference greater than 10 dB between ears at more than one frequency in this range. The one exception was in vision, one subject was myopic without near-vision problems. All subjects were required to have WISC-R full-scale I.Q. above 88 and differences between verbal and performance scales less than 30 points.

B) STIMULUS PRESENTATION

Subjects sat upright at a specially designed table, 78 cm x 124 cm, which inclined toward them at an angle of 18 degrees. The central panel (54 X 58 cm) formed an opaque work surface; the remaining 33 cm on each side was a checkerboard (4 cm square) panel which could be illuminated from below by 2 12-inch flash tubes (Iconix Model 6196-2).

The checkerboard pattern in the illuminated area provides edges and contrast, which produce larger ERP amplitudes than plain flashes (Jeffreys, 1969). Flashes of 37 candelas, against a background of 25 candelas ambient luminance, 12 msec duration, were presented regularly every other second as visual probes.

Most visual ERP paradigms require the subject to keep eye position constant. However, in our experiment some tasks, i.e., reading, involve fixating different areas on the work surface. One might be concerned that for visual ERPs even small eye movements might be significant. For example, it is conceivable that differences in the pattern of small eye movements elicited by tasks such as reading and block design might contribute to task-dependent asymmetries in the ERPS, because the average direction of gaze vis-a-vis the flash source would be different. This potential problem is obviated by delivering flashes in the peripheral field (between 40° and 90° from the fovea) and diffused over a large area rather than from a point source. Several studies have examined effects of variations in retinal locus of stimuli on the asymmetry, amplitude, and latency of the ERP (see especially Andreassi, et al., 1975). The major effects are seen with small stimuli moved from foveal to juxtafoveal loci. With larger stimuli and greater distances from the fovea the effects diminish. In addition, broad peripheral stimulation is minimally intrusive while subjects are performing tasks.

A small loudspeaker centered at the top of the work area presented 66 dB (SL), 600 Hz, 30 msec tone-pips every other second for auditory probes, alternating with the flashes.

C) ERP AVERAGING

EEG was recorded from central (C3,C4), parietal (P3,P4), mid temporal (between T3 and T5, T4 and T6) and linked ears (A1A2) leads, referred to vertex (Cz). EOG was recorded with Beckman miniature electrodes placed obliquely across the left eye. Electrode impedance was less than 10 Kohm. A separate montage referenced to linked-ears was derived off-line by subtracting the A1A2-Cz channel from the other leads and reversing the polarity of the reference channel. Signals were obtained via Grass gold cup electrodes and amplified with a Grass Model 7 polygraph, with Model 7P5 preamplifiers set to half amplitude cutoffs of .3 and 35 Hz. The EEG was digitized by a NOVA minicomputer at 256 points/second for computing Fast Fourier Transforms, and linear interpolation allowed sampling at 5 msec intervals for the ERPs. Digitized data were stored on IBM compatible magtape*. An EOG channel and a marker channel containing stimulus and response data were also recorded. ERPs were averaged for 650 msec following stimuli. The amplitude values were sampled at 5 msec

* In the early phases of the study, recordings were made on analog tape (Ampex SP-300) and transferred to magtape for subsequent processing.

intervals for a total of 130 data points per ERP. The average of the first 30 msec post-stimulus was used to set the baseline of the entire epoch. Epochs containing EOG deflection indicating blinks or movement of eyes away from the work space (based on calibrated eye movements recorded before the session) were automatically rejected prior to averaging. In addition, EOG was averaged and compared with ERP waveforms to be sure any residual EOG remaining after automatic editing did not contribute to the effects appearing on the ERP channels, by visually inspecting the time relation between ERP and EOG deflections. When a correspondence was detected, averages were recomputed off-line with more stringent EOG deflection criteria. Approximately 80 probe stimuli in each modality were averaged for each task. The averages were stored as floppy disk files which were later written onto magtape for transfer to an IBM 4341 for statistical processing. The Statistical Analysis System was used exclusively (Helwig & Council, 1979).

D) PROCEDURE

Probe stimuli were presented continuously from the time subjects were first seated and received instructions, as well as during and between tasks (except briefly during the passive eyes closed and eyes open conditions). Subjects were instructed that the flashes and tones were irrelevant to their various tasks and were to be ignored. They

generally reported them as unobtrusive at post-testing interviews.

ERPs to both visual and auditory probe stimuli were averaged during a series of behavioral tasks designed to engage the subject in a variety of cognitive processes, including spatial processing and several aspects of language. The tasks studied here include only the listening to text, easy reading, and probe-attend tasks. For each child, reading materials were assigned which were two grade levels below his tested reading levels. Comprehension questions were asked after each reading selection; if performance did not meet the pre-established criterion, new materials were presented and the task was repeated. Reading speed (words/minute) was also scored. The listening task was presented in a female voice through a small speaker mounted on the center of the workspace. Materials were taken from age-appropriate texts.

For the probe-attend task, subjects were required to fixate on the center of the workspace and to press a button with the right hand when occasional visual or auditory probe stimuli of longer duration were detected. Longer duration stimuli were presented on a standard pseudorandomized schedule. This schedule contained no more than three of the same modality stimuli in a row. Subjects were not informed of this constraint. The average interstimulus interval for longer duration stimuli was 5 sec. Probe-ERPs were not

averaged during the period of presentation of the longer duration probe stimuli nor during responses to these stimuli.

During each task, subjects were monitored with a closed circuit TV system; an intercom provided two-way communication. An experimenter entered the room to explain the instructions before each condition and answer any questions.

V. DATA ANALYTIC STRATEGY

A) Data Base

The primary data set analyzed consists of 28 ERPs for each subject (3 tasks X 7 electrode locations X 2 modalities), recorded with linked ears reference.

B) Considerations in the Choice of Dependent Measures

No single metric is appropriate for the analysis of ERP data. For the present study, I have relied on the convergence of information obtained by picking peak amplitudes and latencies on individual waveforms, and results of principal component factor analysis (PCA). After careful visual inspection of all waveforms to insure adequate ERP responses, PCA was used to reduce the complex ERP waveform to a smaller set of factors which account for the preponderance of variance in the data. The factor analytic technique was used for two main reasons. First, it is useful in separating functionally distinct components which overlap in time. This is particularly relevant to the present study in that there is a suggestion in the literature on N100 that apparent modulation of this component is due to the superimposition of a slow negative component (reviewed in Naatanen & Michie, 1979; Hansen & Hillyard, 1980; Naatanen, 1982). Factor analysis may be useful in separating the effects of these two components.

In addition, factor analysis has the advantage of using more of the data so that statistical analyses need not be based on single values such as peak amplitudes. This should increase the power and stability of the statistical test.

Peak amplitudes and latencies were scored for visual and auditory probe stimuli at P4-A1A2 and Cz-A1A2 respectively employing a simple algorithm developed within the Statistical Analysis System (Appendix 1). For visual ERPs the maximum value between 90 and 135 msec was chosen; for auditory ERPs, which typically have shorter latencies, the minimum value between 80 and 130 msec was selected. The peak-picking procedure was carried out for each of the three task conditions. After values were selected, they were checked against individual subjects ERPs to insure accuracy of the automatic peak-picking procedure. Peak selection was completely accurate in the auditory modality for all three tasks and in the visual modality for the listening and attending tasks. For the reading condition, peak values were selected incorrectly for five subjects. This was generally due to the superimposition of a small P100 peak on a falling or rising phase of another peak (for example, see Fig. 3). The amplitude and latency values were adjusted on these five cases prior to statistical analysis.

Factor analysis was computed on a scaled covariance matrix computed over 65 data points (every 10 msec.) of the ERP. Previous experience with this method in the large

dyslexia study indicated that 10 msec. resolution was sufficient to reveal many experimental effects. In the present study, when marginal effects were noted, 5 msec resolution and latency adjustment was carried out in order to more clearly examine the nature of the given factor. These factors indicate high intercorrelation among the amplitude values over specific time segments of the ERP and may correspond to the activity of specific neuronal aggregates (Donchin, et al., 1978, pg. 353). They do not necessarily correspond to peaks or troughs in the raw waveforms: certain peaks may be built up of several overlapping factors which are functionally distinct. Varimax rotation re-orients the axes of the factors to maximize discrete factor loading. This type of rotation also forces factors to be orthogonal so that subsequent statistical analysis on factor scores derived from each factor can be carried out without the need for multivariate statistical tests.

PCA is based on the assumption that latencies of underlying factors are constant over experimental conditions (group, leads, tasks) and that the source of variance is amplitude changes. It is therefore necessary to evaluate the extent of latency shifting in interpreting the results of factor analysis. In order to evaluate the significance of latency differences, peak-picking was employed. Since latencies of components for the two sensory modalities are known to be different, separate factor analysis was carried

out for each modality. Factors were computed based on the pooled matrix of all subjects, tasks, and leads. Evaluation of the factor pattern for specific sub-epochs was examined separately.

Since there are generally no obvious shoulders on the distribution of eigenvalues, "scree tests" (i.e., Cattell, 1966) are likely to be inappropriate. In order to determine the number of stable factors in the data, first the number of varimax rotated factors (n) which accounted for 85% of the overall variance in the relevant matrix was extracted. The procedure was then repeated to extract n-1 factors and plots of factor loadings over the entire 650 msec epoch (or 200 msec subepoch) were visually inspected. The appropriate number of factors to use was determined by comparing the changes in the overall pattern of factor shape and latency produced by rotation with the addition of another factor (i.e., n-1 vs. n). An additional factor was used only if it changes the shape or latency of at most one previous factor.

C) Statistical Tests

The factors corresponding to selected peaks (N100, P100) were scored and tested for task differences with matched-pair t-tests. A priori tests were carried out for Cz in the auditory modality and P4 in the visual modality. Follow-up analyses were carried out on other components and leads from these same factor analyses. A priori analyses on

peak amplitudes and latencies were carried out in the same way as for the factor scores.

VI. RESULTS

A) A Priori Analyses

1) Peak Amplitude and Latency.

Grand average waveforms for visual probes at P4 and auditory probes at Cz for reading, listening, and probe-attend tasks are shown in Figs. 1 a,b,c, and 2 a,b,c. (Note that the group averaged values from the tables do not correspond precisely with the peaks on the figures. This is due to selection of peaks from individual subjects for the computations shown in the tables and simple group averaging of waveforms in the figures). The means, standard deviations, and range of the peak amplitudes and associated latencies for both probe-ERP modalities are given in Table 1. The mean latency of the "P100" peak was 110 msec. For the visual probe-ERPs, the listen task yielded the largest P110, the attend tasks next largest, and the reading task the smallest P110. For the auditory probe-ERPs, the mean latency of the "N100" was 110 msec. The pattern of peak amplitudes was reversed compared to the visual modality: the listen task yielded the smallest peak amplitude with read and attend showing nearly identical peaks. Matched-pair t-tests comparing the three task pairs were computed and are shown in Table 2. A clear result emerges: There are no task differences in latency, however the probe ERP presented in the same modality as the primary task is attenuated in peak

amplitude (visual P110 read vs. listen t=-3.14, p=.007, 19.2% of within-subject variance; auditory N110 read vs. listen t=3.63, p=.002, 24.5% of within-subject variance). The visual P110 was not different for listen and probe attend; the auditory N100 was not different for reading and probe-attend.

2) Factor Analyses.

Principal components factor analysis was carried out for each modality separately. The scaled covariance matrix which was used in the analysis incorporated all subjects, the three task conditions, and all seven recording sites (excluding EOG). Visual examination of different numbers of varimax rotated factors (see procedure outlined in Methods) indicated that the set of eight factors was most stable for each modality.

For the visual modality, these factors accounted for 85.8% of the overall variance. The third factor was clearly representative of the P110. No other factor peaked in the range of the P110 peak. This P110 factor accounted for 10.7% of the variance in the matrix, and is shown in Fig. 4. The peak loading is at approximately 115 msec. and ranges from 60-160 msec. Figure 5 shows the scalp topography of this factor pooled across the three tasks. As expected, this factor shows maximum positive loadings at parietal placements (and right mid-temporal) with the P4 response greater than that found at P3.

This factor was scored and analyzed for task differences at the P4 electrode as was done with peak amplitudes. Table 3A shows mean factor scores for the three tasks at this electrode site. Table 4A shows the results of matched-pair t-tests between the three task pairs. The difference in means between read and listen is in the same direction as was found for peak amplitudes but at only the .07 probability level (11.2% of within-subject variance). The other comparisons are both $p > .1$.

For the auditory modality, the set of eight factors accounts for 88.8% of the overall variance. The fourth factor was clearly representative of the N110. No other factor peaks in the range of the N110 peak. This N110 factor accounts for 7.0% of the variance in this matrix, and is shown in Fig. 6. The peak loading is at approximately 120 msec. and ranges from 80-150 msec. A secondary peak is evident for this factor at approximately 280 msec., ranging from 250-310 msec. This secondary peak may correspond to the Nd component discussed by Hansen & Hillyard (1980). There are no components representing a sustained negativity. Figure 7 shows the scalp topography of this factor pooled across the three task conditions. As expected, this factor shows a strong vertex-central maximum. This factor was scored and analyzed for task effects at the Cz electrode. Table 3B shows mean factor scores for the three tasks at Cz. Table 4B shows results of matched-pair t-tests between the three task pairs. The auditory N110 factor results compare

favorably with the results using peak amplitude. Significant differences were found between read and listen ($t=-3.09$, $p=.008$, 21.3% of within-subject variance) and between listen and attend ($t=3.69$, $p=.002$, 21.7% of within-subject variance), while no difference was found between read and attend, completely consistent with the peak amplitude analysis. The variance of the N110 factor appears much smaller in relation to the mean of this factor than is the case with the P110.

B) Follow-Up Analyses

1. Explanation of Difference in Robustness of Results for Visual P100 Using Peak Amplitude and Factor Analytic Methods.

The above findings suggest that the factor analytic method is less sensitive to these task differences than the peak values in the visual probe-ERP analysis. Since it is possible that this result is due to variation in the latency of the P110 across subjects (see Allison et al 1977, pg.190), the factor analysis was recomputed, adjusting the matrix by selecting the epoch from 50 msec before to 50 msec after the peak latency at P4 for each individual, using 5 msec intervals (see Appendix 2 for details of this procedure). This did not substantially improve the result: the difference between reading and listening was $p=.06$.

Another reason for the smaller magnitude of task effect

on the visual P110 factor could be increased variability due to superimposition of another non-task-related component over this time range. Therefore, the next component after the P110 was examined. This component appeared at approximately 170 msec., and accounted for 8.1% of the variance in the waveforms. Loadings greater than .3 ranged from 150 msec. to 220 msec. Inspection of factor scores and grand average waveforms indicates that this component shows a clear polarity inversion. It has negative scores at temporal placements and positive scores at central placements. For the parietal leads the situation is less clear. It appears that there is a greater negativity at P4 over the group, and is more similar to the right mid-temporal response. The subject presented in Figure 3 shows this negativity quite clearly over this range. Further, for this subject the P110 appears to be superimposed on this negativity. However, there are no significant task differences on the 170 msec. component. It is possible that the task-dependent attenuation of the P110 peak is due to a complex interaction between the extent of this superimposition and the extent of polarity inversion for individual subjects. It should be recalled however, that the P110 factor is itself task-dependent at the p=.06 level, implying that this single factor carries the majority of the effect on peak amplitude.

In order to further examine the effect of task-dependent superimposition of components, the P110 factor

scores were submitted to a regression analysis, using task (reading vs. listening), as an independent variable. Residuals of factor scores, representing the variance not accounted for by task effects, were computed. These residuals were then compared to the latency difference between the P110 and N170 peaks, as well as the latency of each peak for each task. The peak values for each individual subject for the N170 peak were selected using the method described above. The correlation between the factor score residuals and the difference in latency between the P110 and N170 peaks for each of the two tasks was computed. For the reading task, which shows a smaller P110 peak amplitude, a significant relation was found between the N170-P110 latency difference and the residuals of the P110 factor, $r=.60$, $p=.02$. This is due primarily to a relation between the residuals and the N170 latency, $r=.67$, $p=.007$; for P110 latency, $r=.40$, $p=.14$. In other words, residuals are smaller when the peaks are closer together (superimposed) due primarily to faster latency of the N170 peak. The mean difference between tasks was 8.7 msec., and the standard deviation was 26.7 msec., suggesting substantial individual variation in the latency difference between peaks. No significant effects were found for the listening task.

2. Within-subject Consistency of Effects on Visual and Auditory Probe-ERPs.

The above results indicate that the P110 component of the visual probe ERP is attenuated in the reading task relative to listening and that the N110 component of the auditory probe ERP is attenuated in listening relative to reading. However, this need not imply interdependence of sensory modalities for all individuals. Some subjects might show much stronger attenuation in one modality than another. Therefore, the within-subject consistency of these effects was examined by correlating the difference scores obtained for each modality. The difference scores (read-listen) for the visual modality were correlated with the difference scores for the auditory modality. No significant correlations were found between modalities for any task pair. Inspection of the scattergrams indicates no complex non-linear relationship.

3. Evaluation of Possible Peripheral Sensory Masking as a Contributor to Results.

Since the hypotheses were developed to test two theories of selective attention involving central nervous system processes, it is important to evaluate the extent to which peripheral modulation might have influenced the present findings. Since the task-related attenuation result was robust in the factor analysis on the auditory probe-ERPs, these data were used to address questions concerning possible peripheral modulation and changes in scalp topography. Follow-up analyses were carried out to

investigate possible attenuation earlier than N110.

If the modulation observed was due to peripheral masking or competition at the primary receptor, it would be expected that components earlier in the auditory pathway than N110 would show a similar attenuation. Therefore the factor occuring prior to N110 was scored and analyzed in the same manner as the N110 factor. This factor accounted for 2.5% of the overall variance in the matrix. The peak was at approximately 70 msec. (10 msec. resolution) and loadings above .3 ranged from 40-110 msec. This factor appears as a small positive peak at approx. 80 msec. (5 msec. resolution) in the grand average waveform. It is particularly noticable at Cz in the listening task (see Fig. 2b). It is clear that this component is not myogenic for several reasons. First, the extensive topographic mapping study by Goff et al. (1977) shows no myogenic components in this time range. It is possible that the peak value found in the present study was somewhat attenuated and longer in latency because it is a relatively fast frequency component and the 1/2 amplitude high cutoff used on the driver amplifier was 35 Hz. Goff et al. did find a positive myogenic component at 35 msec. using filters with -3db at 1100 Hz. However, it is unlikely that this is represented in the P70 factor found here. The P35 described by Goff et al. is a reflex response of the orbicularis oculi muscles. It is sharply localized to the pre-frontal regions and habituates to stimuli delivered at predictable intervals. It is more likely that this

component is analogous to the P50 or P70 peaks both of which are considered to be neurogenic. The topography of this factor in the listening task compares very well to that shown for the P50 component, see Fig. 8. The correspondence for this factor is best for listening and is not quite so clear for reading or probe-attend. In the Goff et al. experiment, subjects were simply told to listen, no vigilance or response was required. These investigators also used click stimuli in contrast to the tone-pips employed in the present study. There is little correspondence between the topography of the P70 component reported by Goff et al. and the P70 found here.

Thus, it appears that the factor at approximately 70 msec. is neurogenic, corresponding to Goff's P50, reflecting activity in the auditory system earlier than the N110. This component shows no significant difference between the reading and listening task ($t=-1.08$ $p=.3$). In fact, the means are in the opposite direction P70 LISTEN > P70 READ. Therefore, the effect is not peripheral.

4. Topographic Analysis of Task Effects.

Finally, an exploratory analysis was carried out to examine the lead specificity of the auditory probe-ERP task effect. A task (read vs. listen) by lead (left mid-temporal, right mid-temporal, C3, Cz, C4, P3, and P4) repeated measures analysis of variance was carried out on N110 factor scores. A significant task by lead interaction

was found (F=2.60, p=.02, df=6,84). Matched-paired t-tests on task differences at each lead showed that these two tasks show differences specifically over the central region (C3,C4,Cz) but not temporal or parietal leads. This is not simply a function of the factor being present only at these sites: the N110 is clearly evident at P3 and P4 in the grand averages and mean factor scores are substantial at these sites, and Goff et al. show that the N110 response at parietal leads was greater than 75% of the N110 maximum.

VII. DISCUSSION

The present study has addressed the question of the mechanism of probe-ERP modulation by making reference to theories of selective attention. The results clearly indicate that "P100" and "N100" probe responses are not modulated by stimulus set. Responses to probe stimuli were reduced when the probes and on-going task were in the same as compared to different modalities. Rather, they support a model wherein probe-ERPs index utilization of particular resources.

These results certainly do not negate reports of gating mechanisms in the nervous system. It is possible that gating or selection based on stimulus set occurs in situations where the task is data-limited. The gating model may apply only to very early components or to dimensions other than modality of stimulus. Hillyard's significant results have been found only within the auditory modality. The study by Neuerberg & Hillyard using visual stimuli was not successful in demonstrating effects of attention on visual ERPs.

In this study, resources related to N110 and P110 appeared to be modality-specific, analogous to the results of numerous behavioral studies using various detection and recognition paradigms reviewed above. In addition to the visual probe response being significantly smaller in reading than listening or probe-attend, the <u>auditory</u> probe-ERP recorded during reading was relatively large, nearly

identical to that found for the probe-attend condition. The responses obtained during listening showed the same effect in the opposite direction. This is a clear dissociation between the modalities and strongly supports the notion of modality-specific channels with relatively independent resources.

It is also clear that individual subjects do not show the same magnitude of effect for each modality of stimulus. Subjects who show strong suppression of the P110 in reading do not necessarily show strong suppression of the N110 during listening. The degree of suppression of the P110 during reading vs. listening was not significantly correlated with the degree of suppression of the N110 in reading vs. listening. There is little reason to expect that a strong relation between suppression in the two modalities studied would occur for individuals. Individual subjects may process these different stimuli in different ways (i.e. more efficiently in one modality) or may have a preference for processing in one modality over the other. The distinction between visual and auditory learning styles has been noted in the psychoeducational literature (Wepman, 1971; Boder, 1973). This lack of relationship also supports the argument that these channels represent relatively independent resources.

It is worthwhile noting that Hansen & Hillyard also have rejected the concept of simple gating of sensory input

based on stimulus set. However, the principal reason for their arrival at this conclusion is not analogous to the interpretation of the present results. The main reason that Hansen & Hillyard rejected the gating model was that the modulation of "N100" appeared to be accounted for by the activation of sustained endogenous components at longer latencies than the "N100", with onset latencies overlapping the "N100" peak. Naatanen et al., (1978), also report such a prolonged negativity. There is not general agreement on this finding however (cf. Buchsbaum et al., 1981).

The present results show that an "N100" factor, orthogonal to the other factors derived from PCA due to varimax rotation, was strongly affected by the modality of the on-going task. No sustained negative factor (Nd) was evident over the time range studied by Hansen & Hillyard. Distortions introduced by failure to meet assumptions of PCA (e.g., independence of error variance of time points over the ERP epoch), may have prevented extraction of such a factor. A small side lobe on the N100 factor could possibly represent one of the subcomponents of the Nd described by Hansen & Hillyard; however this subcomponent was not dissociable from the N100 component.

Further, the second study by Hansen & Hillyard indicated that differences between stimuli which are "rapidly analyzable" attenuate processing along more slowly analyzable dimensions, implying a hierarchy of processing.

Modality is presumably a very easily analyzable dimension. In the present study, stimuli presented in a different modality than the primary task tended to generate large rather than attenuated responses. Thus, the model proposed by Hansen & Hillyard may be specific to dimensions within the the auditory modality and not generalizable to the between-modality situation studied here.

Rejection of the stimulus set model as an explanation for the modulation of probe-ERPs does not necessarily imply support for the resource model. The findings reported here are clearly consistent with the resource model, but consideration still must be given to alterative interpretations, such as simple peripheral masking. However, analyses performed on the factor preceding the N100 factor in the auditory modality, and other experimental results for both the visual and auditory modalities reported in the literature argue against this possibility.

In the visual modality, factors such as lateral inhibition in the retina, and changes in ocular fixation should be considered. It is conceivable that lateral inhibitory mechanisms, known to be present at the level of the retina, lateral geniculate nucleus, and visual cortex, could attenuate responses to peripheral stimuli due to heightened activity of foveal photoreceptors during reading. A study by Boynton, et al. (1954) indicated that retinal spatial interaction may not be due to inhibitory mechanisms.

Boynton, et al. noted that changes in sensitivity of a spatially remote retinal area cannot be accounted for simply on the basis of lateral inhibitory mechanisms. Changes in threshold were found to be the same whether the stimuli were projected to the same retinal locus or a remote area. Further, if the change in threshold was due to inhibitory mechanisms, a time delay would be expected . That is, presenting an adapting stimulus concurrently with a test stimulus should cause less threshold change to the test stimulus than if the test stimulus was presented slightly after the adapting stimulus. A rise in threshold was found independent of such a delay. Boynton et al. suggest that threshold changes are related to the presence of stray light rather than inhibitory processes. The stray light explanation cannot be applied to the interpretation of probe ERPs in the present study since the same light source was used for both the reading and listening tasks. Although we cannot so easily dismiss the possibility of inhibitory interactions at the lateral geniculate or visual cortex, there is further evidence to support the resource model.

The possibility that ocular fixation can account for these results is considered unlikely based on the report by Neuerburg & Hillyard (cited in Hillyard & Picton, 1977). These workers used flashes which "filled most of the visual field, in order to mitigate the effects of any changes in ocular fixation." This procedure was also employed in the present study for the same reason (see Methods). Neuerburg &

Hillyard saw no significant modulation of the visual EP when subjects attended to auditory stimuli vs. attending directly to the flash stimuli. This result is supported in the present study by the lack of significant differences between the probe-attend and listening tasks. Thus the results reported here are more likely due to the nature of the task demands which were very different in the two studies (i.e. reading vs. simple attention to flashes) as opposed to ocular fixation and stimulation parameters which were comparable.

The magnitude of our visual ERP effect argues against the interpretation that the visual probe response was attenuated due to a decrease in the effective stimulus. Halliday (1977) reports that the amplitude of the "P100" decreases approximately 15% per log unit of decreasing brightness. In the present study, the P110 amplitude was reduced by more than 50% (4.45 uV during listening vs. 1.77 uV in reading). It is unlikely that effective stimulus is reduced by a corresponding amount on the basis of peripheral factors in the context of the present task situation. Further, Regan (1972), in a review of the effect of visual stimulus intensity on the evoked response reports that "Most workers have found that the latencies of all components of the transient EP to flashes are decreased when the intensity of the stimulus is increased" (pg. 40). In the present study, the latency of the P110 was identical for the two language tasks, as well as for the probe-attend task. This

again suggests that effective stimulus was not the crucial factor in the modulation of probe ERP amplitude described here. Taken as a whole, these peripheral factors do not seem compelling as artifacts accounting for modulation of visual probe-ERPs. An interpretation based on the resource allocation model appears to be a more likely explanation. The follow-up analyses of the auditory probe-ERP data and consideration of the auditory masking literature tend to converge on the same interpretation.

For the auditory probe-ERP data, the "N100" factor appeared to index the same phenomenon as the N110 peak. This correspondence was taken as an indication that the results obtained from the auditory PCA were relatively robust and was used as a rationale for examining the factor occuring prior to the N100 factor, namely the P70 component. Evaluation of the possibility that the P70 was myogenic was carried out by comparison with the auditory components extensively described by Goff, et al. (1977). It was clear that the P70 found in the present study was neurogenic in nature by examining the scalp topography and timing of this factor (see RESULTS). It was determined that this factor probably corresponds to the P50 described by Goff, et al. An analysis of task effects on the P70, comparable to those carried out for the N110, found no significant task differences. In fact, the means fell slightly in the opposite direction from the N110. This was taken as direct evidence that the attenuation effects found for the N110

were not the passive result of events occuring earlier in the auditory pathway. Again, no significant latency differences between the tasks were found for the N110 peak, as with the P110, strongly implying that a decrease in effective stimulus was not the principal factor underlying auditory probe-ERP modulation.

It is also important to note that the speech delivered through the loudspeaker during the listening task ranged from approximately 500 to 2000 hz. in a relatively broad band. The frequency of the tone pip was constant and centered at 600 hz. in a much narrower band. There is no reason to suspect that overlapping frequencies in the speech message would be systematically time-locked to the presentation of the brief probe stimulus.

Further evidence for minimizing the importance of the contribution of masking effects is found in a study by Robinson & Sabat (1975). This study showed that very difficult auditory shadowing of speech messages completely eliminated responses to superimposed tone-pips presented at 400 hz. whereas speech production itself did not. Passive listening to two different speech messages presented dichotically (with no instruction or monitoring for comprehension) showed no significant difference from tone-pips presented without superimposed speech. Thus, again there is evidence that the physical characteristics of continuous, natural speech do not significantly mask tone-

pip stimuli which are presented at frequencies toward the lowest end of the speech range. Thus the considerations of possible masking are rejected, and it is concluded that the resource allocation model clearly seems to more adequately account for auditory probe-ERP response modulation.

The reduction in amplitude of specific components may not be attributable to a single underlying physiological mechanism. The attenuation of responses noted in the present results could be due to a reduction in the number of neurons available to respond to the stimulus. That is, a majority of neurons in the system of interest may be deployed in the performance of the complex task and few are "left over" to respond to the external stimulus. Alternatively, it may be that most neurons are firing asynchonously due to performance of the task, such that the stimulus is not effective in causing a mass synchronization which can be measured at the scalp. Following the recovery cycle model, it is possible that the neuron pool is activated causing slow recovery and hence reduced amplitudes are obtained to repeated probe stimulation. Each of these physiological mechanisms would be consistent with a limited capacity model.

Acceptance of the resource model raises certain theoretical issues. Most importantly, what is the nature of the resources which are or can be utilized? Is it meaningful to call a unit as small as a cortical column or

as large as a cerebral hemisphere a "resource"? We may assume that behavior is largely the product of the interaction of discrete brain sub-systems which have finite processing capacities. It is possible that resources of such sub-systems are multiply determined, with the size of the neuronal population as well as the "interconnectedness" of the population being of primary importance. In addition, these sub-systems may be used in different combinations or configurations for different types or amounts of information-processing. It is likely that certain configurations are more efficient than others for carrying out a given task. The probe-ERP has not been well-studied in relation to performance, but since responses may index "spare capacity", they should be related to the efficiency of the configuration of resources which a subject can organize for a given level of difficulty of the task. For example, one subject may be able to organize a configuration of resources which is highly efficient for performance of a given task and have "spare capacity" to allocate to monitoring probe stimuli. In this case, the subject is both performing the primary task at a high level as well as responding to probe stimuli. Another subject may configure resources less efficiently and not be able to respond to probe stimuli but nevertheless also perform the task at a high level. It would be of interest to compare the strategies of two such subjects (or groups of subjects) who perform a task at the same level but where one continues to

respond to probe stimuli and the other does not. The nature of the responses to probe stimuli may index the efficiency of the strategy employed rather than simply reflecting the level of task performance. As such, the application of the probe-ERP technique may allow us to monitor cognitive processes heretofore unavailable to systematic study in relation to brain function.

It may ultimately be possible to use probe-ERPs to monitor the extent of covert visual or auditory processing by using both modalities of probe stimulation. For example, one subject may show unusually strong attenuation of probe responses in the auditory modality during reading. This might reflect reliance on phonological mechanisms as opposed to primary reliance on visual word recognition. Since presentation of more difficult reading material typically results in a greater degree of phonological processing, it might be predicted that the auditory probe-ERP would be more attenuated during during difficult reading than easy reading and that the increase in attenuation with difficulty in the auditory modality would be greater than that in the visual modality. Similar predictions might be made concerning the extent of covert visual imagery employed during listening tasks.

The probe-ERP studies reviewed have used only adult subjects. The pattern of results reported here with children appears generally consistent with adult studies in

showing task-dependent attenuation of particular components. However, certain of the specific findings may not be genrealizable and must be specifically examined in adults. For example, the lack of correlation between effects found for visual and auditory probe stimuli may be related to a finding reported by Yingling et al. (1983), on these same children. Using task-relevant stimuli in a P300 experiment, Yingling et al. found significantly different scalp distributions for visual as compared to auditory P300 components, in contrast to the adult literature which suggests that the P300 reflects a modality non-specific process (Snyder, 1976; Simson et al., 1977). Thus children may show more independence of sensory modality than adults.

Results from this study provided insight into the nature of the visual "P100" and auditory "N100" components. It has been shown above that modulation of "P100" can be obtained by latency changes in the N170 component. If the latency of this component becomes shorter the superimposition on the "P100" can cause apparent attenuation of "P100" amplitude. Conversely, when latency of N170 is longer, the P100 may appear larger due to less superimposition. It is thus critical to measure latency effects on surrounding peaks in interpreting amplitude changes on a given peak. If factor analysis is employed to extract components, it is clearly necessary to evaluate latency shifting as a possible source of variance producing factors.

The nature of the auditory "N100" component as a unitary phenomenon is also called into question by results obtained in the present study and those reported by Hansen & Hillyard. First, both studies report topographical differences in features of "N100". Hansen & Hillyard showed differences between anterior and posterior placements on the phase of the N100 during reading. The rising phase was more posteriorly distributed than the falling phase. In the present study, differences between reading and listening were found exclusively at central placements, although this component was clearly evident at parietal placements also. Both of these results suggest that "N100" may not have a unitary generator source. Secondly, the presence of longer latency sustained potentials in the Hansen & Hillyard study and the presence of side lobes on the N100 factor in the present study suggest multiple components closely related to the "N100" peak. The possibility that these "sub-components" may share a common generator source should not be overlooked.

The probe-ERP technique has been shown to be quite generally applicable to the study of psychological issues. It is particularly useful in that it can be applied to complex "real-life" task situations. These situations may supply a large and naturalistic "load" on the subjects and thus be useful in studying brain activity in a more profitable context than most ERP studies which tend to use simple stimuli and task demands. Further, the probe-ERP

procedure has the methodological advantage over EEGs of averaging out artifacts such as eye, hand, and tongue movements which are not time-locked to the probe stimulus. These methodological advantages regarding the choice of psychological tasks and artifact rejection certainly justify further exploration of the mechanism of the probe-ERP so that further applications in such applied fields as education, clinical neurology, and rehabilitation medicine can be fruitfully pursued.

In summary, it has been shown that modulation of auditory "N100" and visual "P100" probe-ERP responses by concurrent tasks is not the result of selection based on stimulus set. Peripheral masking was rejected as a significant influence in the task conditions employed. It was concluded that probe-ERPs index utilization of resources. The nature of such resources may involve complex, changing configurations of neuronal subsystems. In the relatively simple case of sensory channels, it appears that there are separate pools corresponding to the structures of each modality. Probe-ERPs may index spare capacity and should be studied in relation to performance and information-processing strategies. The present study has also provided additional insight into the nature of the "P100" and "N100" components. The peaks measured may not represent unitary generators, and modulation of the peaks may be due to the activity of multiple generator sources. Finally, the general applicability of the probe-ERP

FIGURE 1A

VISUAL PROBE-ERPs

DURING READING

P4-A1A2

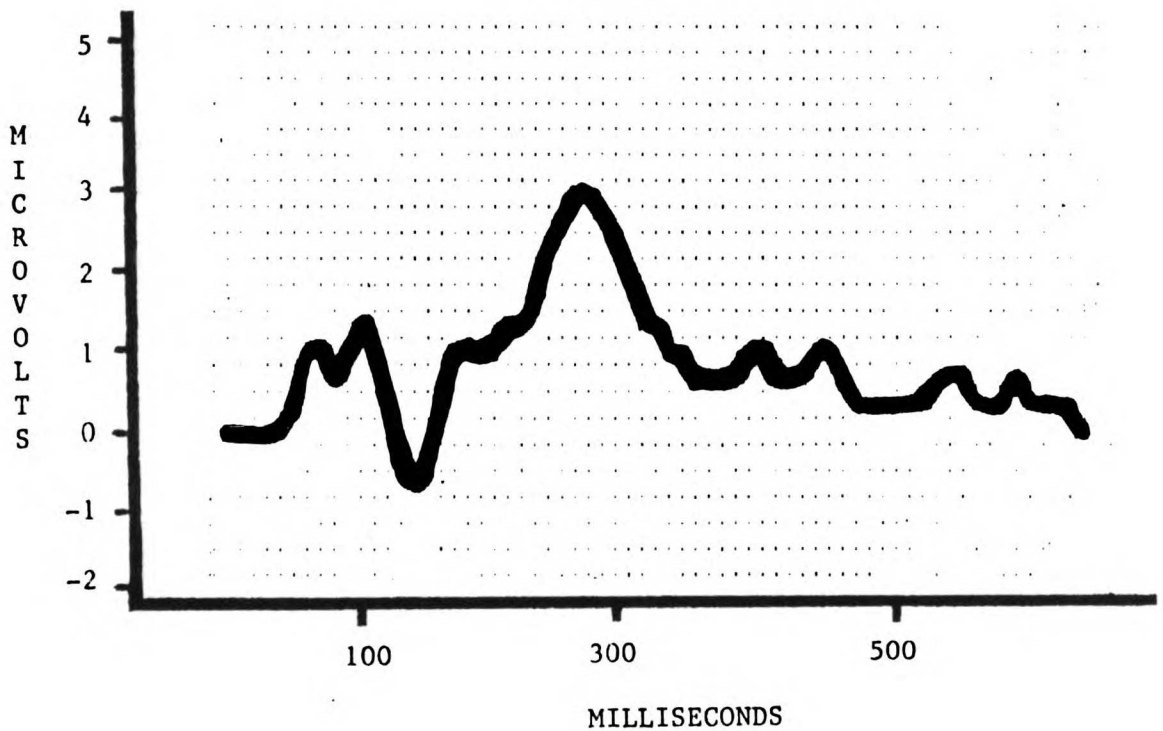


FIGURE 1B

VISUAL PROBE-ERPs

DURING LISTENING

P4-A1A2

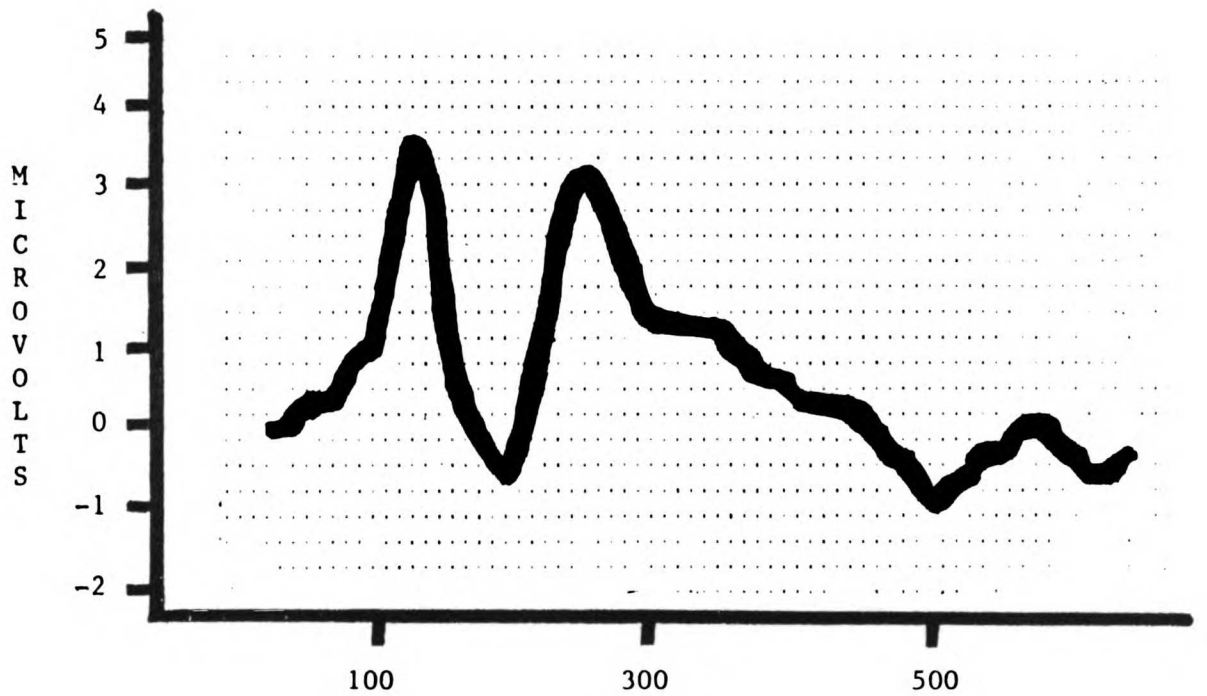


FIGURE 1C

VISUAL PROBE-ERPs

DURING ATTENTION TO STIMULI

P4-A1A2

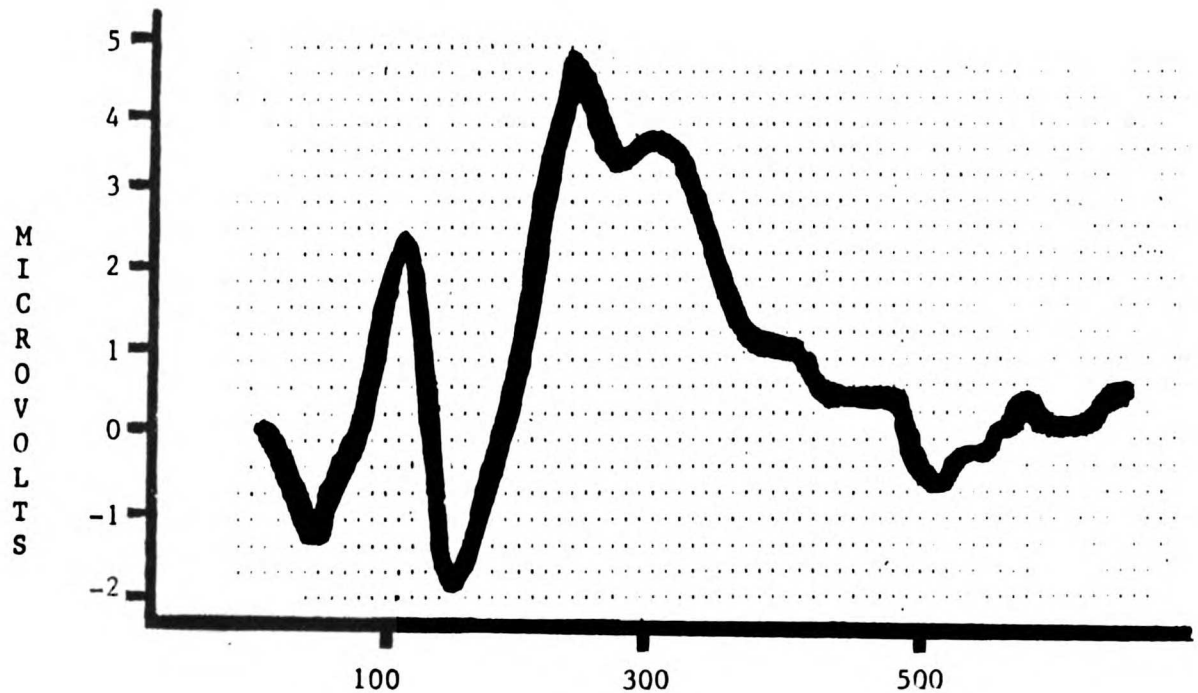


FIGURE 2A

AUDITORY PROBE-ERPs

DURING READING

CZ-A1A2

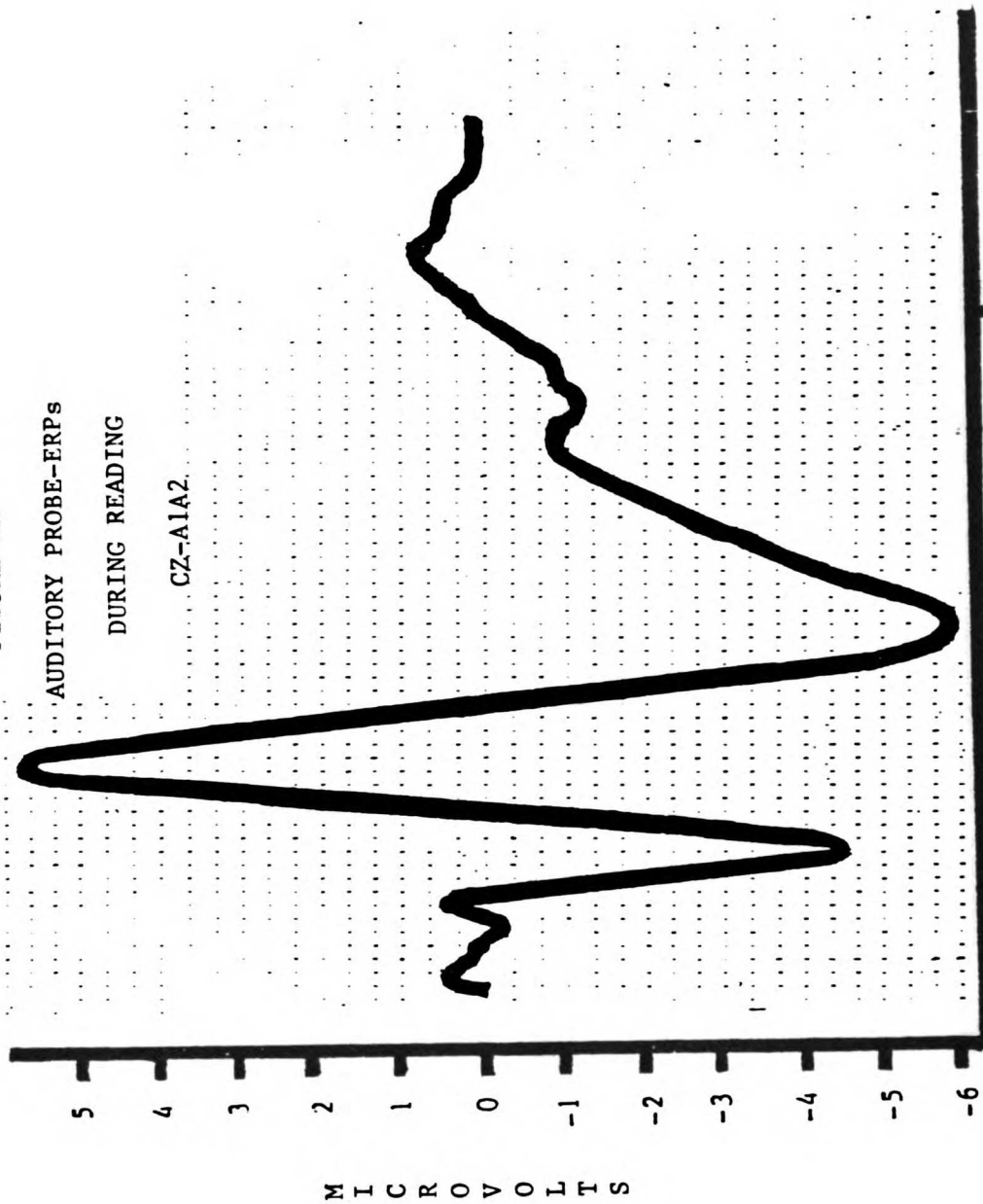


FIGURE 2B

AUDITORY PROBE-ERPs

DURING LISTENING

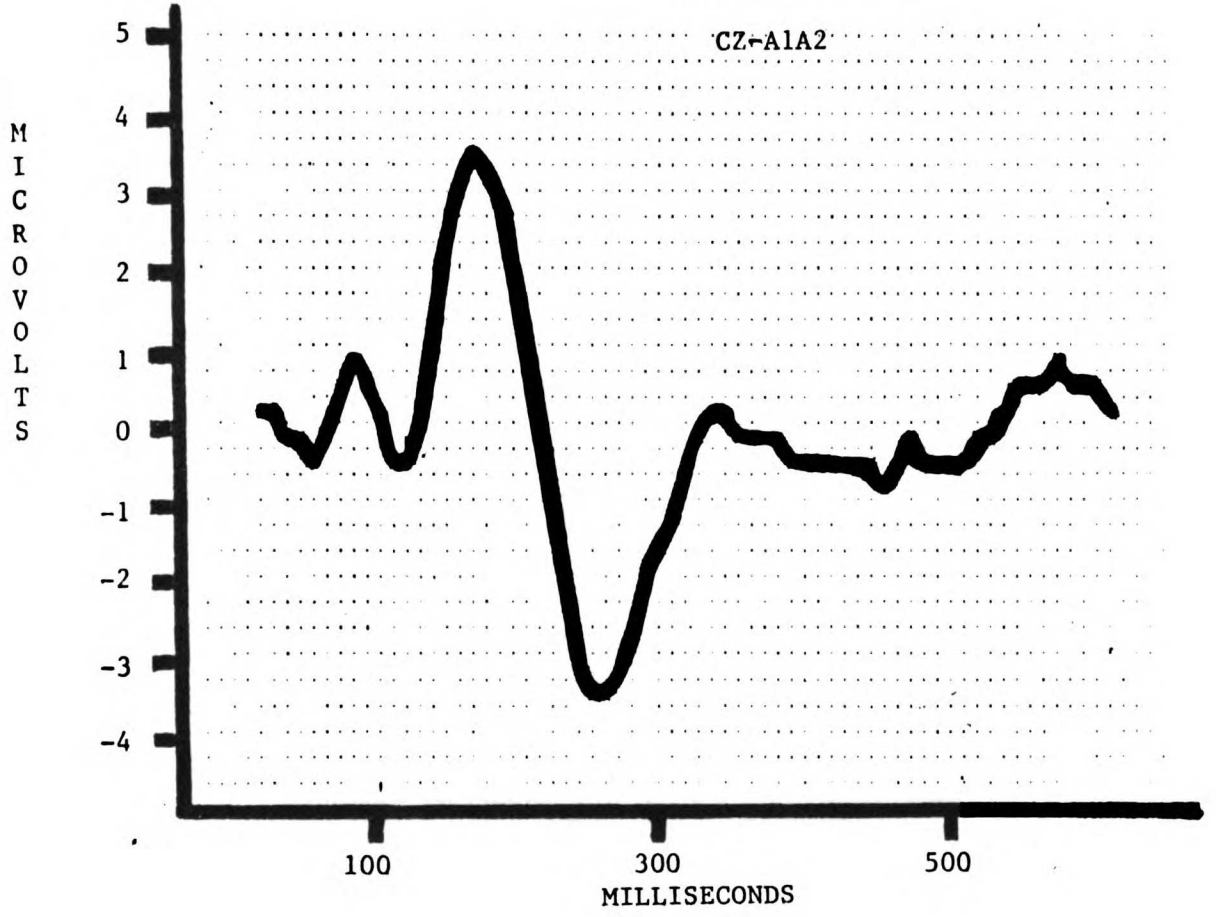


FIGURE 2C

AUDITORY PROBE-ERPs

DURING ATTENTION TO STIMULI

CZ-A1A2

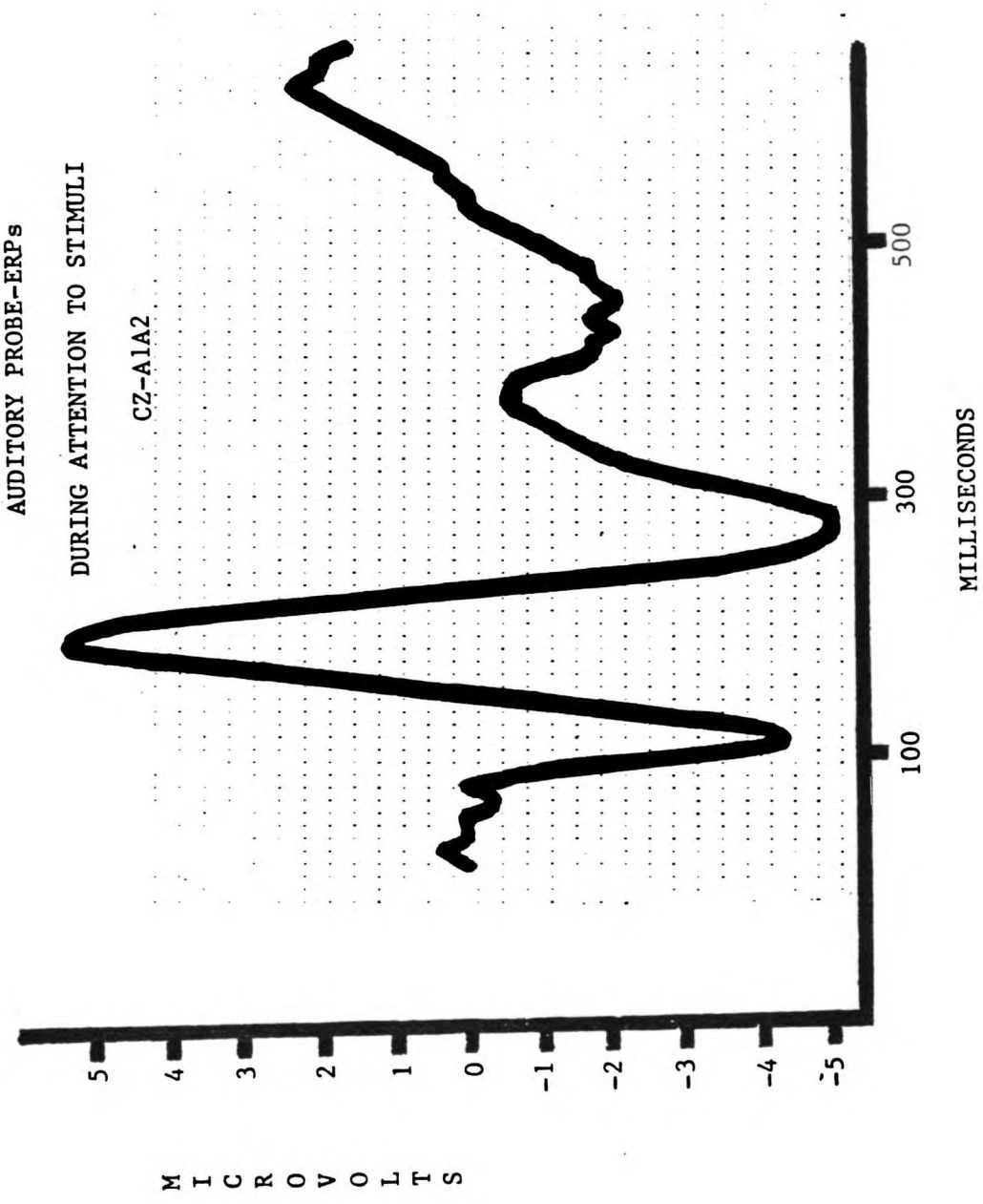


FIGURE 3

PROBE-ERP DURING READING

P4-A1A2

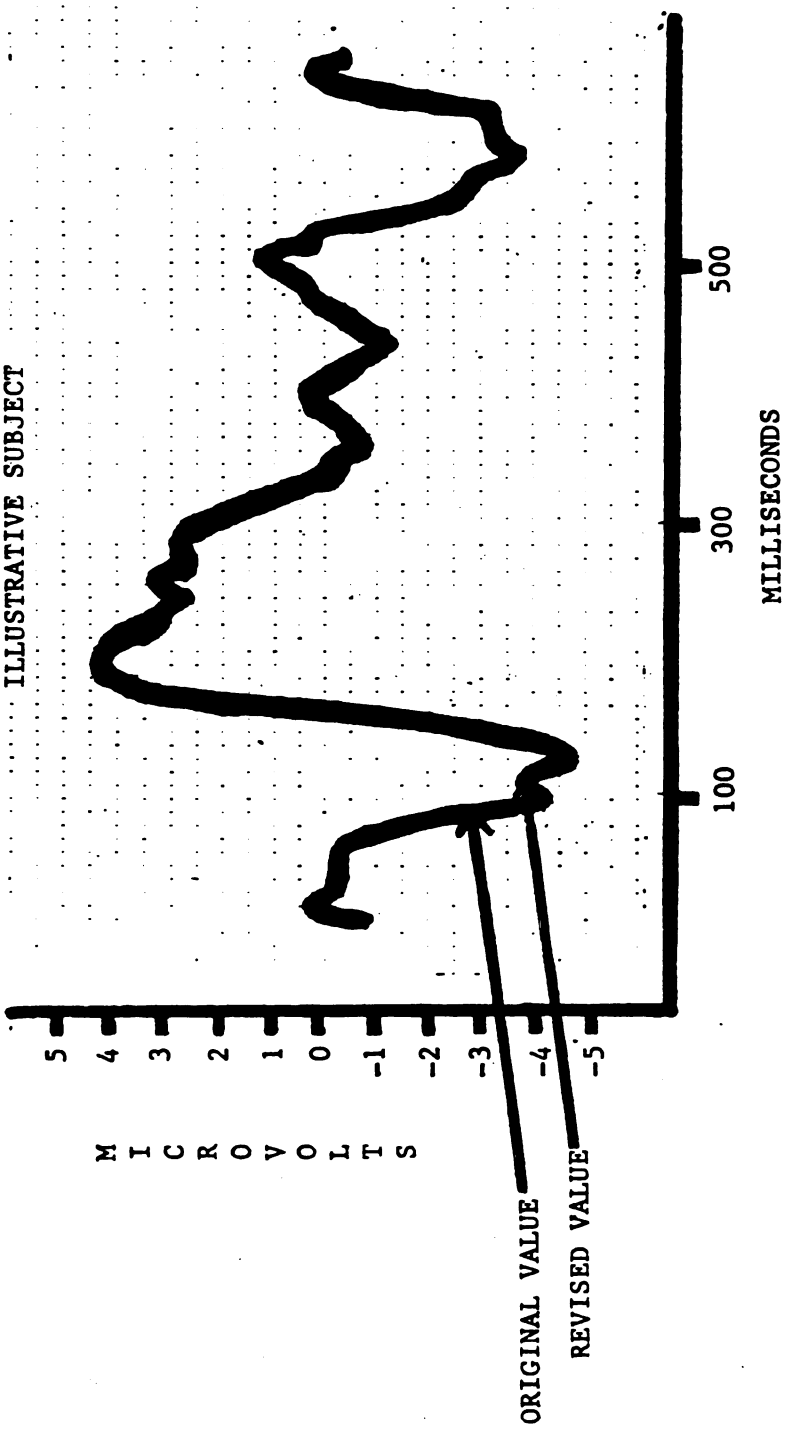


FIGURE 4

VISUAL P100 FACTOR

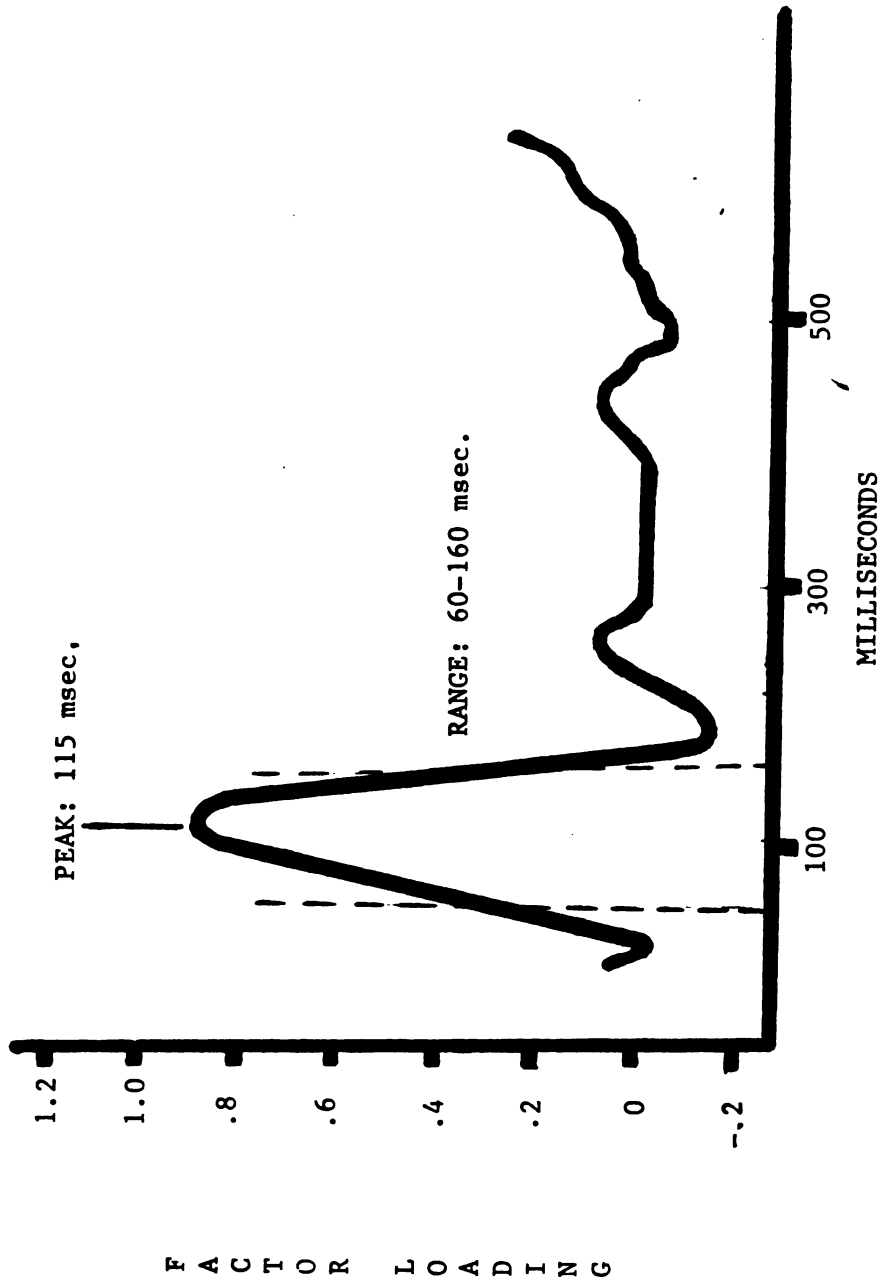


FIGURE 5

SCALP TOPOGRAPHY OF

FACTOR SCORES:

VISUAL P100

(Tasks Combined)

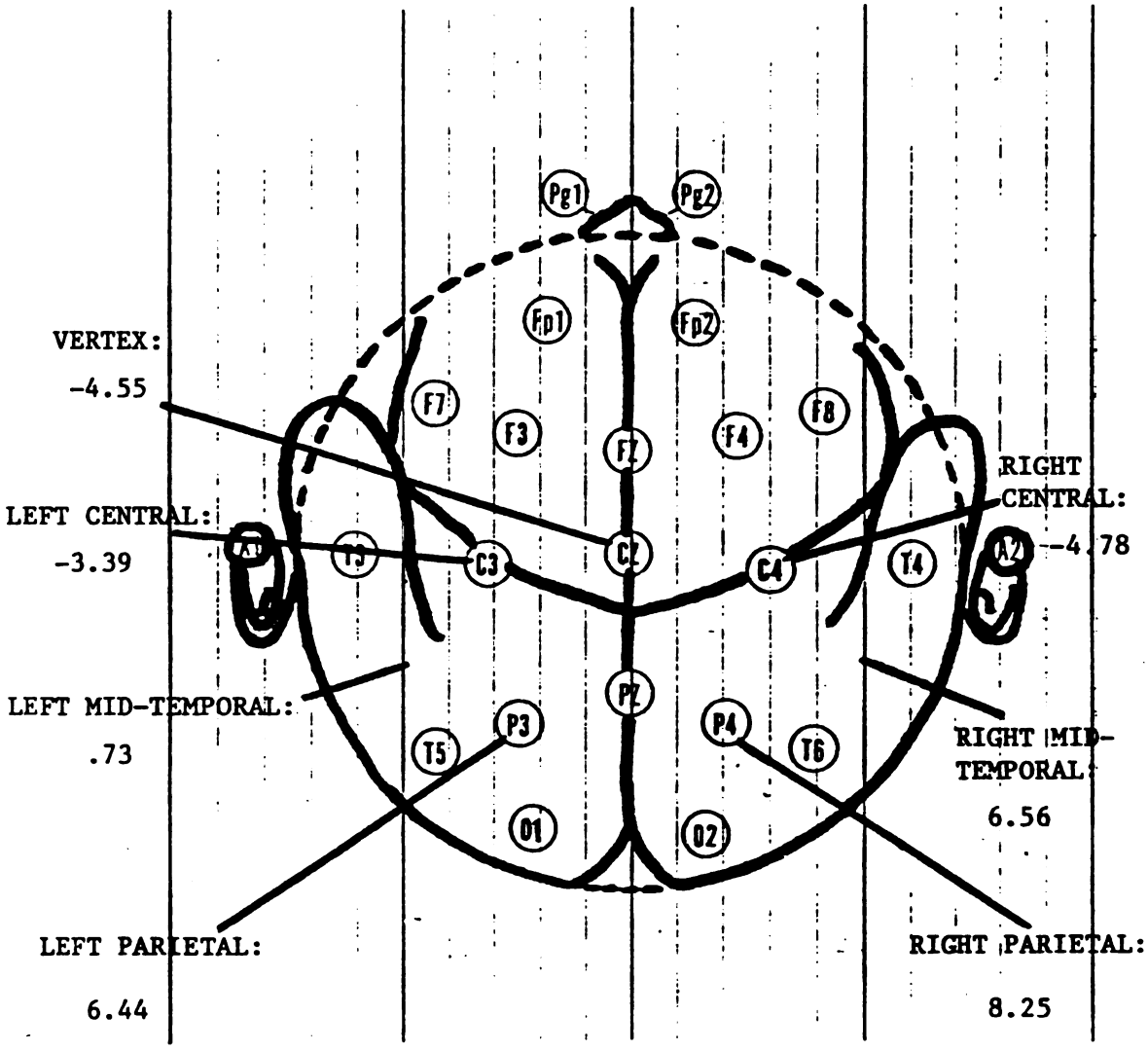


FIGURE 6

AUDITORY N100 FACTOR

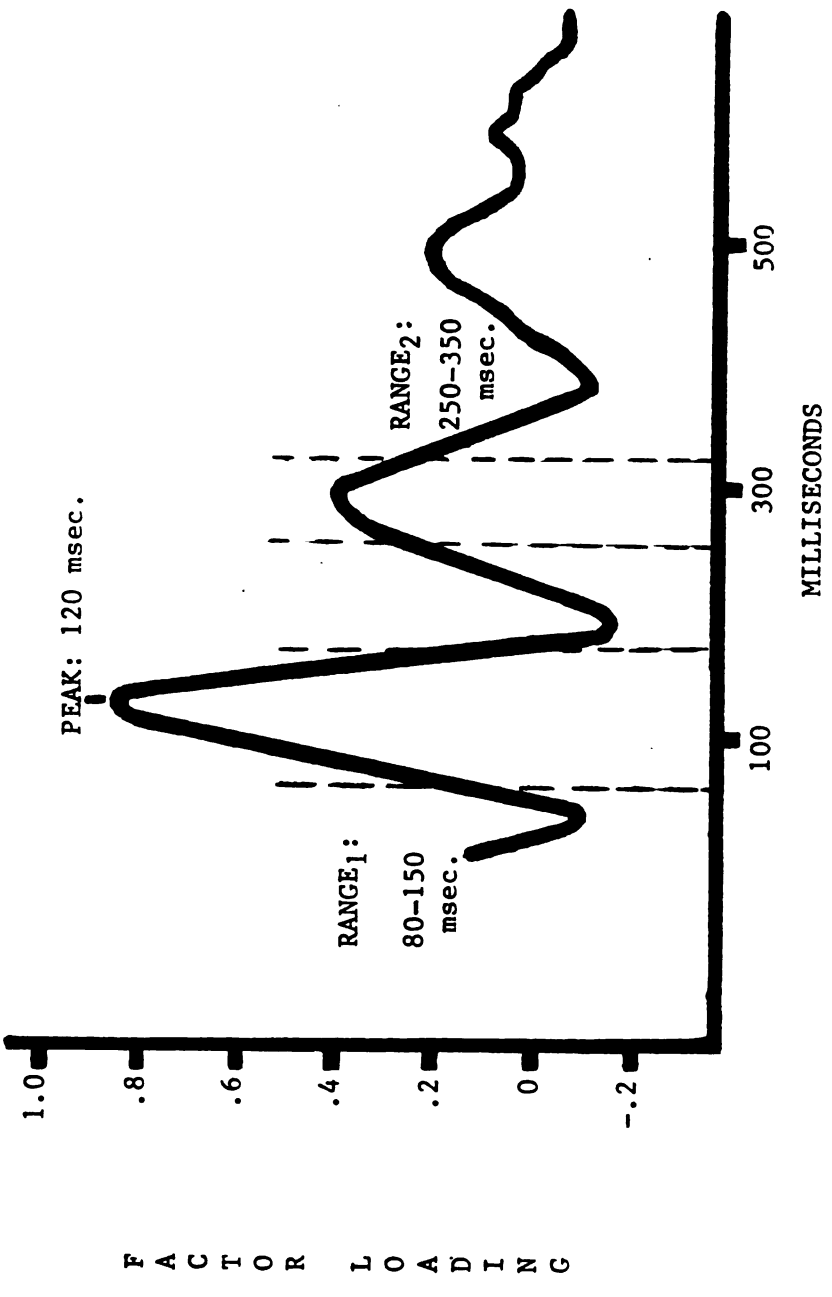


FIGURE 7

SCALP TOPOGRAPHY OF

FACTOR SCORES:

AUDITORY N100

(Tasks Combined)

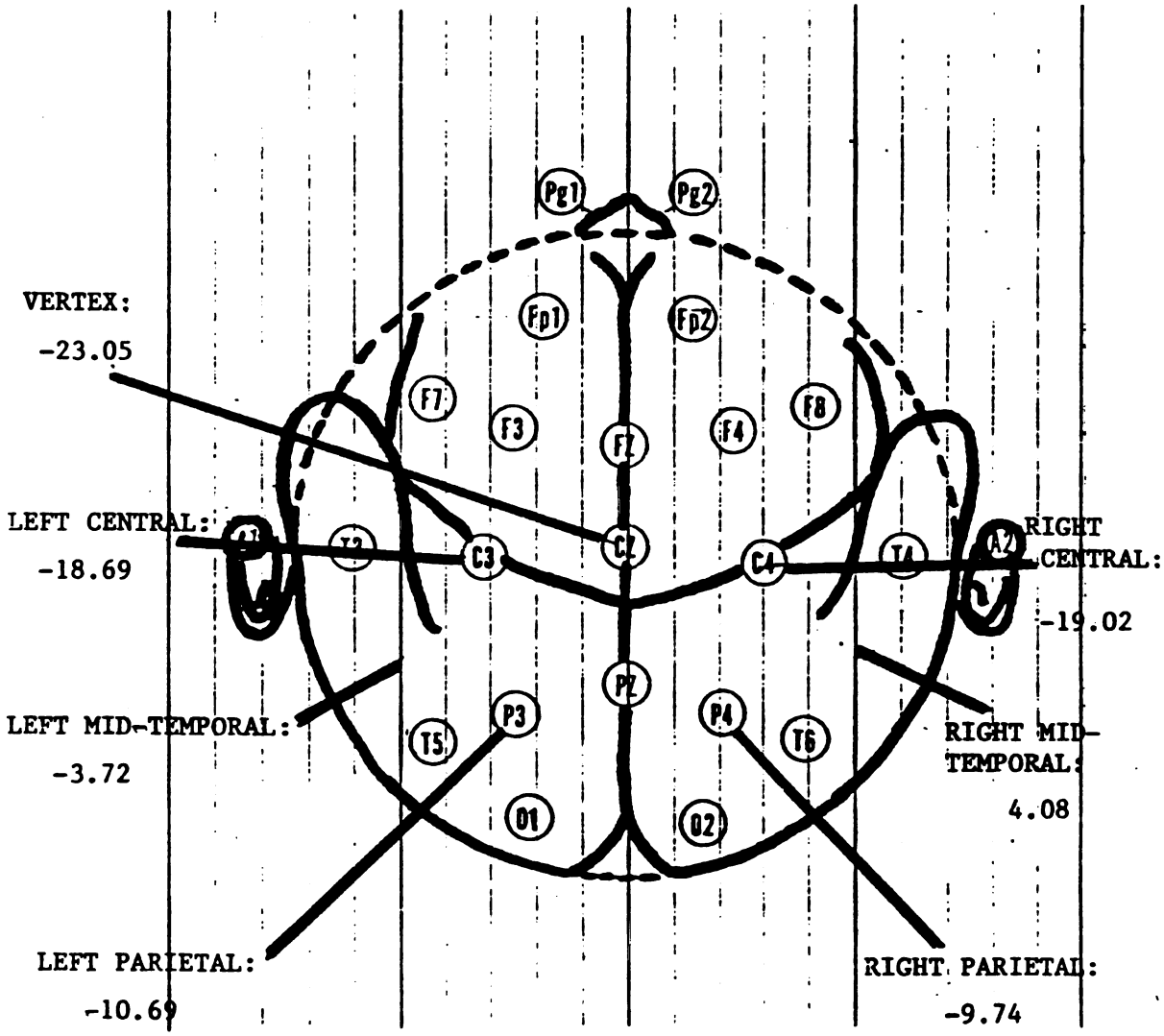
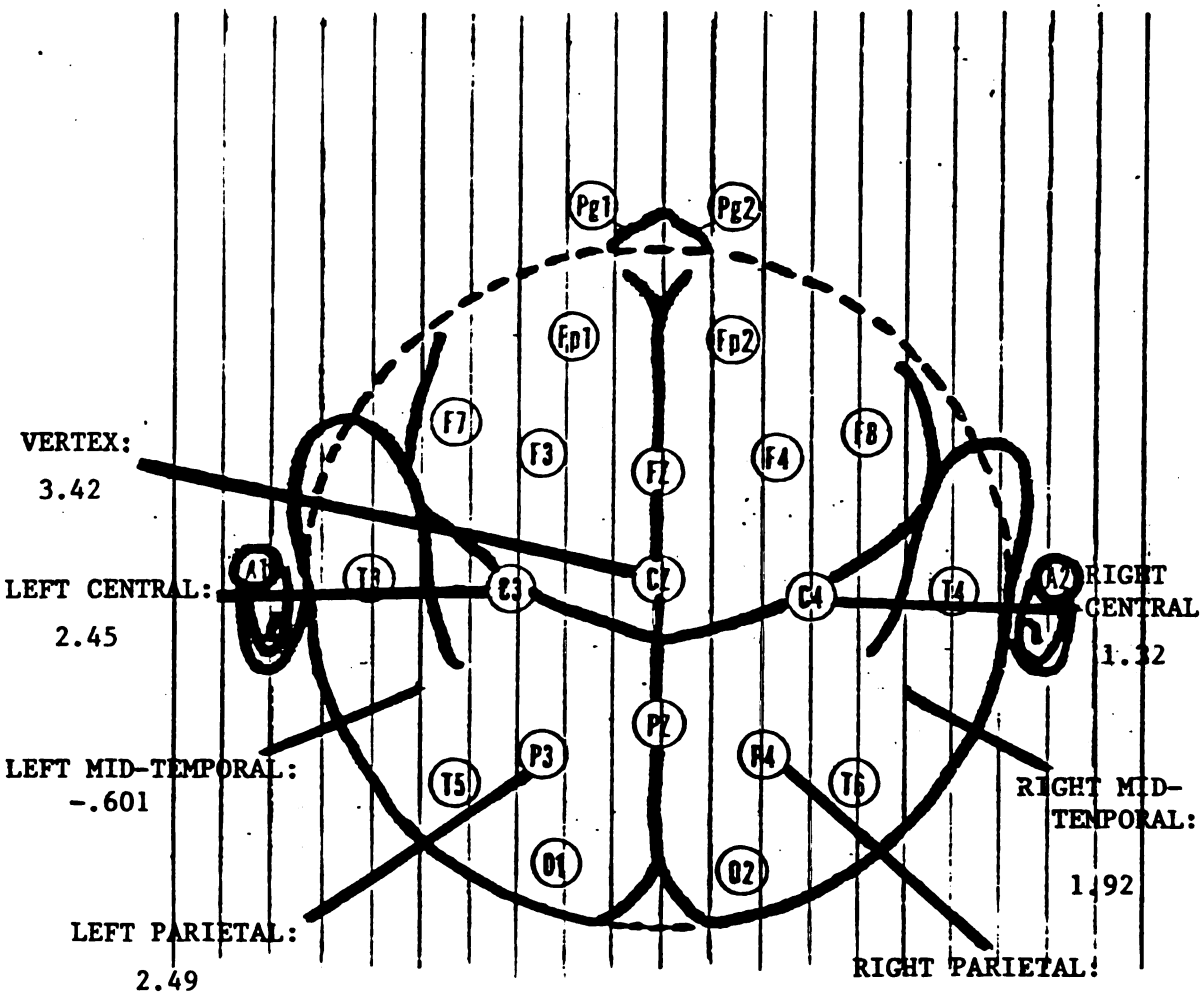


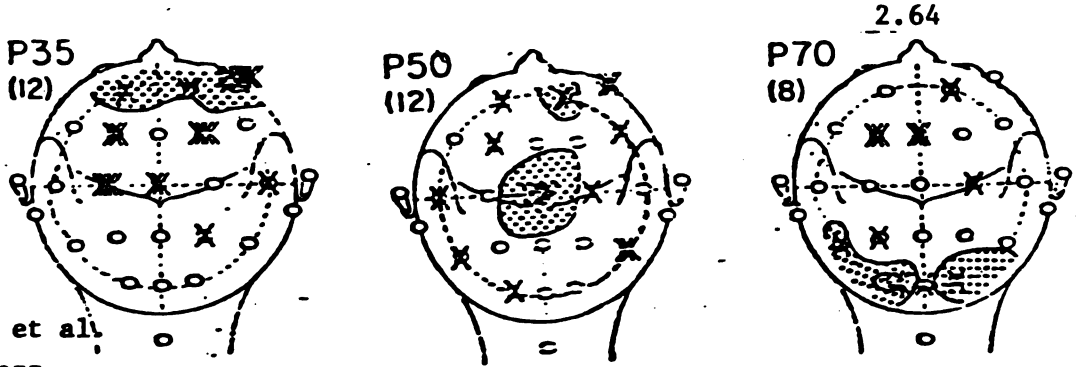
FIGURE 8

SCALP TOPOGRAPHY OF

FACTOR SCORES:

AUDITORY P70- LISTEN TASK





FROM:

GOFF, et al.

1977

TABLE 1

PEAK AMPLITUDES AND LATENCIES

A. VISUAL P100

AT P4-A1A2

	AMPLITUDE (μV)			LATENCY (MSECS)		
	$\bar{X}$	S.D.	RANGE	$\bar{X}$	S.D.	RANGE
READ	1.77	3.04	-3.60 - 7.56	110	11.8	90-130
LISTEN	4.45	2.56	0 - 8.03	110	9.6	90-130
ATTEND	3.80	3.56	-.44 - 12.41	110	12.7	90-135

B. AUDITORY N100

AT CZ-A1A2

	AMPLITUDE (μV)			LATENCY (MSECS)		
	$\bar{X}$	S.D.	RANGE	$\bar{X}$	S.D.	RANGE
READ	-4.92	3.55	-9.95 - 3.14	108	11.8	80-120
LISTEN	-1.35	2.11	6.22 - 2.07	108	16.2	80-130
ATTEND	-5.04	2.88	-9.56 - .19	113	11.4	100 130

TABLE 2A

T-TESTS ON DIFFERENCES

BETWEEN TASKS:

AMPLITUDE & LATENCY

VISUAL P100 AT P4-A1A2

△ AMPLITUDE

	$\bar{X}$	S.D.	t	prob.
READ-ATTEND	-2.03	2.99	-2.62	.02
READ-LISTEN	-2.68	3.31	-3.14	.007
LISTEN-ATTEND	.65	3.16	.80	.44

△ LATENCY

	$\bar{X}$	S.D.	t	prob.
READ-ATTEND	0	8.86	.00	1.00
READ-LISTEN	0	11.81	.00	1.00
LISTEN-ATTEND	0	11.80	.00	1.00

TABLE 2B

T-TESTS ON DIFFERENCES

BETWEEN TASKS:

AMPLITUDE & LATENCY

AUDITORY N100 AT CZ-A1A2

Δ AMPLITUDE

	$\bar{X}$	S.D.	t	prob.
READ-ATTEND	.12	3.51	.13	.90
READ LISTEN	-3.57	3.63	-3.81	.002
LISTEN-ATTEND	3.69	3.52	4.07	.001

Δ LATENCY

	$\bar{X}$	S.D.	t	prob.
READ-ATTEND	-5	12.68	-1.53	.15
READ-LISTEN	0	16.53	-.08	.94
LISTEN ATTEND	-5	22.16	-.82	.43

TABLE 3

MEAN FACTOR SCORES

A. VISUAL P100 FACTOR

P4-A1A2

	MEAN	S.D.
READ	5.09	17.66
LISTEN	13.34	12.99
ATTEND	6.34	21.56

B. AUDITORY N100 FACTOR

CZ-A1A2

	MEAN	S.D.
READ	-29.78	27.32
LISTEN	-9.39	17.34
ATTEND	-29.97	16.39

TABLE 4

T-TESTS ON DIFFERENCES

BETWEEN TASKS

A. VISUAL P100 FACTOR

P4-A1A2

	MEAN	S.D.	t	prob.
READ-ATTEND	-1.24	16.19	-.30	.77
READ-LISTEN	-8.24	16.11	-1.98	.07
LISTEN-ATTEND	7.00	22.08	1.23	.24

B. AUDITORY N100 FACTOR

CZ-A1A2

	MEAN	S.D.	t	prob.
READ-ATTEND	.19	28.02	.03	.98
READ-LISTEN	-20.39	25.60	-3.09	.008
LISTEN-ATTEND	20.58	21.60	3.69	.002

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APPENDIX 1

Program for Picking

Peak Amplitudes and Latencies

(Statistical Analysis System)

```
1         DATA P4RSE;
2         SET TAPETHES.P4VISPKS;
3         IF IEXP=57;
4         LENGTH DEFAULT=4;
5         ARRAY AEP(I) AEP1-AEP130;
6         P4RSEPK=AEP18;
7         P4RSELT=90;
8         DO I=18 TO 27;
9         IF AEP > P4RSEPK THEN DO; P4RSELT=I*5;
10           P4RSEPK=AEP;
11        END;
12           END;
13        P4RSEPK=P4RSEPK/100;
14        PEAK=P4RSEPK;
15        LATENCY=P4RSELT;
16        KEEP ISBJ GROUP COHORT ICON IREF  IEXP ICHN P4RSEPK P4RSELT PEAK LATENCY;

NOTE: DATA SET WORK.P4RSE HAS 15 OBSERVATIONS AND 11 VARIABLES.
NOTE: THE DATA STATEMENT USED 1.14 SECONDS AND 498K.

17        DATA P4LIS;
18        SET TAPETHES.P4VISPKS;
19        IF IEXP=59;
20        LENGTH DEFAULT=4;
21        ARRAY AEP(I) AEP1-AEP130;
22        P4LISPK=AEP18;
23        P4LISLT=90;
24        DO I=18 TO 27;
25        IF AEP > P4LISPK THEN DO; P4LISLT=I*5;
26          P4LISPK=AEP;
27        END;
28           END;
29        P4LISPK=P4LISPK/100;
30        PEAK=P4LISPK;
31        LATENCY=P4LISLT;
32        KEEP ISBJ GROUP COHORT ICON IEXP IREF ICHN P4LISPK P4LISLT PEAK LATENCY;

NOTE: DATA SET WORK.P4LIS HAS 15 OBSERVATIONS AND 11 VARIABLES.
NOTE: THE DATA STATEMENT USED 1.17 SECONDS AND 498K.

33        DATA P4ATT;
34        SET TAPETHES.P4VISPKS;
35        LENGTH DEFAULT=4;
36        IF IEXP=71;
37        ARRAY AEP(I) AEP1-AEP130;
38        P4ATTPK=AEP18;
39        P4ATTLT=90;
40        DO I=18 TO 27;
41        IF AEP > P4ATTPK THEN DO; P4ATTLT=I*5;
42        P4ATTPK=AEP;
43        END;
44           END;
45        P4ATTPK=P4ATTPK/100;
```

APPENDIX 1

continued

```
46          PEAK=P4ATTPK;
47          LATENCY=P4ATTLT;
48          KEEP ISBJ GROUP COHORT ICON IEXP IREF ICHN PEAK LATENCY P4ATTPK P4ATTLT;

NOTE: DATA SET WORK.P4ATT HAS 15 OBSERVATIONS AND 11 VARIABLES.
NOTE: THE DATA STATEMENT USED 1.18 SECONDS AND 498K.

49          DATA CZRSE;
50          SET TAPETHES.CZAUDPKS;
51          IF IEXP=57;
52          LENGTH DEFAULT=4;
53          ARRAY AEP(I) AEP1-AEP130;
54          CZRSEPK=AEP16;
55          CZRSELT=80;
56          DO I=16 TO 26;
57          IF AEP < CZRSEPK THEN DO; CZRSELT=I*5;
58          CZRSEPK=AEP;
59          END;
60             END;
61          CZRSEPK=CZRSEPK/100;
62          PEAK=CZRSEPK;
63          LATENCY=CZRSELT;
64          KEEP ISBJ GROUP COHORT ICON IEXP IREF ICHN PEAK LATENCY CZRSEPK CZRSELT;

NOTE: DATA SET WORK.CZRSE HAS 15 OBSERVATIONS AND 11 VARIABLES.
NOTE: THE DATA STATEMENT USED 1.20 SECONDS AND 498K.

65          DATA CZLIS;
66          SET TAPETHES.CZAUDPKS;
67          IF IEXP=59;
68          LENGTH DEFAULT=4;
69          ARRAY AEP(I) AEP1-AEP130;
70          CZLISPK=AEP16;
71          CZLISLT=80;
72          DO I=16 TO 26;
73          IF AEP < CZLISPK THEN DO; CZLISLT=I*5;
74            CZLISPK=AEP;
75          END;
76             END;
77          CZLISPK=CZLISPK/100;
78          PEAK=CZLISPK;
79          LATENCY=CZLISLT;
80          KEEP ISBJ GROUP COHORT ICON IEXP IREF ICHN PEAK LATENCY CZLISPK CZLISLT;

NOTE: DATA SET WORK.CZLIS HAS 15 OBSERVATIONS AND 11 VARIABLES.
NOTE: THE DATA STATEMENT USED 1.20 SECONDS AND 498K.

81          DATA CZATT;
82           SET TAPETHES.CZAUDPKS;
83          LENGTH DEFAULT=4;
84           IF IEXP=71;
85          ARRAY AEP(I) AEP1-AEP130;
86          CZATTPK=AEP16;
87          CZATTLT=80;
88          DO I=16 TO 26;
89          IF AEP < CZATTPK THEN DO; CZATTLT=I*5;
90          CZATTPK=AEP;
91          END;
```

APPENDIX 1

continued

```
92          END;
93        CZATTPK=CZATTPK/100;
94        PEAK=CZATTPK;
95        LATENCY=CZATTLT;
96        KEEP ISBJ GROUP COHORT ICON IEXP IREF ICHN PEAK LATENCY CZATTPK CZATTLT;

NOTE: DATA SET WORK.CZATT HAS 15 OBSERVATIONS AND 11 VARIABLES.
NOTE: THE DATA STATEMENT USED 1.20 SECONDS AND 498K.

97        DATA P1;
98        SET P4RSE P4LIS P4ATT;
99        LENGTH DEFAULT=4;
100       KEEP ISBJ IEXP ICON ICHN GROUP COHORT IREF PEAK LATENCY;

NOTE: DATA SET WORK.P1 HAS 45 OBSERVATIONS AND 9 VARIABLES.
NOTE: THE DATA STATEMENT USED 0.51 SECONDS AND 482K.

101       DATA N1;
102       SET CZRSE CZLIS CZATT;
103       LENGTH DEFAULT=4;
104       KEEP ISBJ IEXP ICON ICHN GROUP COHORT IREF PEAK LATENCY;

NOTE: DATA SET WORK.N1 HAS 45 OBSERVATIONS AND 9 VARIABLES.
NOTE: THE DATA STATEMENT USED 0.52 SECONDS AND 482K.

105       PROC SORT DATA=P1; BY IEXP ICHN;

NOTE: DATA SET WORK.P1 HAS 45 OBSERVATIONS AND 9 VARIABLES.
NOTE: THE PROCEDURE SORT USED 0.54 SECONDS AND 1024K.

106       PROC PRINT DATA=P1;
107       TITLE PEAK AMPLITUDES AND LATENCIES FOR READING, LISTENING, ATTENDING;
108       TITLE3 VISUAL MODALITY;

NOTE: THE PROCEDURE PRINT USED 0.82 SECONDS AND 474K AND PRINTED PAGE 1.

109       PROC MEANS DATA=P1 MEAN STD N;
110       TITLE2 MEAN POSITIVE PEAK BETWEEN 90-135 MSEC., AT P4-A1A2;
111         VAR PEAK LATENCY; BY IEXP ICHN;

NOTE: THE PROCEDURE MEANS USED 0.57 SECONDS AND 476K AND PRINTED PAGE 2.

112       PROC SORT DATA=N1; BY IEXP ICHN;

NOTE: DATA SET WORK.N1 HAS 45 OBSERVATIONS AND 9 VARIABLES.
NOTE: THE PROCEDURE SORT USED 0.54 SECONDS AND 1024K.

113       PROC PRINT DATA=N1;
114       TITLE PEAK AMPLITUDES AND LATENCIES FOR READING, LISTENING, ATTENDING;
115       TITLE3 AUDITORY MODALITY;

NOTE: THE PROCEDURE PRINT USED 0.84 SECONDS AND 478K AND PRINTED PAGE 3.

116       PROC MEANS DATA=N1 MEAN STD N;
117         VAR PEAK LATENCY; BY IEXP ICHN;
118       TITLE2 MEAN NEGATIVE PEAK BETWEEN 80 AND 130 MSEC, AT VERTEX-A1A2;

NOTE: THE PROCEDURE MEANS USED 0.58 SECONDS AND 482K AND PRINTED PAGE 4.
```

APPENDIX 1

continued

```
119     DATA P4TTESTS;
120     MERGE P4RSE P4LIS P4ATT; BY ISBJ;
121     LENGTH DEFAULT=4;
122     RSEATTDF=P4RSEPK-P4ATTPK;
123     RSELISDF=P4RSEPK-P4LISPK;
124     LISATTDF=P4LISPK-P4ATTPK;
125     RSEATT2=P4RSELT-P4ATTLT;
126     RSELIS2=P4RSELT-P4LISLT;
127     LISATT2=P4LISLT-P4ATTLT;
128     LABEL RSEATTDF=READ VS. ATTEND PEAK DIFFERENCE
129           RSELISDF=READ VS. LISTEN PEAK DIFFERENCE
130           LISATTDF=LISTEN VS. ATTEND PEAK DIFFERENCE
131           RSEATT2=READ VS. ATTEND LATENCY DIFFERENCE
132           RSELIS2=READ VS LISTEN LATENCY DIFFERENCE
133           LISATT2=LISTEN VS. ATTEND LATENCY DIFFERENCE;
134     KEEP RSEATTDF RSELISDF LISATTDF RSEATT2 RSELIS2 LISATT2;

NOTE: DATA SET WORK.P4TTESTS HAS 15 OBSERVATIONS AND 6 VARIABLES.
NOTE: THE DATA STATEMENT USED 0.65 SECONDS AND 1002K.

135     PROC MEANS DATA=P4TTESTS T STD N PRT; VAR RSEATTDF RSELISDF LISATTDF
136           RSEATT2 RSELIS2 LISATT2;
137     TITLE DIFFERENCE SCORES BETWEEN TASKS - P4 VISUAL;
138     TITLE2;
139     TITLE3;

NOTE: THE PROCEDURE MEANS USED 0.55 SECONDS AND 1002K AND PRINTED PAGE 5.

140     DATA CZTTESTS;
141     MERGE CZRSE CZLIS CZATT; BY ISBJ;
142     LENGTH DEFAULT=4;
143     RSEATTDF=CZRSEPK-CZATTPK;
144     RSELISDF=CZRSEPK-CZLISPK;
145     LISATTDF=CZLISPK-CZATTPK;
146     RSEATT2=CZRSELT-CZATTLT;
147     RSELIS2=CZRSELT-CZLISLT;
148     LISATT2=CZLISLT-CZATTLT;
149     LABEL RSEATTDF=READ VS. ATTEND PEAK DIFFERENCE
150           RSELISDF=READ VS. LISTEN PEAK DIFFERENCE
151           LISATTDF=LISTEN VS. ATTEND PEAK DIFFERENCE
152           RSEATT2=READ VS. ATTEND LATENCY DIFFERENCE
153           RSELIS2=READ VS LISTEN LATENCY DIFFERENCE
154           LISATT2=LISTEN VS. ATTEND LATENCY DIFFERENCE;
155     KEEP RSEATTDF RSELISDF LISATTDF RSEATT2 RSELIS2 LISATT2;

NOTE: DATA SET WORK.CZTTESTS HAS 15 OBSERVATIONS AND 6 VARIABLES.
NOTE: THE DATA STATEMENT USED 0.65 SECONDS AND 1002K.

156     PROC MEANS T STD N PRT; VAR RSEATTDF RSELISDF LISATTDF
157           RSEATT2 RSELIS2 LISATT2;
158     TITLE DIFFERENCE SCORES BETWEEN TASKS - CZ AUDITORY;

NOTE: THE PROCEDURE MEANS USED 0.53 SECONDS AND 1002K AND PRINTED PAGE 6.
```

APPENDIX 2

Program for Computation of

Latency-Adjusted Covariance Matrix

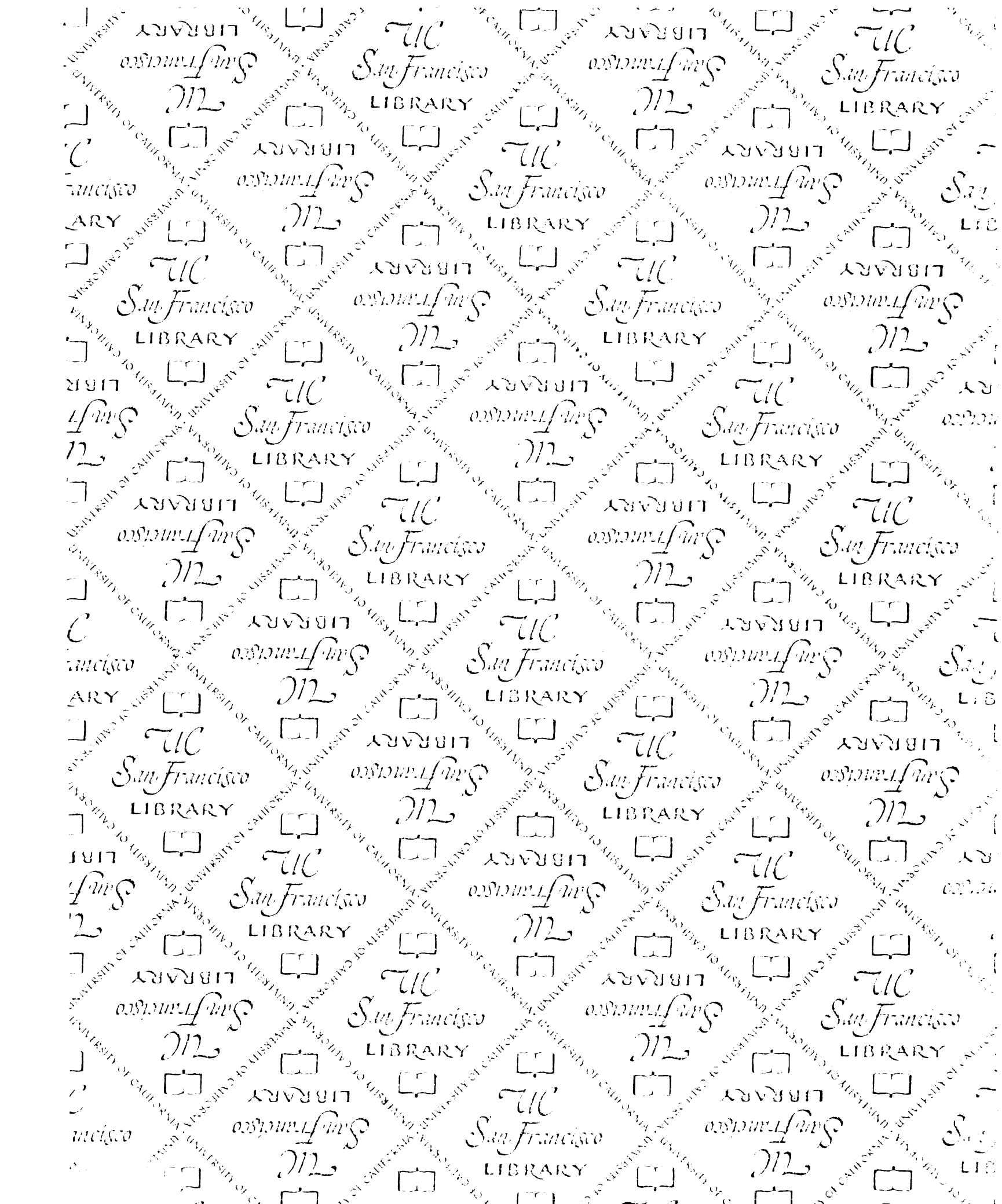
(Statistical Analysis System)

```
1          DATA A;
2          INPUT ISBJ P3RSELT P3LISLT P3ATTLT P4RSELT P4LISLT P4ATTLT;
3          PARLATE=P4RSELT;
4          IEXP=57;
5          OUTPUT;
6          PARLATE=P4LISLT;
7          IEXP=59;
8          OUTPUT;
9          PARLATE=P4ATTLT;
10         IEXP=71;
11         OUTPUT;
12         KEEP ISBJ IEXP PARLATE;
13         CARDS;

NOTE: DATA SET WORK.A HAS 45 OBSERVATIONS AND 3 VARIABLES. 680 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.31 SECONDS AND 170K.

29         ;
30         DATA B;
31          SET TAPETHEZ.VISDATA;
32         LENGTH DEFAULT=4;

NOTE: DATA SET WORK.B HAS 360 OBSERVATIONS AND 136 VARIABLES. 34 OBS/TRK.
NOTE: THE DATA STATEMENT USED 1.58 SECONDS AND 186K.

33         PROC SORT DATA=B; BY IEXP ISBJ;

NOTE: DATA SET WORK.B HAS 360 OBSERVATIONS AND 136 VARIABLES. 34 OBS/TRK.
NOTE: THE PROCEDURE SORT USED 1.70 SECONDS AND 338K.

34         PROC SORT DATA=A; BY IEXP ISBJ;

NOTE: DATA SET WORK.A HAS 45 OBSERVATIONS AND 3 VARIABLES. 680 OBS/TRK.
NOTE: THE PROCEDURE SORT USED 0.66 SECONDS AND 332K.

35         DATA FORADJ;
36         MERGE B A; BY IEXP ISBJ;
37         IF ICHN~=8;
38         LENGTH DEFAULT=4;
39         KEEP ISBJ IEXP ICHN AEP1-AEP130 PARLATE;

NOTE: DATA SET WORK.FORADJ HAS 315 OBSERVATIONS AND 134 VARIABLES. 35 OBS/TRK.
NOTE: THE DATA STATEMENT USED 1.65 SECONDS AND 206K.

40         PROC PRINT;
41          VAR ISBJ IEXP ICHN AEP20 PARLATE;

NOTE: THE PROCEDURE PRINT USED 2.31 SECONDS AND 226K AND PRINTED PAGES 1 TO 6.

42         PROC MATRIX ;
43           FETCH X DATA=FORADJ;
```

APPENDIX 2

Continued

```
44          NI=NCOL(X); NJ=NROW(X);
45          Y=J(NJ,32,0);
46            DO M=1 TO NJ;
47            DO II=1 TO 3;
48          Y(M,II)=X(M,II);
49            END;
50          LAT=(X(M,NI)*8/5)+3;
51          BEG=LAT-15;
52            DO JJ=1 TO 29;
53          KK=JJ+3;
54          LL=BEG+JJ;
55          Y(M,KK)=X(M,LL);
56           END;
57          END;
58          OUTPUT Y OUT=ADJSTD.P100FAC;

NOTE: DATA SET ADJSTD.P100FAC HAS 315 OBSERVATIONS AND 33 VARIABLES.
NOTE: THE PROCEDURE MATRIX USED 18.28 SECONDS AND 642K AND PRINTED PAGE 7.

59          PROC PRINT DATA=ADJSTD.P100FAC;

NOTE: THE PROCEDURE PRINT USED 10.84 SECONDS AND 258K AND PRINTED PAGES 8 TO 20.

NOTE: SAS USED 642K MEMORY.

NOTE: SAS INSTITUTE INC.
      SAS CIRCLE
      BOX 8000
      CARY, N.C. 27511
```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