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# THE EFFECTS OF ARROW DIRECTION, LENGTH OF INTERSTIMULUS INTERVAL, AND CERTAINTY OF INTERSTIMULUS INTERVAL LENGTH ON EVENT RELATED POTENTIALS OCCURRING DURING THE COURSE OF THE INTERSTIMULUS INTERVAL

by

Alvin L. Keyes

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# APPROVAL PAGE

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# ABSTRACT

KEYES, ALVIN L., Ph.D. The Effects of Arrow Direction, Length of Interstimulus Interval, and Certainty of Interstimulus Interval Length on Event Related Potentials Occurring During the Course of the Interstimulus Interval. (1995)
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This study examined the electrophysiological correlates of the preparatory processes intervening between the presentation of an attention-directing arrow cue and the presentation of a target stimulus. A paradigm used in earlier studies by Harter and associates and UNCG was employed wherin a peripherally-presented target stimulus followed by 600 ms a foveally-presented arrow cue directing attention to the right or left visual field. The subject was required to respond to the target within a designated time period if it appeared in the cued field. No response was required if the stimulus appeared in the uncued field.

The primary purpose of the study was to determine the electrophysiological changes, as reflected in scalp recorded ERPs, which accompany the attentional preparatory processes developing during the course of the interstimulus interval (ISI). The time course of the attentional preparatory process was studied as a function of the length and certainty of length of the preparatory interval.

Recordings were obtained from O1, O2, P3, P4, C3, C4, F3, and F4; referenced to yoked earlobes. Amplified signals evoked by the attention directing stimulus (right or left) were averaged with a computer. Combined left hemisphere averages to right arrow cues and right hemisphere averages

to left arrow cues formed the database for the contralateral arrow condition. The two hemisphere averages for the ipsilateral arrow cue were likewise combined to form the database for the ipsilateral condition.

The earliest arrow direction effects were observed over a latency interval of 250-500 ms which "rode" on P300. During this interval the ERP was relatively more negative over a given hemisphere when the arrow cue pointed to the contralateral visual field than when the arrow cue pointed to the ipsilateral field. The amplitude of this endogenous contralateral negativity, as reflected in difference potentials, varied inversely with ISI length. The onset latency and duration of the activity was unaffected. In addition to this early effect, the rate of buildup of a negative slow wave (NSW) which began at about 400 ms and lasted until presentation of the target stimulus also varied with arrow direction, being greater over a given hemisphere when the arrow pointed to the contralateral field. Also, rate of buildup varied inversely with ISI length. The rate of buildup also was dependent on the subject's degree of certainty of ISI length on a given trial. These results indicate attention related processes are initiated soon after presentation of the arrow cue. The NSW reflects both differential hemispheric preparation as a function of the arrow cue as well as intensity of preparation as a function of the length and certainty of length of the ISI.

# ACKNOWLEDGEMENTS

It is with much gratitude that I dedicate this project to the memory of Dr. M. Russell Harter, whose insight, knowledge and significant contributions to ERP research motivated me to to continue research in this area. To Dr. Robert G. Eason I extend sincere thanks for accepting me as a student, and providing profound scholarship and unwavering support and mentorship during the development and completion of the dissertation. I would also like to thank my committee members, Drs. DeCasper, Shull, Soderquist, and Nile who in their own unique ways challenged me to continue to learn and develop intellectually.

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# CHAPTER 1

# INTRODUCTION

Organisms, humans in particular, are constantly bombarded with stimuli from the external environment (i.e. through the auditory, visual, olfactory, tactile, and gustatory systems) and internally-derived sources (i.e. thoughts, ideas and perceptions). Both sources of stimulation appear to help us understand and detect the surroundings, and make decisions about how to approach our environment. Consequently, we must constantly monitor what sensations are transferred into short-term memory to be later interpreted as perceptions, and yet remain consciously aware of a limited amount of pertinent and immediately useful information at any moment.

The processes of mental monitoring and utilizing one set of stimuli over another are collectively called attention, a concept that has engaged the mental inquiry of philosophers and scientists for many decades. Wijers (1989) has summarized the historical development of the concept of attention. According to him, Wundt suggested that attention is the crux of sensation and perception. Titchner, having observed that when two events are presented simultaneously the one to which attention is diverted seems to occur earlier, concluded that prior entry of stimuli into an organism's sensory system plays a major role in the selection process. James viewed attention as a mechanism which permits the discrimination of objects in the world and the focusing on specific aspects of the environment, thus avoiding the perception of one's surroundings as an undifferentiated mass or space. To James, attention is a purposeful event which orients one to the environment in such a way as to increase the likelihood of survival.

Early ideas about attention assumed that consciousness plays a central role in the attending process. With the advent of behaviorism, the study of attention greatly diminished, because conscious processes were considered to be intangible and unobservable phenomena. With the emergence of the information processing approach for studying psychological phenomena in the 1950s, interest in the study of attentional processes from that perspective also emerged. This approach carries the assumption that the state of the organism at the time of stimulation, along with a number of discrete mental operations occurring between the moment of external stimulation of the organism and the overt response in reaction to this stimulation, can be distinguished (Cowey, 1985). These states and conceptual operations are summarized below.

One is selectivity. This process involves the selection of those stimuli or features of stimuli in the environment which must be fully processed in order to produce an appropriate response to a specified stimulus. An example would be the selection of a red #3 embedded in an array of blue, yellow, and green alphanumeric stimuli.

A second is alertness. This state variable, whether tonic or phasic, plays an important role in the attentional process. It is assumed that an optimal level of arousal or alertness is required for maximal attentiveness.

A third concept is limited capacity. The availability of neuronal clusters required for the processing of two or more tasks is assumed to place a limit on the rapidity with which relevant features of given stimuli can be selected and processed. Because of the limited number of neural channels and networks available for processing specific features, attention must be allocated to the stimulus field so as not to overload the limited capacity system.

## EARLY VS LATE PROCESSING OF SPATIAL ATTENTION

An issue of continuing interest to neuroscientists is whether information about the various features of a given stimulus are processed sequentially or in parallel, and whether all of the information must be processed before a decision can be made as to how to respond to the presence or absence of a given feature.

The early processing model first proposed by Broadbent (1958) assumed that the number of neural channels available for processing the various features of a stimulus are limited, and that a mechanism exists which restricts the number of features that can be processed at any given time. He proposed the mechanism selects only one input channel at a time and switches between channels no more than about twice a second. The restriction and switching mechanisms collectively act as a dynamic "filter" which prevents overloading the serial, limited capacity processing system. This filter is presumed to be engaged immediately upon the arrival of information at the sensory register. When an individual is instructed to attend to a specific stimulus feature ("stimulus set" in Broadbent's terms), the filter rejects and discards irrelevant attributes while passing relevant information to the next stage for further processing.

In contrast to the early selection model, the late selection model assumes that when one selectively attends to a given stimulus feature, the appropriate response to that feature cannot be made until all features of the stimulus have been processed. This late processing model assumes that all of the stimulus features are simultaneously processed in parallel pathways (Deutsch & Deutsch, 1963; Treisman, 1960).

The validity of each of these models has stimulated much interest among cognitive psychologists and neuroscientists (Posner, 1975, 1980; Posner & Boises, 1971; Hillyard & Hansen, 1986; Hillyard & Kutas, 1983). An extensive body of neuroscience literature has accrued over the past two decades which has attempted to resolve the so-called early vs late processing issue (Hillyard, et al. 1986; Harter, et al. 1979; Heinze, Luck, Mangun, & Hillyard, 1990; Donchin, 1981). Numerous studies, including studies by Hillyard and associates (Hillyard & Mangun, 1987; Hillyard, Munte, & Neville, 1985), Harter, et al (Harter & Aine, 1984) and others (Mangun & Hillyard, 1987; Mangun & Hillyard, 1990), have provided data which suggest that specific ERP components reflect the separate processing of specific stimulus features at different points in time. Although a stimulus situation can be devised which requires that all stimulus features be processed before an appropriate decision can be made as to how to react to that situation, it is now generally accepted that the features of a complex stimulus are analyzed separately and at different stages, with processing occurring both sequentially and in parallel. There is now general agreement among cognitive neuroscientists that by careful analysis of the onset, amplitude, and duration of ERP components recorded from widespread locations over the scalp, the time course for processing various features of a stimulus can be ascertained (Luck & Hillyard, 1990; Bergen & Julesz, 1983; Coles, Gratton, Bashore, Eriksen, & Donchin, 1985).

## SPATIAL ATTENTION

Posner and associates (Posner, Inhoff, & Friedrich, 1987; Posner & Petersen, 1990) have proposed that when one shifts attention from a given location in space to another location, a process Posner calls spatial orienting, three sequential mental operations are engaged. They are (a) disengagement from the location presently being attended to; (2) shifting to the new location; and (3) reengagement or focusing attention on the new location.

### Spatial Attention Effects on ERPs Evoked by Relevant and Irrelevant Target Stimuli

The vast majority of the ERP literature has focused on the effects of instructing individuals to selectively attend to specific locations and features of a to-be-presented stumulus on ERP components evoked by the stimulus (including latency, amplitude, duration, and scalp distribution (Hanson & Hillyard, 1984; Naatanen, 1982; Picton and Hillyard 1988; Oakley and Eason, 1990, Harter and Aine, 1984).

The first report that selectively attending to a specified location results in larger amplitude ERPs evoked by stimuli presented at that location, compared to ERPs evoked at that same location when it is not being attended, dates back to 1969 (Eason, Harter, and White, 1969).

In the paradigm employed by Eason, et al. subjects were instructed to maintain sustained attention at a specified peripheral location in either the right or left visual field for brief periods of time while keeping their eyes fixated straight ahead. Small spots of light were presented quasi randomly and sequentially (i.e., never simultaneously) to each visual field at an average rate of 1/sec. The subject was instructed to make a finger-lift response as quickly as possible to each stimulus appearing at the attended location while attempting to ignore stimuli appearing in the opposite field.

These results have been replicated numerous times in subsequent studies using the same or modified versions of the Eason, et al. paradigm (Picton & Hillyard, 1988; Eason, 1981; Harter and Aine, 1984; Hillyard and Munte, 1984; Van Vooris and Hillyard, 1977). It is now widely accepted that focusing attention at a spatial location prior to the presentation of a stimulus at that location influences the brain's response to that stimulus (Picton and Hillyard, 1988).

In addition to showing that early ERP components (100-300 msec. latency) recorded over posterior regions of the scalp are larger when attention is focused on the location at which the target stimulus is presented, most studies have shown that the degree of increase is larger over the hemisphere contralateral to the visual field being attended. Differences in the scalp distribution of these early components suggest that focusing attention at a given spatial location engages at least two neural mechanisms, one of which is located in occipital cortex and the other in parietal cortex (Hillyard and Munte, 1984; Wurtz, Goldberg, and Robinson, 1980).

When a target stimulus appears in the attended visual field and the subject is instructed to respond to it only if it contains a specific feature (e.g., is red rather than green), the amplitude of an ERP component of positive polarity with a peak latency of 300-400 msec (referred to as P300) is enhanced when the stimulus contains that feature (Friedman, 1990; Johnson, Pfefferbaum, & Kopell, 1985; Harter, Anllo-Vento, Wood, & Schroeder, 1988). The enhanced amplitude is assumed to reflect increased activation of neural processes associated with making a decision as to the presence or absence of the feature and whether a response is required (Courchesne, Hillyard, & Galambos, 1975; Donchin & Coles, 1988). It is now generally accepted that P300 represents an endogenous neural process associated with higher-order cognitive functions pertaining to late stages of stimulus feature selection and to memory updating, and is more dependent on the psychological context in which the stimulus is presented than on the physical characteristics of the stimulus per se (Donchin, Ritter, & McCallum, 1978; Donchin, 1979; Fabiani, Karis, & Donchin, 1986; Polich, 1986; Polich, 1887a, 1987b).

## Effects of Warning and Attention-Directing Stimuli on ERPs Recorded in the Interval Between the Cue Stimulus and the Target Stimulus

In contrast to the extensive work referred to above which has focused on changes in ERP components evoked by a target stimulus as a function of the attentional conditions which precede that stimulus, relatively few human ERP studies have examined the neural processes which underlie the attentional preparatory process antecedent to the presentation of the target stimulus.

### Negative Slow Wave ("CNV") Studies

However, a large number of studies, commonly referred to as "CNV" studies, have examined the neural processes associated with preparation to respond to a target stimulus signalled by and immediately preceding warning stimulus. Since the CNV paradigm shares many elements in common with the cue-target interstimulus interval attention paradigm emplyed by Harter and others (Harter, et al, 1989; Friedman-Hill & Mangun, 1993; Yamaguchi & Kobayashi, 1993), it bears some relevance to the findings and conclusions derived from attention paradigm studies summarized in the next section. Therefore, a brief summary of the CNV work will first be presented.

CNV studies typically have used a reaction time paradigm in which a target (imperative) stimulus is followed after some delay by a cue (warning) stimulus (McCallum, 1988). Unlike the Harter paradigm, the warning stimulus in the CNV paradigm carries no directional information as to where the subject is to attend since there is only one stimulus location and the subject already knows where it is. However, the warning stimulus shares an important overlapping function with Harter's cue stimulus in that it alerts the subject to get ready to respond to a target stimulus.

CNV studies traditionally have been concerned with slow wave activity manifested in ERP recordings which develops relatively late after the presentation of the warning stimulus (WS) and shortly before the presentation of the target stimulus (TS). Such slow wave activity tends to be negative in polarity and has a duration of 300 ms or more, depending on the length of the WS-TS interval.

The first study to clearly establish the existence of a negative slow wave during this interval was conducted by Walter, et al., in 1964. These researchers named it contingent negative variation (CNV), because it constituted a negative variation from the resting baseline level of the EEG, and it appeared to be contingent on the expectation that a target (imperative) stimulus would follow the warning (conditional) stimulus.

Shortly thereafter, Kornhuber and Deecke (cited in Birbaumer, Elbert, Canavan, & Rockstroh, 1990) reported that a slow negative potential begins to build up about 30 seconds before a subject makes a voluntary button press at intervals of their own choosing. The negativity was reported to reach a maximum just prior to the initiation of the motor action. This wave, which is referred to in English as the Readiness Potential (RP) probably summates with the latter portion of the CNV obtained with the WS-TS paradigm.

Since these early studies the slow wave negativity has been found to be influenced by a host of variables, including expectancy, probability of occurrence of the target stimulus, energy required to respond to the target stimulus, motivation, distraction, learning and memory, orienting, arousal, and alerting (McCallum, 1988). It is now generally accepted that the overall shape of the negative slow wave recorded at the scalp represents the algebraic summation of the composite activity of two or more brain areas activated by some combination of the factors mentioned above (McCallum, 1988).

Despite these complexities, many if not most investigators have emphasized activational and attentional constructs in their interpretations of the functional significance of the "CNV". In their initial study, Walter et al. (1964) suggested that the buildup in negativity preceding the target stimulus reflects an attentional process, as did Hillyard and Galambos (1967) three years later. In his review of the CNV literature, McCallum (1988) surmised that the CNV may be associated "...with sustaining a focus of awereness on a given configuration or succession of stimuli" (p.447). Although the results are far from consistent, when the subject is required to perform an extraneous task concomitantly with the WS-TS reaction time task, the degree of buildup of the CNV wave immediately prior to the presentation of the TS is decreased (Tecce and Hamilton, 1973; Rockstroh, Elbert, Lutzenberger, & Birbaumer, 1986). These results have been interpreted as evidence that the magnitude of the negative slow wave reflects the extent to which the subject's attention is focused on the target stimulus prior to its occurrence.

Rohrbaugh and Gaillard (1983) have interpreted the early part of the NSW occurring in the 600-800 msec range after the warning stimulus as reflecting an orienting or arousal reaction to the warning stimulus. These investigators have interpreted the later phase of the NSW, which can be observed in ISIs longer than 1000 msec, as being a manifestation of the Readiness Potential associated with preparation to make a motor response. In fact, they have suggested that the NSW is comprised solely of these two comonents, a conclusion to which McCallum strongly objects (McCallum, 1988). McCallum feels that the findings reported in the literature, in toto, provide evidence that arousal, expectency, and attention contribute to the NSW along with an orientation response to the warning stimulus and a

Readiness Potential in preparation to respond to the target stimulus.

Studies of the relationship between the NSW and response speed have yielded highly inconsistent results. For those researchers who report a relationship, a negative correlation usually is obtained in which increases in CNV amplitude is accompanied by decreases in reaction time (McAdam, Knott, and Rebert, 1969; Hillyard and Galambos,1967). Gaillard and Naatanen (1973) and others (Rebert, 1972; Rebert and Sperry, 1973) have been unable to find a consistent relationship, leading Nattanen and Gaillard (1983) to conclude that if reaction time is interpreted as an index of prepardness, then the NSW cannot serve as such an index. This issue still is being debated.

### Cue-Target Interstimulus Interval Studies

To the investigator's knowledge, the first studies to focus on ERP correlates of spatial attention preparatory processes which precede the presentation of a target stimulus were conducted by Harter and associates (Harter, Anllo-Vento and Wood, 1989; Harter, et al., 1990; Harter and Anllo-Vento, 1991; Anllo-Vento, 1991; Keyes, 1991). Although few in number, they provide the empirical foundation and rationale, in conjunction with the "CNV" findings summarized above, for the proposed project. A few other researchers have very recently begun to look for ERP changes accompanying the attentional preparatory processes of an expected target stimulus (Friedman-Hill, et al., 1993; Yamaguchi, et al., 1993).

## SUMMARY OF FINDINGS BY HARTER AND ASSOCIATES

The paradigm employed by Harter consisted of a two-stimulus presentation sequence in which a foveally presented arrow cue directed the subject to attend to one of two (sometimes three) possible locations (e.g., left, right, or central visual field). The arrow cue was followed after a brief time interval by a target stimulus presented with equal probability at one of the possible locations. The subject was instructed to attend to the cued location in the designated visual field and to respond as quickly as possible to the target stimulus if it appeared at the cued location (relevant response condition). No response was required if the stimulus appeared at an uncued location (irrelevant response condition). ERPs were recorded from standardized scalp locations throughout the cue-target interstimulus interval, and for a period of time after presentation of the target stimulus.

Studies conducted by Harter and associates using the above paradigm, among others, began in 1983 as part of an eight-year, NIH-supported project dealing with neural correlates of reading disabilities in children. At the time of his death in 1990, Harter had published findings based on only a small portion of the total data base (Harter, et al., 1990). At his request shortly before his death, Eason presented a paper for him at the EPIC-IX Conference in The Netherlands (1989) contrasting the same sample of children's data with data obtained from adults in Alvin Keyes' masters thesis. An expanded report of this paper was prepared by Anllo-Vento and published posthumuously (Harter and Anllo-Vento, 1991).

## Results and Intrepretation of Childrens' Data

Two major findings were reported for the children. One was that after about 200 msec following the presentation of the arrow cue, the ERP became relatively more negative over a given hemisphere when the arrow pointed to the visual field located contralaterally to that hemisphere, compared to its pointing to the field located ipsilaterally to that hemisphere. This contralateral negativity reached its peak approximately at the time that P300 was at its maximum, and its duration spanned approximately 300 ms. Its occipito-frontal scalp distribution showed larger amplitudes at parieto-central regions than at either occipital or frontal regions.

Approximately 450-500 ms after the presentation of the arrow cue, the ERP-waveforms recorded for the contra- vs ipsilateral arrow directions converged, thus ending the relative negativity over the contralateral hemisphere. The two waveforms then crossed over thereby producing relatively greater positivity over the hemisphere lying contralaterally to the cued visual field. This contralateral positivity progressively grew in amplitude, reaching its peak at 700 ms (about 60-100 msec. after the target stimulus had been presented). Its development occurred during the buildup of the late negative slow wave (NSW) or "CNV" of the ERP (onset latency approximately 450-500 msec), which typically peaks about the time of presentation of the target stimulus.

Harter interpreted the earlier contralateral negativity and later contralateral positivity as reflecting the neural processes underlying two different attentional mechanisms. The first involved the shifting of attention from the foveal fixation point to the location designated by the arrow cue. The second involved cortical priming associated with focusing attention on the designated location in the contralateral field (Harter, et al.. 1990; Harter, 1991).

Based on this two-process interpretation, he labelled the contralateral negativity "EDAN" (an acronym for "Early Directing Attention Negativity") and the later contralateral positivity "LDAP" (for "Late Directing Attention Positivity"). These acronyms will be used only in a purely descriptive sense in this document, serving as short-hand labels for observed ERP voltage differences and not as inferred observations of attentional shifts or cortical priming.

## Results and Interpretation of Adults' Data

For the adults an even greater early negativity ("EDAN"), compared to the children's data, was observed in the 250-500 msec latency range over the hemisphere contralateral to arrow direction. However, the robust late contralateral positivity ("LDAP") observed in the children's data was nonexistent at central and frontal scalp locations and much smaller in magnitude at parietal and occipital locations than for the children. It was postulated that the observed differences between the children and adults may have been due to developmental factors (Harter and Anllo-Vento, 1991).

## SUMMARY OF RESULTS BASED ON A SUBSEQUENT ANALYSIS OF THE COMPLETE DATA BASE OBTAINED FOR THE NIH PROJECT

Findings based on the complete bank of childrens' data accrued with the spatial attention paradigm described above, along with findings based on a more complete analysis of Keyes' M.A. thesis data, are summarized below. These findings recently were presented at the Society for Neuroscience annual meeting (Keyes and Eason, Soc. for NS Abstr., 1993).

The effects of the direction of the arrow cue on the grand-averaged ERPs obtained at occipital, parietal, central, and frontal sites for the children (collapsed across all reading groups, recording sessions, and other conditions) and adults (collapsed across all other conditions) are shown in the left-hand column of Fig. 1. Each tracing is the composite ERP-response (collapsed across hemispheres) evoked by an arrow cue pointing in a direction either contralateral to or ipsilateral to a given hemisphere. Because of the very large number of presentations upon which each grand average is based (60,000 for the children; 4,000 for the adults) these waveforms constitute highly stable, composite representations of the ERP responses obtained for each arrow direction. While the waveforms varied in degree under various experimental conditions, they did not vary in overall shape. The major deflections reflected in the grand averages also were observed in the ERPs of single individuals, although they tended to be "noisier" due to the small N's comprising each average for a given experimental condition (N=24).

## Early ERP and DERP Components.

The early ERP components occurring during the CS-TS interstimulus interval are identified in the upper-left tracing of Fig. 1. Occipital P1, N1, P2, and N2 are sequential oscillatory components which typically occur in response to any visual stimulus, and are considered to reflect neural activity associated with processing the sensory information contained in the stimulus (e.g., location, brightness, color, size, shape, etc.). The occipital P1-N1-P2 configuration gradually inverts in polarity at progressively more frontal scalp regions. This polarity transition can readily be seen by drawing three imaginary vertical lines through occipital P1, N1, and P2 down to the point of intersection of frontal N1, P1, N1.

For the children, occipital P4 also inverts in polarity at more frontal regions.

The gradual inversion in polarity along the longitudinal axis of the scalp suggests that all of the electrodes lying along this axis registered the same neural activity but from differing angular orientations. The neural circuitry involved produced oscillatory current flow along the longitudinal axis of the brain such that the occipital and frontal electrodes were approximately aligned with it. The parietal and central electrodes were displaced laterally to the primary direction of current flow with the parietal electrode being closer to the occipital pole and the central electrode being closer to the frontal pole of the alternating voltage source responsible for the oscillatory current flow. The relatively unfavorable locations of the latter two electrodes with respect to the primary direction of current resulted in the registration of relatively small deflections of opposite polarity at these locations.

It is now generally accepted that these early components reflect the neural processing of the physical properties of the stimulus (Picton and Hillyard, 1988). They are stimulus-driven responses which occur regardless of the physical or psychological state of the normal individual. However, it has long been known that their amplitude can be modulated by preexisting state variables such as level of arousal, expectancy, and direction of focused attention (Eason, Harter, and White, 1969; Naatanen & Mitchie, 1979; Naatanen, Gaillard, & Mantysalo, 1978; Harter & Guido, 1980; Harter, Previc, & Towle, 1979; Harter & Aine, 1984; Hillyard & Mangun, 1987; Hillyard & Galambos, 1967; Hillyard & Munte, 1984).

As depicted in Fig. 1, no significant differences were observed in the amplitude of these early components as a function of arrow direction. These negative results are consistent with those reported earlier by Harter and Anllo-Vento (1991), and support their conclusion that the attention-directing information contained in the arrow cue was not reflected in these early potentials. Since the subject was instructed to focus attention on the central fixation point prior to the presentation of the arrow cue at that location, the attentional state of the subject should have been the same, on the average, when either a right or left arrow cue was presented. Thus, the failure to demonstrate an amplitude difference in these early ERP components was not surprising, and suggests there is at least a 200-ms latency prior to the onset of the neural activity associated with shifting and focusing attention in response to the arrow cue.

### ERP and DERP Components in the 250-500 Range ("EDAN")

The effects of arrow direction on ERP components with onset latencies in excess of 200 msec, based on analyses of the entire data base (Keyes and Eason, 1993), were consistent with those reported earlier by Harter and associates. These effects are depicted in the difference potentials (DERPs) displayed in the right-hand column of Fig. 1. The DERPs were derived by subtracting the ERPs obtained to the ipsilateral arrow cue from those obtained to the contralateral cue. As previously observed by Harter et al, in the latency range of approximately 250-500 ms, the potential recorded over a given hemisphere was relatively more negative when the arrow cue pointed to the contralateral than to the ipsilateral visual field. Onset, peak-amplitude, and termination latencies were shortest occipitally and longest anteriorly. Also, as previously had been observed, the contralateral negativity was of greater magnitude over parietal and central cortex than over occipital and frontal regions for both children and adults. The degree of contralateral negativity was greater for adults than for children at all brain regions.

It is apparent in Fig. 1 that the latency range within which the contralateral negativity occurred greatly overlapped the latency range within which P300 occurred. Since studies by Donchin and associates (Donchin, 1979, 1981; Donchin & Coles, 1988; Donchin et al., 1978) have suggested that P300 reflects neural activity involved in processing the instructional significance of a stimulus, in contrast to earlier components which presumably process its physical characteristics, the post hoc conclusion drawn by Harter and associates (Harter, et al., 1989; Harter & Anllo-Vento, 1991) that the contralateral negativity may reflect neural processes associated with shifting attention to the directed location merits further scientific investigation.

## The Later ERP and DERP Components ("LDAP")

The later contralateral positivity ("LDAP") previously observed in the childrens' data by Harter and associates (Harter, Miller, Price, LaLonde, and Keyes, 1989; Harter and Anllo-Vento, 1991) was confirmed by the complete analysis of all the data (Keyes and Eason, 1993).

As manifested in the difference potentials of Fig. 1, this late positivity was far more pronounced for the children than for the adults, being greater at posterior than at anterior sites for both groups.

For the children, the onset latency of "LDAP" was shortest occipitally (about 400 msec) and longest frontally (about 600 msec). At all electrode sites, its peak latency occurred at approximately 700 msec, or 100 msec after the target stimulus had been presented. In contrast to the children's data, only a slight degree of contralateral positivity was exhibited in the adult's difference potentials, and this was limited to occipital and parietal locations. In further contrast to the children's data, this "LDAP" activity peaked earlier in time and returned to baseline prior to the presentation of the target stimulus.

Comparison of Late Positivity to the CNV

A comparison of the ERP waveforms in the 400-700 ms range (left panel of Fig. 1) to the DERP waveforms in the same latency range (right panel of the figure) reveals that "LDAP" "rode" on the late negative slow wave (NSW) or "CNV" of the ERP.

In the children's waveforms it can be observed that the slope of the CNV (left column) and its peak amplitude was greater at posterior than at anterior regions. The relatively flat slopes of the CNV waves manifested at more anterior regions (left panel) were accompanied by relatively small "LDAP" amplitudes. These observations suggest that, in children, the processes responsible for changes in onset latency, duration, slope and peak amplitude of the CNV appear to be linked to those responsible for "LDAP."

Examination of the adult waveforms in the two panels of Fig. 1 indicates that the peak latency of the NSW, in contrast to that of the children, peaked either before or by the time the target stimulus was presented (i.e., within 600 ms). Also, their slopes were steeper than those of the children at all scalp locations, the differences in slope being greatest at central and frontal regions. It can be seen that the large slope discrepancies between the adults' and childrens' NSWs at more frontal locations were accompanied by dramatically reduced slopes in the children's NSWs, compared to more posterior locations, there being no such reduction in slope in the adult NSWs. It also can be observed that the differences in CNV slope at central and frontal sites between the adults and children were accompanied by ERP polarity differences, relative to zero baseline, at the time of CNV onset.

## Concluding Remarks

Findings based on a complete analysis of all of the children's data obtained in the NIH project completely confirm the preliminary findings reported by Harter and associates (1990, 1991). As stated earlier, Harter et al. interpreted "EDAN" as reflecting neural processes associated with shifting attention to the visual field designated by the arrow cue, and "LDAP" as reflecting neural priming in the hemisphere lying contralaterally to the designated field.

While the phenomenological existence of "EDAN" and "LDAP" manifested in the children's data are consistent with this two-component interpretation, the absence, or near absence, of "LDAP" in the adults' data is not.

## STATEMENT OF THE PROBLEM

Since the two-component interpretation was in actuality a post-hoc hypothesis, and since the "LDAP" component was minimal or absent in the adults' data, a major objective of the present study was to test further the validity of this hypothesis in the adult population. A related objective was to determine whether the waveform configurations manifested in the adult ERPs of Fig. 1, as well as the contralateral effects manifested in the difference potentials, were specific to a 600 msec ISI, or whether they can be altered by varying the length of the ISI. A third objective was to clarify to what extent, if any, the effects of ISI variations on the contralateral activity manifested in the difference potentials are yoked to the effects of such variations on the latency and amplitude of P300 and the negative slow wave activity (NSW or "CNV") manifested in the raw ERPs.

## Hypothesis Testing Strategy

The strategy used in addressing these objectives involved the manipulation of the length of the ISI between the arrow cue and the target stimulus and the probability of occurrence of a given length. These two factors were manipulated across three data collection sessions. In two of the sessions, the length of the ISI was held constant at either 1000 ms (Fixed 1000-ms ISI condition) or 1400 ms (Fixed 1400-ms ISI condition), making the probability of occurrence of a target stimulus after a specified time interval 100%. In the third, ISI length varied randomly between 1000 ms and 1400 ms (Mixed 1000- and 1400-ms conditions), making the probability of occurrence on a given trial of a target stimulus for each ISI length 50%. Thus, in two of the sessions the subject knew with certainty whether the target stimulus would appear at 1000 or 1400 ms. In the third session s/he could not predict above chance level whether the target would appear after 1000 or 1400 ms. length.

## Experimental Hypotheses

### Under Conditions of Certainty of ISI Length

(1) It was postulated that variations in the length of the ISI should alter the task demands being placed on the attentional system, the shorter the ISI the greater the demand. Thus, if the contralateral negtativity ("EDAN") manifested in the difference potentials of Fig. 1 does in fact reflect the process of shifting attention to the cued location, then, when the subject is certain of ISI length on a given trial (constant conditions), the peak amplitude of "EDAN" might be expected to vary inversely with ISI length while its onset latency and duration might vary directly with ISI length. It was therefore predicted that the peak amplitude of "EDAN" should be largest for the 600-ms ISI condition employed in the M.A. thesis and smallest for the 1400-ms ISI employed in the current study, with the peak amplitude for the 1000-ms ISI condition falling in between. A corollary prediction was that the onset of "EDAN", as well as its duration, would be shortest for the 600-ms ISI condition and longest for the 1400-ms condition, with the latencies for the 1000-ms condition falling in between.

(2) If the P300 wave of the raw ERPs, upon which "EDAN" "rides", reflects neural processing related to determination of the direction to which the arrow cue signals a shift in attention, and if the shifting process is contingent upon the completion of this process, then the onset and duration of P300 should be affected in the same manner by ISI length as was predicted for "EDAN" above.

(3) If "LDAP" is a reliable correlate of "cortical priming" in the hemisphere located contralaterally to the signalled visual field, then despite the failure to obtain a clear-cut response in adults in the M.A. thesis study, it should be possible to demonstrate the existence of this contralateral positivity in adults in the present study, as was the case for children in the NIH study. Furthermore, the onset latency and duration of this endogenous process should be longer for the 1400- than for the 1000-ms ISI condition.

(4) If the cortical priming process hypothesized to be responsible for "LDAP" modulates the same neural processes responsible for the generation of the NSW component of the raw ERP waveforms, then the onset and peak latencies of this CNV-like wave should closely parallel the onset and duration of "LDAP" as a function of ISI length.

(5) If the NSW reflects preparation to respond to a target stimulus, as has been reported in the literature (McCallum, 1988), then further predictions were: (a) that

the rate of buildup in negativity (slope) of the NSW would vary inversely with ISI, being steepest for the 600-ms and shortest for the 1400-ms ISI condition; (b) the peak latency of the wave would be shortest for the 600-ms and longest for the 1400-ms ISI condition; and (c) NSW amplitude would be about the same for all three ISIs, provided the subject was equally prepared to respond to the TS for each ISI. If an "LDAP" should be found to occur at these longer latencies, its amplitude and duration should parallel that of the NSW.

### Under Conditions of Uncertainty as to ISI Length

Since, in the third experimental condition, the ISI varied randomly from trial to trial between 1000 and 1400 ms, to optomize performance, the subject had to be prepared to respond to the cued location by 1000 ms on all trials. The purpose of the randomized manipulation was to determine whether differences in preparatory strategy engaged in under certain vs uncertain conditions as to ISI length would be manifested in the NSW, as well as in "LDAP", should it be found to occur at longer latencies.

(6) On the assumption that subjects would optimize their performance strategy under conditions of uncertainty, and would therefore be prepared to respond within 1000 ms, it was predicted that for the first 1000 ms of the uncertain ISI condition, irrespective of whether the target stimulus was presented at 1000 or 1400 ms, the slope of the NSW, as

well as the amplitude of "LDAP" should it be found to exist, should be essentially the same as that obtained under the certain 1000-ms ISI condition (Fixed 1000-ms ISI condition).

(7) After performing a few trials under the Mixed condition wherein the stimulus appears randomly at 1000 or 1400 ms, the subject should learn to discriminate between the two ISI lengths. After the occurrence of such temporal learning, if a target stimulus should not appear at 1000 ms on a given trial, its absence should signal to the subject that the TS will appear at 1400 ms latency. Thus, on those trials in which the ISI length is 1400 ms, at some point between 1000 and 1400 ms, the subject's subjective degree of certainty as to when the TS will occur should shift from 50% to 100%. Thus, for 1400-ms TS presentations, the subject should know with certainty when the TS would appear when performing under both Fixed or Mixed conditions. Based on this rationale, it seemed plausible to predict that the amplitude of the NSW (and "LDAP") for the Mixed 1400-ms condition would be about the same as that obtained for the Fixed 1400-ms ISI condition. This would require a convergence of the NSW waves for the Fixed and Mixed 1400-ms conditions during the last 400 ms of the ISI (i.e., between 1000 and 1400 ms). Such convergence would be expected to be achieved by a leveling off in amplitude of the NSW (and "LDAP") after 1000 ms for the Mixed ISI condition, indicating that the subject's readiness to respond was being

sustained at the same level as it was at 1000 ms; whereas for the Fixed condition, NSW amplitude would be expected to continue to increase after 1000 ms in order for the subject to be fully prepared to respond at 1400 ms. (8) There is a possibility that, for the Mixed 1400-ms condition, the failure of a 1000-msec stimulus to appear may produce a positive deflection in the NSW wave at that time. Such positivity has been observed by others (Ruckin and Sutton, 1978) in the absence of an expected stimulus at a given point in time, and is believed to be functionally equivalent to P300. If this should occur, the NSW wave might not recover to its pre-1000 ms level by the time the 1400-msec stimulus appears even though the subject is equally ready to respond by that time as he/she was at 1000 ms. If this should happen, then the amplitude of NSW at 1400 ms would be expected to be smaller for the Mixed than for the Fixed 1400-ms ISI condition.

(9) Reaction time (RT), on the average, should mirror the degree to which subjects are ready to respond to target stimuli for each ISI, as manifested by NSW amplitude. If subjects are more ready to respond at 1000 than at 1400 ms, NSW amplitude should be greater and RTs should be shorter to stimuli presented at 1000 ms. If subjects are equally prepared to respond to stimuli presented at each ISI, then no differences should be observed in either NSW amplitude or RT as a function of ISI length. An exception would be in

the event of the suppression of NSW amplitude by a P300 response following the absence of presentation of a stimulus at 1000 ms for the Mixed 1400-ms ISI condition discussed in the preceding paragraph. In this case, the RTs to the 1400-msec targets would be expected to be no different for the Mixed than for the Fixed conditions, since the subject should be equally ready to respond under each condition.

# CHAPTER 2

# METHOD

## SUBJECTS

A sample of 24 subjects ranging in age from 18 to 26 years were chosen from the student population at UNCG. Each either had normal vison or wore corrective lenses, and, based on personal report, with no history of neurological damage or modality impairment.

## EXPERIMENTAL DESIGN

Each of the 24 subjects participated in three data recording episodes involving four conditions with respect to ISI. Episode _A_ was comprised of a Fixed 1000-ms ISI condition; _B_ consisted of a Fixed 1400-ms ISI condition; and _C_ involved two conditions consisting of Mixed (randomly presented) 1000- and 1400-ms ISI conditions.

With 2 exceptions, all of the subjects completed the three episodes in a single three-hour session. Due to scheduling problems, the other 2 subjects participated in two experimental sessions on two different days, completing the two Fixed condition episodes in one session and the Mixed condition episode in the other.

It took about 15-20 minutes to complete a Fixed condition episode, depending on the number of artifact-induced rejection trials encountered. Since the number of stimulus presentations for the randomly presented 1000- and 1400-ms ISI conditions were equivalent to the total number of stimulus presentations for both of the two Fixed conditions, about twice as much time was required to complete the Mixed condition episode.

The order in which the three episodes were presented to each subject was systematically varied across blocks of six subects in the following manner: ABC, ACB, BAC, BCA, CAB, and CBA. This sequence was repeated four times.

## STIMULUS SETUP AND RECORDING PROCEDURE

The subjects were seated at a table in a sound-attentuated and electronically shielded room. A Princeton Graphic Systems video monitor, the center of which was positioned 45 cm from the subject's eyes, was used to display the stimuli in a game-like task. At the onset of each trial, a cuing stimulus (CS), consisting of a 7-mm long white arrow imposed on a blue background, appeared in the center of the monitor. The arrow, which remained on throughout the 2000-msec recording epoch, cued the subject to attend to a specified location in the visual field to which it pointed. After either 1000 or 1400 ms following arrow onset, depending on the ISI condition, a target stimulus (TS) consisting of a 5-mm white square appeared randomly to the right or left of the cuing stimulus at a visual angle distance of 8 degrees. Prior to each data collection episode the subject was reminded not to move or blink his/her eyes during the time that a 2000-msec recording epoch was in progress.

When a TS appeared in the cued visual field (relevant target condition), the subject was required to respond as quickly as possible by lifting his/her index fingers of each hand simultaneously from a response key. This response stopped a timer activated in synchrony with the presentation of the relevant target stimulus, and the elapsed reaction time was registered by the computer. The joint index finger response of both hands was used to prevent any hemispheric bias appearing in the ERP data associated with unilateral motor activity.

On each trial the subject received feedback as to whether he/she responded correctly (by receiving a "hit" or a "correct rejection") or incorrectly (by generating a "miss" or "false alarm"). A "hit" was recorded when the subject responded within 300 msec to a (relevant) target stimulus appearing in the cued field. A "correct rejection" was recorded when the subject did not make a finger-lift response to a target stimulus appearing in the uncued field (irrelevant target). A "miss" was recorded when the subject failed to respond within 300 msec to a target stimulus appearing in the cued field. A "false alarm" was recorded when the subject responded to a target stimulus appearing in the uncued field or responded too quickly (an anticipation error) to a target stimulus appearing in the cued field. A correct response was immediately followed by a high-pitched beep sound, and a point was registered for the correct response. Upon earning three points, a musical "charge" sound was played and the word "BONUS" appeared on the screen. A "boop" sound was made by the computer, with no earning of points, when a "miss or "false alarm" occurred.

## COLLECTION OF EVENT-RELATED POTENTIALS

An Electro cap, manufactured by Electro-cap International, Inc., embedded with 24 electrodes was placed on the subject's head. The cap was held firmly in place by attaching it to a strap tied around the chest, and by taping its front edge to the forehead with two strips of surgical tape. The point of intersection of two lines at the top of the head with one line extending along the sagittal plane from the inion to the nasium and the other along a coronal plane from ear to ear was used to determine the objective center of the head. This position was used as the reference point for centering the cap on the head. Electrode gel was then inserted into each electrode cup from which recordings were to be obtained. The gel was inserted by means of a syringe through tiny openings in the cap and the top of each electrode cup. The scalp was massaged with the blunt tip (about 2-mm wide) of the syringe until the resistance was reduced to 10,000 ohms or less.

Recordings were obtained from the following electrode sites: O1, O2, P3, P4, C3, C4, F3, and F4. All electrodes were referenced to yoked earlobes. An additional electrode, also referenced to both earlobes, was placed near the lower-left corner of the left eye for detecting eye movements and blinks. Recording epochs contaminated by such artifacts were automatically rejected by the computer program, and were not included in the averaged ERPs.

Electrical activity detected at each electrode site was amplified through separate AC amplifier channels of a Grass bioamplifier console (model IGMEB25), with high and low half-amplitude frequency filter settings of 100 and 0.1 Hz respectively. The amplified signals were digitized by a Scientific Solutions Lab Master Interface board and recorded by a Compaq-386 computer.

Before beginning data collection in a given session, an artifact rejection factor was established for the subject. This was accomplished by having the subject close his/her eyes for a period of 30 seconds so as to establish the average amplitude of the spontaneous EEG activity level, and then setting the miminum amplitude for rejection by the computer at twice the spontaneous level. If during a recording epoch, the signal recorded at any recording site exceeded the assigned value, that epoch of activity was automatically excluded from the averaged waveforms.

### Comparison to Procedures used in the M.A. Thesis Study

Since some of the results involving the Fixed 1000- and

1400-ms ISI lengths in the present study were compared to results involving a Fixed 600-ms ISI in Keyes' M.A. thesis study, methodological differences between the two need to be mentioned. The paradigm, stimuli, and recording procedures were identical in both studies with three exceptions. As just noted, one of these was the use of a Fixed 600 ms ISI in the M.A. study. The second was the length of time allowed for obtaining a "hit." In the current study it was 300 ms whereas in the thesis study it was 400 ms. The third exception was the number of subjects used. Twenty-four subjects were used in the current study; 20 in the thesis study.

## DATA PROCESSING

### ERP Averaging and Smoothing

Each averaged ERP was based on a minimumum of 24 presentations of the arrow cue for each experimental condition. These averages did not include trials contaminated with artifacts. As stated above, such trials were automatically rejected by the computer at the time of data collection.

After the initial averaging process for each condition, the two averages obtained at homologous pairs of electrodes over the two hemispheres (e.g., right and left occipital areas) to arrow cues pointing to the visual field located contralaterally to the recording hemisphere (i.e., right hemisphere recordings to left arrow cues and left hemisphere recordings to right arrow cues) were then averaged together. This resulted in a single averaged response, based on a minimum of 48 stimulus presentations for a contralateral arrow cue. An analogous single averaged response was obtained to arrow cues pointing ipsilaterally to the recording hemisphere (i.e., right hemisphere recordings to right arrow cues and left hemisphere recordings to left arrow cues). Thus, the basic ERP data base consisted of one contralateral arrow ERP and one ipsilateral ERP for each electrode site, experimental condition, and subject.

Due to the one-half amplitude high frequency cutoff of the Grass preamplifier units having been set at 100 cps, the units tended to amplify relatively high frequency signals generated by external electromagnetic sources which rode on the ERP signal. This high frequency "jitter" ranged in frequency from 40-100 hz, which was well above the upper frequency range of the dominant components of the ERP. To eliminate this "jitter" from the averaged ERP waveforms, a smoothing process was employed which involved calculating a sliding average around each of the 200 data points comprising the ERP epoch. Each smoothed data point was based on the voltage at that data point plus the voltage of the two data points lying immediately on either side of it divided by five. This process resulted in virtual elimination of the "jitter" with virtually no distortion of the ERP components.

## Quantification

The specific procedure for quantifying each ERP measure subjected to analysis is presented in the Results Section. The baseline voltage, against which the polarity and magnitude of each measure was determined, was based on the average voltage manifested in the waveform during the first 60 ms following the onset of the arrow cue. The average voltage level over this 60 ms interval was considered to be equivalent to the "resting" voltage at the time of stimulus onset, since the minimal latency (about 80-100 ms) of the earliest scalp-recorded cortical response to a visual stimulus previously had been established to exceed this latency (Oakley and Eason, 1991).

## Statistical Analyses

### Analyses Involving Factors Manipulated in the Current Study

All analyses involving data collected in the current study employed the 1990 version of the BMDP Repeated Measures ANOVA model (BMDP 2V) which applied Greenhouse-Geisser and Huynh-Feldt corrections to all F-values involving more than two factors (i.e., more than one degree of freedom).

Depending on the experimental question being assessed, ANOVAs were performed which encompassed all or some combination of the factors manipulated in the study. The specific ANOVAs performed for determining the statistical significance of the effects of various combinations of factors will be described in the Results section.

In all of the analyses, gender (male vs female) constituted a group variable. All other factors involving all or some combination of the variables manipulated in the study were treated as repeated-measures variables. These were (A) cortical region (occipital, parietal, central, frontal), (B) arrow direction (arrow pointing to visual field contralateral to recording hemisphere vs pointing to field ipsilateral to recording hemisphere; CVF vs IVF), (C) ISI length (1000 ms vs 1400 ms), (D) certainty of ISI length (fixed vs mixed condition), (E) hemispheres (RT vs LT), and (F) replications (I vs II).

Factor (F) involving the two replications was generated by the existence of two target stimulus conditions involving the random presentation of the TS to either the right or left visual field. This factor was irrelevant to any changes in the ERP waveform occurring within the cue stimulus-target stimulu (CS-IS) interstimulus interval since the TS was presented at the termination point of the ISI. Thus, the two ERP records generated by the target stimuli presented to either the right or left visual fields were treated as replications in analyses involving measures falling within the ISI and which preceded the presentation of the TS.

### Analyses Involving Comparisons Between Results Obtained in the Current Study with those Obtained in the M.A. Study

Analyses involving a comparison of the ISI data obtained in the current study to the Fixed 600-ms ISI data obtained in Keyes' thesis study were comprised of two separate ANOVAs. One compared the 600-ms ISI data to the Fixed 1000-ms ISI and the other compared the 600-ms data to the Fixed 1400-ms ISI data. In each of these analyses ISI was treated as a between-group variable since different groups of subjects were used in the two studies. The data were collapsed across gender, eliminating it as a group variable. All other factors were treated as repeated measures variables.

### Exclusion of ERPs Evoked by Target Stimuli From Analysis

Since the primary purpose of this study was to examine the ERP changes occurring during the arrow cue-target stimulus interval in relation to preparatory events *preceding* the occurrence of the target stimulus, analyses of responses to the target stimulus (TS) have not been included in this report. As stated in the Introduction, ERP responses to target stimuli as a function of manipulations designed to alter the subjects' attentional state and general readiness to respond have been widely studied since the initial demonstration by Eason, Harter, and White (1969). The target-evoked data obtained in the present study will be analysed at a later time.

## STATISTICAL FINDINGS EMPHASIZED IN THE RESULTS SECTION

Because of the number of factors manipulated in the current study and the large number of analyses performed, the total number of sources of variance involving various combinations of factors numbers into the hundreds. Using an alpha level of 0.05 for rejecting the null hypothesis, one would expect approximately five out of every 100 comparisons among various sources of variation to be significant by chance. To lessen the probability of committing a Type I error, the apriori alpha level for rejecting the null hypothesis was set at 0.03 rather than 0.05. Findings based on F-values of 0.04 or 0.05 were considered marginal, and those which were not expected or predicted have been interpreted as having been most likely due to sampling error. Even if a finding was predicted, if only marginally significant, it has been interpreted with extreme caution in the Discussion Section.

# CHAPTER 3

# RESULTS

## COMPARISONS INVOLVING ERP COMPONENTS OCCURRING PRIOR TO 250 MS AFTER THE ARROW CUE

The earliest ERP component evoked by the arrow cue consisted of a deflection with a peak latency of approximately 140 ms. As can be observed in Fig. 2, this deflection was of positive polarity at occipital cortex, but it gradually inverted in polarity more anteriorly to become distinctly more negative at frontal cortex. The next deflection, also visible in Fig. 2, peaked at about 180-200 ms. Its polarity was negative at occipital cortex, but it also gradually inverted in polarity to become clearly positive at frontal cortex. As stated in the Introduction, these components traditionally have been labelled occipital P1 and N1, and are considered to be sensory evoked responses produced by the occurrence of a physical stimulus (the arrow cue).

These components were quantified by measuring the peak-to-peak difference in voltage between them at latencies of 130-140 and 170-180 ms respectively. Repeated-measures ANOVAs were performed on the data for each cortical region, with sex as a group variable and arrow direction (contra- vs ipsilateral), cortical region, hemispheres, ISI length, certainty of length, and replications as repeated factors.

A significant contra- vs ipsilateral arrow direction effect was obtained only at the occipital region [$F(1, 22) = 9.30$, $p < .01$], along with a marginally significant certainty by sex interaction [$F(1, 22) = 4.64$, $p < .05$]. A significant certainty effect was obtained (marginally) at parietal [$F(1, 22) = 5.08$, $p < .05$], and at central [$F(1, 22) = 8.52$, $p < .01$] and frontal regions [$F(1, 22) = 10.91$, $p < .01$]. In each case, the peak amplitude of P1N1 at 200 ms was relatively more negative for the uncertain than for the certain condition. A significant hemisphere effect was obtained at the central region [$F(1, 22) = 12.23$, $p < .01$], P1N1 amplitude being greater over the right than over the left hemisphere. At the frontal region the difference between hemispheres was marginally significant [$F(1, 22) = 4.76$, $p < .05$], P1N1 being slightly greater over the left hemisphere. The differences did not approach significance at occipital and parietal regions.

## COMPARISONS INVOLVING ERP MEASURES FALLING WITHIN THE 250-500 MS LATENCY RANGE

### Arrow Cue Effects as a Function of the Cue Pointing to the Visual Field Lying Contralateral to vs Ipsilateral to the Recording Hemisphere

#### Main Effects and Interaction with Cortical Region

The effects of the arrow cue pointing to the visual field lying contralaterally (vs ipsilaterally) to the recording hemisphere (e.g., right arrow/left hemisphere site vs left arrow/left hemisphere site) are illustrated graphically in Figs. 2, 3, 4, 5. The superimposed ERP tracings of Fig. 2 are grand averages which have been collapsed across all factors except arrow direction. Inspection of this figure reveals that at parietal, central, and frontal cortical regions the polarity of a positive deflection occurring during the latency interval of 250-500 ms (demarcated by the two vertical lines) was relatively more negative when the arrow pointed to the contralateral field. This difference in polarity can be seen more clearly for each cortical region in the bar graph of Fig. 3 which shows the average amplitude of the ERP waveforms during the 250-500 ms interval for the contra- and ipsilateral conditions. Fig. 4 depicts the difference in polarity between the two conditions in terms of difference potentials (DERPs) which were obtained by subtracting the ERPs for the ipsilateral condition from those for the contralateral condition. These DERPs reflect the buildup, peak amplitude, and decline in degree of contralateral negativity during the course of the 250-500 ms interval. The bar graph of Fig. 5 shows the average amplitude of the contralateral negativity manifested at each cortical region in the DERPs of Fig. 4 during the 250-500 ms interval.

As previously noted (pp. 20-21), Harter et al. (1989) interpreted the contralateral negativity as an early sign of shifting attention to the visual field designated by the arrow cue. Having placed this interpretation on the observed contralateral negativity, they labelled it "EDAN", an acronym for "early directing attention negativity".

In describing the findings of the current study involving ERP activity in the 250-500 ms latency range, the "EDAN" label, which has interpretative connotations, has been replaced by the purely descriptive label "CN-375." The "CN" segment designates the greater negativity to a contralateral than to an ipsilateral arrow cue observed over a given hemisphere. The "375" refers to the midpoint of the 250-500 ms latency period over which the contralateral negativity was observed. In addition to the use of "CN-375" as a means of reducing the long phrase for which it stands, the term, "arrow direction" is used as a short hand expression for the phrase "contra- vs ipsilateral arrow direction relative to the recording hemisphere." Unless otherwise noted, the term "arrow direction" is not used to refer to the right or left visual field to which the arrow pointed.

Based on a comprehensive ANOVA of the entire data matrix for the 24 subjects participating in the current study, which treated subjects as a between-group factor and arrow direction, recording region (occipital, parietal, central, frontal), length of interstimulus interval (1000- vs 1400-ms ISI), certainty of length (fixed vs mixed ISIs), hemispheres (RT vs LT), and replications (valid vs invalid target stimuli) as repeated measures (within-group) factors, a significant main effect for arrow direction emerged [F(1, 22) = 28.80; p < .0001]. This highly significant result reflects the relatively greater degree of negativity (-0.22 uv) for the contra- than for the ipsilateral arrow condition across the four cortical regions in Figs. 2-5.

The comprehensive ANOVA also revealed a highly significant arrow direction by cortical region interaction [F(1, 22) = 18.99, p <.0001)] indicating that the magnitude of the arrow effect differed across cortical regions. The nature of this interaction can be seen in all four figures, although it is most clearly manifested in Figs 3, 4, and 5. A visual scan of these figures reveals that the largest degree of contralateral negativity occurred over central cortex (-0.42 uv), with progressively decreasing amounts at frontal (-0.29 uv), parietal (-0.18 uv) and occipital (-0.02 uv) regions.

Contrast analyses for the arrow direction by region interaction revealed that, compared to occipital cortex, the degree of contralateral negativity was significantly greater over parietal [F(1, 22) = 8.61, p < .10], central [F(1, 22) = 40.70, p. < .0001], and frontal regions [F(1, 22) = 40.31, p < .0001]. The analyses also revealed that, compared to parietal cortex, greater contralateral negativity occurred at central [F(1, 22) = 14.74, p. < .001] cortex. Also, the apparently greater degree of negativity at frontal, compared to parietal cortex (see Fig. 5), approached significance [F(1, 22 = 6.13, p. < .07]. The greater degree of contralateral negativity at central cortex, compared to frontal cortex, was marginally significant [F(1, 22) = 5.09, p. < .05].

Separate ANOVAs performed for each cortical region revealed that the greater degree of negativity manifested in the waveforms during the 250-500 ms when the arrow pointed to the contralateral visual field was significant at parietal [F(1, 22) = 9.07, p < .01], central [F(1, 22) = 43.83, p < .0001], and frontal [F(1, 22) = 47.19, p < .0001] regions but not at the occipital region.

### Three-way Interaction Involving Arrow Direction, Cortical Region and Hemispheres

In addition to being dependent on the cortical region from which the 250-500 ms measures were obtained, as described in the above section, the magnitude of the difference in voltage in the ERP waveforms during this latency interval as a function of arrow direction also was found to be dependent on the hemisphere from which recordings were obtained at a given cortical region. This hemispheric dependency was revealed in terms of a three-way interaction between arrow direction, region, and hemispheres in the comprehensive ANOVA referred to in the preceding section [F(3, 66) = 9.32, p < .01].

The nature of this three-way interaction is manifested in varying formats in Figs. 6 through 9. Fig. 6 shows the raw ERP waveforms for contra- and ipsilateral arrow cues (superimposed tracings) as a function of region and hemispheres. The bar graph in Fig. 7 depicts the average amplitude of the waveforms for each arrow direction during the 250-500 ms interval plotted as a function of region and hemispheres. Fig. 8 displays the arrow direction difference potentials (DERPs) derived by subtracting the ipsilateral from the contralateral ERPs shown in Fig. 6. Fig. 9 presents in bar-graph format the average amplitude of the DERPs during the 250-500 ms interval.

Although the nature of the three-way interaction is apparent in all four figures, variations in the direction and magnitude of the DERPs across cortical region and hemispheres as a function of the arrow cue manipulation can most readily be seen in the bar graphs of Figs 7 and 9. In each of these graphs it is apparent that for the left hemisphere, the 250-500 ms voltage was relatively more negative for the contra- than for the ipsilateral arrow cue condition, with the maximum difference in voltage occurring at parietal cortex and the least at the frontal region. On the other hand, for the right hemisphere, the voltage level for the contralateral arrow condition was relatively more positive, compared to the ipsilateral condition, at occipital cortex. The difference in polarity gradually shifted more frontally such that at frontal cortex the voltage level was relatively much more negative for the contra- than for the ipsilateral arrow condition.

Contrast analyses (based on 1 and 22 df in every case) revealed that the voltage difference profiles between the contra- and ipsilateral arrow cue conditions obtained for each hemisphere at occipital cortex differed significantly from the profiles obtained at central ($F = 14.11$, $p < .01$) and frontal ($F = 11.46$, $p < .01$) regions. Also the profile obtained for the parietal region different significantly from that obtained at central ($F = 12.12$, $p < .01$) and frontal ($F = 8.71$, $p < .01$) regions. The difference in hemispheric profiles between the central and frontal regions approached but did not reach the apriori statistical criterion ($p < .02$) for statistical significance ($F = 18.21$, $p < .06$). These hemispheric profile differences across regions are clearly discernible in Fig. 9.

Despite the significant profile differences summarized above, separate ANOVAs performed for each region revealed no significant hemisphere by arrow direction interactions. Thus, the profile differences manifested across regions, although statistically significant, do not appear to have been strong enough to produce hemisphere-dependent attention-related differences in ERP amplitude during the 250-500 ms interval at any given cortical region.

### Two-way Interaction Between Arrow Direction and ISI Length

The major effects of length of the ISI on the magnitude of the contralateral negativity manifested in the 250-500 ms latency range as a function of contra- vs ipsilateral arrow direction are manifested in Figs. 10 and 11.

Fig. 10 shows the difference potentials (DERPs) between the two arrow conditions for each ISI interval at each cortical region. Fig. 11 provides a bar graph representation of the average amplitude of the DERPs during the 250-500 ms latency interval for each ISI and region.

The data shown in the two figures are based on two different experiments. The fixed 600-ms ISI data were derived from Keyes' M.A. thesis project. It should be recalled that this was the only ISI condition used in that study. The 1000- and 1400-ms ISI data were derived from the fixed ISI condition of the current experiment. Data for the mixed condition are excluded here, since this variable was not manipulated in the thesis study.

### Between-Group Comparisons of Arrow Direction Effects Obtained for the 600-vs the 1000-ms ISI Condition and for the 600- vs the 1400-ms ISI Conditions

Tests of significance involving comparisons of the 600-ms ISI with either the 1000- or 1400-ms ISI intervals were based on analyses which treated ISI as a between-group variable. Comparisons between the 1000- and 1400-ms ISI intervals were based on analyses which treated ISI as a within-group variable.

Based on an overall ANOVA of the fixed 600- and 1000-ms ISI data involving arrow direction, ISI, cortical regions, hemispheres, and replications, the average amplitude of the difference potentials in the 250-500 ms range (CN-375) manifested in Figs. 10 and 11 (collapsed across all other variables) was found to be significantly greater for the 600- than for the 1000-ms condition [$F(1, 42) = 4.46$; $p < .05$]. A comparable ANOVA of the fixed 600- and 1400-ms ISI data revealed that the even greater differences manifested in the two figures between these two ISI conditions also was significant [$F(1, 42) = 11.28$; $p < .002$].

Separate regional analyses revealed significantly greater arrow direction differences for the 600- than for the 1400-ms ISI conditions at occipital [$F(1, 42) = 5.74$, $p < .03$], parietal [$F(1, 42) = 7.54$, $p < .01$], central [$F(1, 42) = 11.96$, $p < .01$] regions. The same trend occured at the frontal region, but only approached significance [$F(1, 24) = 3.52$, $p < .06$]. Although in the same direction, the differences for the 600- vs the 1000-ms ISI reached statistical significance only at the central region [$F(1, 42) = 5.80$, $p < .02$].

## Within-Group Comparison of Arrow Direction Effects Obtained for the 1000- vs the 1400-ms ISI Condition

A repeated Measures ANOVA of the 250-500 ms measure for the Fixed 1000- and 1400ms ISI data (which treated arrow direction, cortical regions, ISI length, hemispheres, and replications as within-group variables, with sex as a group variable), yielded a nearly significant interaction between arrow direction and length of the ISI [F(1, 22) = 3.62, p < .07]. Although the alpha level for rejecting the null hypothesis was not reached, the nearly significant F-value lends some credibility to the overall trend reflected in Figs. 10 and 11 that the difference potentials tended to be larger for the 1000- than for the 1400-ms ISI condition. Another F-value which only approached significance involving a three-way interaction between arrow direction, length of ISI, and cortical region [F(3, 66) = 2.42, p < .08] at least suggests, although not definitively, that the degree to which the DERPs were affected by the two ISI conditions varied across cortical regions.

Followup ANOVAs for each region revealed that the amplitude of the difference potentials manifested in Figs. 10 and 11 were significantly greater for the 1000- than for the 1400-ms ISI condition at occipital [(F1, 22) = 6.63, p < .01] and parietal regions [F(1, 22) = 7.08, p < .02], but the differences manifested at the central and frontal regions, although in the expected direction, did not reach significance.

### Three-way Interaction of Arrow Direction with ISI Length (1000 vs 1400 ms) and Certainty of Length (Fixed vs Mixed Condition)

As noted above, since only one ISI length was used in the earlier study (M.A. thesis), comparisons of DERP amplitudes for CN-375 obtained for the 600-ms ISI condition with the amplitudes obtained for the 1000- and 1400-ms ISI conditions could only be made for the fixed condition; that is, under circumstances in which the subject knew with certainty what the ISI length would be on a given trial. However, since, in the current study, data were obtained for the 1000- and 1400-ms ISIs under both certain and uncertain conditions (fixed vs mixed length trials), it was possible to test for the existence of a three-way interacton involving arrow direction, ISI length, and certainty of length.

The comprehensive ANOVA encompassing all the variables of the current study revealed that a significant interaction involving arrow direction, ISI length, and certainty of length did in fact exist [$F(1, 22) = 6.53$, $p < .02$]. The nature of this three-way interaction is manifested in the DERPs of Fig. 12 and in the bar graph of Fig. 13, the latter of which shows the average amplitude of the DERPs in the 250-500 ms latency range for each region, arrow direction, ISI length, and certainty of length. Upon examination of these graphs, it is apparent that for the fixed ISI condition, the DERP amplitudes obtained for the 1000-ms ISI condition were more negative than those obtained for the 1400-ms condition. On the other hand, for the mixed ISI condition, the DERPs tended to be relatively more positive for the 1000- than for the 1400-ms ISI condition.

Regional contrast analyses derived from the comprehensive ANOVA revealed that the profile of the three-way interaction differed only between the occipital and parietal regions [$F(1, 22 = 4.87$, $p < .04$].

In an effort to better understand the nature of the three-way interaction, a composite ANOVA was performed on the the 1000- and 1400-ms data for the <u>mixed</u> condition data only in order that the results could be compared to those previously obtained for the two ISIs during the <u>fixed</u> ISI condition (summarized in the preceding section).

Since under the mixed condition the subject did not know whether on a given trial the target stimulus would appear at 1000 ms or 1400 ms after the arrow cue, the actual length of the ISI would be expected to have no effect on the magnitude of the DERPs occurring 250-500 ms after the arrow cue (and hundreds of milliseconds prior to the actual presentation of the target stimulus). Although there was a tendency for the DERPs to be less negative (i.e., more positive) for the 1000- than for the 1400-ms ISI condition under the uncertainty of length (Mixed) condition (see Figs. 12 and 13), the composite ANOVA performed on the Mixed condition data revealed that this tendency was only marginally significant [F(1, 22) = 4.42, p < .05]. Followup analyses performed separately for each region revealed a nearly significant difference between the DERPs as a function of ISI length only at the parietal region [F(1, 22) = 5.14, p < .05]. None of the differences approached significance at the other three regions. The marginally significant effect at the parietal region, is in a direction opposite to that obtained under the fixed ISI condition, and does not lend itself to a plausible explanation other than having been a chance effect.

### Summary of Effects of Arrow Direction and ISI Length on the 250-500 ms Measure

The results of the above analyses, taken as a whole, indicate that when the subject knew the length of the ISI on a given trial (fixed condition), the contralateral negativity manifested in the 250-500 ms range of the DERPS (Fig. 10) and in the bar graph presentation of the average amplitude of the DERPs in this latency range (Fig. 11) was of greatest magnitude for the 600-ms ISI, of intermediate size for the 1000-ms ISI, and least for the 1400-ms ISI. For the two ISIs (1000 and 1400 ms) in which data were obtained under both certain and uncertain conditions as to ISI length, the length of the ISI affected the magnitude of the DERPs under the certain (fixed) but not under the uncertain (mixed) condition.

## COMPARISONS INVOLVING THE NEGATIVE SLOW WAVE (NSW)

### Between-Group Comparisons of NSW Measures Obtained in M.A. Thesis to Those Obtained in the Current Study as a Function of ISI Length (600- vs 1000- vs 1400-ms)

#### General Description of Effects Manifested in Fig. 14

The effect of ISI length on the rate of buildup (slope) and peak amplitude of the negative slow wave (NSW) when the subject knew with certainty at what latency the target stimulus was to appear (fixed ISI condition) is shown in Fig. 14. The superimposed tracings are the grand averaged ERPs obtained in the M.A. thesis study for the 600-ms ISI condition and in the current study for the fixed 1000- and 1400-ms ISIs.

The large positive-going deflections occurring shortly after 600, 1000, and 1400 ms are responses to the target stimuli. Since they are not part of the slow wave responses which precede the presentation of the target stimuli, they will not be considered here.

Visual inspection of the tracings reveals that, starting at about 500 ms, the rate of buildup in negative polarity (slope) of the NSW was greatest for the 600-ms ISI and least for the 1400-ms ISI. Commensurate with these slope differences, it can be seen that in the latency window of 550-650 ms, the amplitude of the NSW was greatest for the 600-, intermediate for the 1000- and least for the 1400-ms ISI condition. Similarly, in the latency window of 950-1050 ms, NSW amplitude was greater for the 1000- than for the 1400-ISI condition. Further observation reveals that the latency at which the NSW reached its peak amplitude for each ISI (peak latency) occurred at approximately the time the target stimulus was presented (600, 1000, or 1400 ms).

### Between-Group Comparisons Involving Differences in NSW Amplitude in the 550-650 ms Range (NSW-600) as a Function of the 600- vs 1000- and 600- vs 1400-ms ISI Lengths

As was the case for determing the reliability of the differences manifested in the 250-500 ms measure between the 600- and 1000-ms ISI conditions and the 600- and 1400-ms ISI conditions (summarized in the preceding section), ANOVAs treating ISI length as a group variable were performed on the average amplitude measures in the 550-650 ms latency range to determine whether the mean amplitude manifested in Fig. 14 for the 600-ms ISI differed significantly from that obtained for the fixed 1000- and 1400-ms ISIs. These analyses were followed by separate regional analyses in the event the comprehensive analyses revealed significant interactions between ISI length and recording region.

The measures obtained in the 550-650 ms latency range will hereafter be referred to as NSW-600.

A significant main ISI effect was found for both the 600- vs 1000- [F(1, 32) = 18.75, p < .001] and 600- vs 1400-ms [F(1, 42) = 56.56, p < .0001] ISIs, indicating the mean amplitude of NSW-600 (collapsed across cortical regions and all other variables) was generally greater for short than for long ISIs.

For the 600- vs 1400-ms ISI comparison, ISI length also interacted with recording region [F(3, 126) = 5.66, p < .02]. The nature of this interaction becomes clear upon further inspection of Fig. 14 which shows that the difference in amplitude between the 600- and 1400-ms ISIs was considerably greater at parietal and central regions than at occipital and frontal regions. The smallest difference occurred at occipital cortex.

Contrast analyses revealed that, compared to occipital cortex, the amplitude difference was significantly greater at parietal [F(1, 42) = 32.65, p < .0001] and central [F(1, 42) = 11.98, p < .01] regions but not at the frontal region. The amplitude differences obtained at parietal and central regions did not differ significantly from one another. Compared to the frontal region, greater differences were obtained at both the parietal [$F(1, 42) = 15.92$, $p < .0001$] and central regions [$F(1, 42) = 14.86$, $p < .0001$].

For the 600- vs 1000-ms ISI comparison the interaction between ISI length and recording region did not quite reach statistical significance [$F(3,126) = 3.25$, $p < .07$].

Separate ANOVAs performed for each region revealed that the difference in NSW-600 amplitude for the 600- vs 1400-ms ISIs were highly significant at occipital [$F(1, 42) = 13.34$, $p < .001$], parietal [$F(1, 42) = 43.68$, $p < .00001$], central [$F(1, 42) = 61.62$, $p < .00001$], and frontal regions [$F(1, 42) = 12.72$, $p < .001$]. Comparable ANOVAs revealed that the amplitude differences between the 600- vs 1000-ms ISIs were significant at occipital [$F(1, 42) = 7.52$, $p < .01$], parietal [$F(1, 42) = 17.08$, $p < .001$], and central [$F(1, 42) = 22.56$, $p < .0001$] regions; and distantly approached significance at the frontal region {$F(1, 42) = 2.82$, $p < .10$].

## Within-Group Comparisons of NSW Measures Obtained in Current Study as a Function of ISI Length

### Comparison of Differences in NSW Amplitude in the 550-650 ms Latency Range (NSW-600) as a Function of 1000- vs 1400-ms ISI Lengths

In order to determine the reliability of the differences manifested in the NSW-600 measure (Fig. 14) for the 1000- vs the 1400-ms ISI condition, a comprehensive

ANOVA was performed on the <u>fixed</u> ISI data which treated ISI length, along with all other factors except sex, as within-group variables. This analysis was supplemented by regional contrast analyses and separate ANOVAs for each cortical reigon.

The comprehensive analysis revealed a main ISI effect [$F(1, 22) = 14.39$, $p < .001$], indicating that NSW-600 was of generaly greater magnitude (collapsed across cortical regions and all other factors), for the 1000- than for the 1400-ms ISI. The analysis also revealed a nearly significant ISI by region interaction [$F(3, 66) = 3.79$, $p < .05$], suggesting that the difference in amplitude for the 1000- vs the 1400-ms condition varied across cortical regions. Inspection of Fig. 14 indicates that the interaction, if real, was primarily due to larger amplitude differences having been obtained at parietal, central, and frontal regions than at occipital cortex.

This observation was bolstered by contrast analyses which showed significant differences in the magnitude of the effect between the occipital and parietal regions [$F(1, 22) = 16.10$, $p < .001$], as well as the occipital and central regions [$F(1, 22) = 9.95$, $p < .01$]. Although a similar difference occurred between occipital and frontal cortex, it did not approach statistical significance [$F(1, 22) = 2.11$, $p < .16$]. There were no significant differences between parietal, central, and cortical regions.

Separate regional ANOVAs added further support for the reliability of the effects manifested in Fig. 14, with significant amplitude differences between the 1000- vs 1400-ms ISI conditions being obtained at parietal [F(1, 22) = 12.95, $p < .01$], central [F(1, 22) = 20.20, $p < .001$] and frontal [F(1, 22) = 7.30, $p < .02$] regions, but not at the occipital region.

### Comparison of Differences in NSW Amplitude in the 950-1050 Latency Range as a Function of ISI Length

As can be seen in Fig. 14, NSW amplitude in the 950-1050 latency range (hereafter referred to as NSW-1000) was greater for the 1000- than for the 1400-ms ISI condition. A comprehensive ANOVA of the NSW-1000 amplitude data for the fixed ISI condition revealed that, collapsed across all cortical regions, the differences in amplitude manifested in Fig. 14 at this latency range were statistically significant [F(1, 22) = 17.00, $p < .001$]. Also, there was a marginally significant region by ISI interaction [F(3, 66) = 3.40, $p < 0.05$], suggesting that the magnitude of the ISI effect was greater at some regions than at others.

Contrast analyses established that the ISI effect was greater at both parietal [F(1, 22) = 6.59, $p < .02$] and central [F(1, 22) = 6.43, $p < .02$] regions than at the occipital region. There were no other statistically significant regional differences.

Separate regional ANOVAs revealed that the ISI effect was significant at parietal [$F(1, 22) = 15.56$, $p < .001$), central [$F(1, 22) = 19.32$, $p < .001$), and frontal [$F(1, 22) = 10.21$, $p < .01$] regions, but not at the occipital region.

### Summary

All tolled, the statistical analyses performed on the amplitudes of NSW-600 and NSW-1000 indicate that the effects of ISI length manifested in Fig. 14 for these two latencies were statistically reliable. To summarize these effects, the amplitude of NSW-600 was largest for the 600-ms ISI, of intermediate size for the 1000-ms ISI and smallest for the 1400-ms ISI. The amplitude of NSW-1000 was larger for the 1000- than for the 1400-ms ISI. These differences in amplitude are consistent with the general observation to be made from Fig.14 that the rate of growth in amplitude of the NSW varied inversely with the length of the ISI, and that the peak amplitude of each wave occurred near the terminal point of its respective ISI.

## Within-Group Comparisons Involving Effects of Certainty of ISI Length on NSW Amplitude as a Function of ISI Length (1000 vs 1400 ms)

Since only fixed-interval data (600 ms) were collected in the M.A. study, the comparisons described above involving all three ISIs (600, 1000, and 1400 ms) were limited to the fixed-interval data collected in the current study.

This section summarizes the effects of ISI length on the NSW in relation to other variables manipulated in the current study, with special emphasis being placed on comparisons pertaining to hypotheses and predictions noted in the introduction.

The first analysis consisted of a comprehensive Repeated- Measures ANOVA involving cortical region (occipital, parietal, central, frontal), arrow direction (contra vs ipsi), ISI length (600- vs 1000-ms), certainty of length (fixed vs mixed), amplitude measurement latency (NSW-600 ms vs NSW-1000), hemispheres (right vs left), replications (RVF target vs LVF target), and sex (as a group variable). A second comprehensive ANOVA involving the same variables was performed on the 1000-ms ISI data only. A third was performed on the same variables and the three NSW measurements (NSW-600, NSW-1000, NSW-1400) for the 1400-ms ISI data only. Contrast Analyses were performed to aid in the interpretation of significant interactons involving either region or amplitude measurement latency. Also, separate ANOVAs for each region and latency of measurement were performed for each ISI, when needed.

The effects of certainty are depicted graphically in various formats in the ERP tracings plotted in Figs. 15 and 16 and in the bar graphs of Figs. 17 and 18. An overview of the effects manifested in these figures, which were found to be statistically significant, will first be presented before giving the details of the statistical analyses.

In Fig. 15 the grand ERPs for each cortical region (collapsed across all variables except ISI length and certainty of length) have been superimposed with respect to certainty (fixed vs mixed conditions) for each ISI length (1000 vs 1400 ms). In Fig. 16 the same data have been superimposed with respect to ISI length (1000 vs 1400) for each level of certainty (fixed vs mixed conditions). Fig. 17 depicts the average amplitude of NSW-600 AND NSW-1000 for the 1000-ms ISI condition plotted as a function of certainty. Fig. 18 shows the amplitudes of NSW-600, NSW-1000, and NSW-1400 for the 1400-ms ISI condition plotted as a function of certainty.

Upon inspection of the left panel of Fig. 15 it can be seen that for the 1000-ms ISI condition, certainty of ISI length had little or no apparent effect on the rate of buildup of the NSW or on its peak amplitude. It is evident that the superimposed tracings virtually fall on top of one another throughout the duration of the NSW. By contrast, as can be observed in the right panel of Fig. 14, for the 1400-ms ISI condition the amplitude of the NSW tended to be smaller for the certain than for the uncertain condition until about 1000 ms latency. Further examination of the right panel of Fig. 15 reveals that during the latency interval from 1000 to 1400 ms, the waves converged and either completely crossed over (at occipital, parietal, and central regions) or converged without crossing. Thus, while at 1000 ms latency NSW amplitude was smaller for the certain than for the uncertain condition, at 1400 ms latency NSW amplitude was either about the same for both certain and uncertain conditions or somewhat greater for the certain than for the uncertain condition.

The differential effect of certainty on the NSW for the two ISIs also can be observed in Fig. 16 which shows that for the certain condition (fixed ISIs), NSW amplitude was greater for the 1000- than for the 1400-ms ISI (left panel) whereas for the uncertain condition (mixed ISIs) the differences manifested between the two ISIs were absent or minimal.

The effects of certainty on NSW amplitude are displayed quantitatively in Fig. 17 for the 1000-ms ISI condition. Consistent with the nearly perfect superimposition of the NSWs depicted for the 1000-ms ISI under certain and uncertain conditions (left panel of Fig. 15), the bar graphs of Fig. 17 depicting the average amplitude of NSW-600 and NSW-1000 can be seen to be virtually identical for both the certain (fixed) and uncertain (mixed) conditions.

In concordance with the NSW changes observed in the grand ERPs shown in the right panel of Fig. 15 for the 1400-ms ISI condition, it can be observed in Fig. 18, with one exception at occipital cortex, that the mean amplitude of both NSW-600 and NSW-1000 was smaller for the certain (fixed) than for the uncertain (mixed) condition. In contrast to this effect, the amplitude of NSW-1400 was either about the same (for frontal cortex) or somewhat larger (at all other regions) for the certain than for the uncertain condition, reflecting the convergence or crossing over of the NSW amplitudes noted in Fig. 15.

### Results of Comprehensive ANOVA Involving NSW-600 and NSW-1000 for Both the 1000- and 1400-ms ISIs.

The comprehensive Repeated Measures ANOVA involving the two NSW measures (NSW-600 and NSW-1000) and the two ISI lengths (1000 and 1400 ms) revealed a marginally significant certainty by ISI interaction [$F(1, 22) = 4.78$, $p < .04$]. This interaction reflects the differential impact of the certainty factor on the magnitude of the NSW for the 1000- vs the 1400-ms ISI noted in Figs. 15 and 18 above.

### Results of Comprehensive ANOVA Involving NSW-600 and NSW-1000 for the 1000-ISI Only

Consistent with the nearly identical NSW patterns manifested in the left panel of Fig. 15 for both the certain and uncertain conditions, and with the essentially equal amplitudes of the bar graphs of Fig. 17, the comprehensive ANOVA for the 1000-ms ISI condition, revealed that the certainty factor had no main effect on NSW amplitude (collapsed across NSW-600 and NSW-1000), nor did the certainty factor interact with these two measures.

## Results of Comprehensive ANOVA Involving All Three Measures: (NSW-600, NSW-1000, and NSW-1400)

The comprehensive analysis for the 1400-ms ISI condition encompassing all three measures (NSW-600, NSW-1000, and NSW-1400) revealed that the interaction between the three measures and the certainty factor, collapsed across cortical regions, was highly significant [$F(2, 44) = 11.48$, $p < .0001$].

This same analysis also revealed a marginally significant region by measure by certainty interaction [$F(6, 132) = 3.0$, $p < .04$], suggesting that the effect of certainty on NSW amplitude at the three different latency intervals varied across cortical regions. Regional contrast analyses indicated that the pattern or profile of the certainty by measure interaction differed significantly between the occipital and parietal regions [$F(2, 44) = 6.18$, $p < 0.01$], the occipital and central regions [$F(2, 44) = 7.15$, $p < .01$], and the central and frontal regions [$F(2, 44) = 5.39$, $p < .01$]. The remaining differences in pattern across cortical regions (occipital vs frontal, parietal vs central, and parietal vs frontal) were not significant. These differing profiles across cortical regions can readily be seen in Fig. 18.

Followup ANOVAs encompassing all three measures performed separately for each region revealed that the measure by certainty interaction was marginally significant at occipital [F(2, 44) = 3.27, p < .05], and clearly significant at parietal [F(2, 44) = 9.36, p < .001], central [F(2, 44) = 16.93, p < .0001] and frontal [F(2, 44) = 5.41, p < .01] regions.

## Results of ANOVAs Performed on the 1400-ms ISI Data for Each Measure Taken Separately

### NSW-600

Separate analyses performed on the 1400-ms ISI data for each of the three measures revealed, for NSW-600, a significant region by certainty interaction [F(3, 66) = 3.27; p < .03] for NSW-600; also a main certainty effect approached significance [F(1, 22) = 3.86; p < .07]. These effects can be seen by comparing the first two bars across the four cortical regions in Fig. 18. Except for the occipital region, NSW-600 amplitude was larger for the uncertain (mixed) than for the certain (fixed) condition, the difference between conditions becoming progressively larger more anteriorily. Separate analyses performed for each region revealed that the greater amplitude for the certain than for the uncertain condition was significant at central [F(1, 22) = p < .02] and frontal regions [F(1, 22) = 6.22, p < .02]. The effect of certainty did not approach significance at occipital and parietal regions, although at the latter region there was a significant certainty by arrow direction interaction [F(1, 22) = 9.42, p < .01].

### NSW-1000

The analysis performed on NSW-1000 for the 1400-ms ISI revealed a main certainty effect [F(1, 22) = 6.25, p < .03]. This effect can be observed by comparing the middle two bars of Fig. 18 across the four cortical regions. In every case, NSW-1000 amplitude was larger for the uncertain than for the certain condition. Subsequent regional analyses revealed a significant difference in amplitudes at parietal [F(1, 22) = 5.62; p < .03], central [F(1, 22) = 9.28; p < .01], and frontal regions [F(1, 22 = 7.43; p < .02].

### NSW-1400

A comprehensive ANOVA of NSW-1400, collapsed across cortical regions, did not produce a significant difference as a function of certainty for the 1400-ms ISI. Thus, even though the NSW tracings in Fig. 15 and bar graphs of Fig. 18 suggest that the amplitude of NSW-1400 was larger for the certain than for the uncertain condition, the differences manifested at each cortical region for this ISI interval did not reach statistical significance.

## Between-Group Comparisons Involving the Effects of the Attention Manipulation (Contra- vs Ipsilateral Arrow Direction) on the NSW as a Function of Cortical Region andISI Length

### Magnitude of NSW-600 for the 600- vs 1000-ms ISIs.

The comprehensive ANOVA performed on NSW-600 for the

600-ms ISI utilized in the M.A. thesis vs the fixed 1000-ms ISI data obtained in the current study revealed a three-way interaction between ISI length, arrow direction, and region [$F(3, 126) = 4.27$, $p < .01$]. The nature of this interaction is manifested in Fig. 19 wherein it can be seen that the contra- vs ipsilateral profiles differed both with respect to region and ISI length. For the 600-ms ISI condition, NSW-600 was more negative for the contra- than for the ipsilateral arrow at occipital and parietal regions, whereas the wave was of about the same magnitude at central and frontal regions.

On the other hand, for the 1000-ms ISI condition, NSW-600 was more _positive_ for the contra- than for the ipsilateral arrow at occipital and parietal regions, while being of about equal magnitude at central and frontal regions.

Followup regional analyses indicated that the arrow direction manipulation interacted significantly with ISI length only at parietal cortex, and there only marginally [$F(1, 42) = 4.04$, $p < .05$]. Separate analyses of the parietal data for each ISI revealed no significant arrow direction effect for either the 600- or the 1000-ms ISI conditions.

### _Magnitude of NSW-600 for the 600- vs 1400-ms ISIs._

The comprehensive ANOVA of NSW-600 comparing the M.A. thesis 600-ms ISI to the fixed 1400-ms ISI condition of the current study exhibited a significant two-way interaction between arrow direction and ISI length [F(1, 42) = 5.35, p < .03] as well as a significant three-way interaction involving arrow direction, ISI length, and cortical region [F(3, 126) = 9.25, p < .001].

The nature of these interactions also is depicted in Fig. 19, and can be readily observed by comparing the first two bars of each cortical region to the last two bars. The interactive patterns are similar to those described in the preceding section for the 600- vs the 1000-ISI conditions, except that they are more pronounced. Even so, no significant contra- vs ipsilateral arrow direction effects were found to exist at any cortical region for either the 600- or the 1400-ISI condition.

## Within-Group Comparisons Involving the Effects of the Attention Manipulation (Contra- vs Ipsilateral Arrow Direction) on the NSW as a Function of Cortical Region and ISI Length

### Magnitude of NSW-600 for the 1000- vs 1400-ms ISIs

A Repeated-measures ANOVA performed on NSW-600 for the 1000- vs 1400-ms ISI conditions revealed no significant interactions involving arrow direction, region, and ISI, indicating that the slight differences manifested between contra- vs ipsilateral arrow direction in Fig. 19 for the

1000- vs the 1400-ms ISI conditions were not statistically reliable.

Thus, despite the significant interactions noted above involving arrow direction, cortical region, and ISI length for the 600- vs fixed 1000-ms ISI conditions as well as the 600- vs fixed 1400-ms ISI conditions, none of the contra- vs ipsilateral arrow direction differences observed at a given cortical region for any one of the three ISIs were strong enough to reach statistical significance.

### Magnitude of NSW-1000 for 1000- and 1400-ms ISIs.

The Repeated-Measures ANOVA performed on the NSW-1000 amplitude data for the 1000- and 1400-ms ISI conditions revealed a main arrow direction (contra- vs ipsilateral) effect [F(1, 22) = 13.51, p < .002]. This effect is manifested in Fig. 20 wherein it can be seen that NSW-1000 was of consistently greater magnitude for the contra- than for the ipsilateral arrow at all cortical regions for both ISIs. There was no significant interaction between arrow direction and ISI length at any cortical region, indicating the magnitude of the arrow direction effect was about the same in all cases. The consistency of the effect across regions and ISIs is evident in Fig. 20.

Separate ANOVAs encompassing both ISIs performed for each region revealed that the differences in NSW-1000 amplitude as a function of arrow direction was significant at occipital [F(1, 22) = 5.49, p < .03], parietal [F(1, 22)

= 19.37, p < .01], central [F(1, 22) = 6.84, p < .02] and frontal regions [F(1, 22) = 6.34, p < .02]. There was no significant interacton between arrow direction and ISI length.

## Magnitude of NSW-1000 for 1000-ms ISI Only

Based on an analysis of NSW-1000 for only the 1000-ms ISI condition, encompassing all cortical regions, the amplitude of NSW-1000 was marginally significantly greater for the contra- than for the ipsilateral arrow condition [F(1, 22) = 4.56; p < .05]. This effect is manifested in the different heights of the two left-hand bars for each region in Fig. 20. Separate regional analyses revealed that the difference in magnitude for the two arrow direction conditions was significant at parietal [F(1, 22) = 13.80, p < .01], marginally at central [F(1, 22) = 4.82, p < .04] and at frontal regions [F(1, 22) = 7.01, p < .02] and approached significance at the occipital region F(1, 22) = 3.90, p < .07].

## Magnitude of NSW-1000 for 1400-ms ISI Only

Based on an analysis of the amplitude of NSW-1000 for the 1400-ms ISI alone encompassing all cortical regions, the difference in amplitude between the contra- and ipsilateral conditions (manifested in the different heights of the two right-hand bars for each region in Fig. 20) approached statistical significance [F(1, 22) = 3.72, p. < .07]. Accordingly, separate regional analyses revealed no significant differences, with only the occipital region approaching significance [$F(1, 22) = 4.02$, $p < 0.06$].

### Magnitude of NSW-1400 for 1400-ms ISI.

For the 1400-ms ISI, the mean amplitude of NSW-1400 as a function of arrow direction manifested in Fig. 21, was slightly greater for the contra- than for the ipsilateral arrow condition at all cortical regions. However, an ANOVA encompassing all cortical regions performed on the NSW-1400 amplitude measure for the 1400-ms ISI condition alone revealed that the differences were not significant.

## Summary of Effects Involving Arrow Direction, Cortical Region, and ISI Length

In summary, the analyses involving arrow direction, region, and ISI length indicate that the arrow direction effects manifested in Figs. 19, 20, and 21 were significant only for the NSW-1000 measure (Fig. 20). For this measure the effect of arrow direction, collapsed across the four cortical regions and two ISIs, was highly significant ($p < .002$). Also, separate regional analyses of the arrow direction effect, collapsed across both ISIs, was at least marginally significant at every cortical region ($p < .05$ at occipital, central, and frontal regions; $p < .01$ at the parietal region). The magnitude of the effect at this latency was approximately the same across all cortical regions and for both the 1000- and 1400-ms ISIs.

Separate analyses performed on the NSW-1000 data for each ISI condition revealed that for the 1000-ms ISI condition, the attention effect manifested in Fig. 20, collapsed across cortical regions, was marginally significant ($p < .05$). Separate regional analyses revealed that only the arrow direction effect manifested at the frontal region approached significance ($p < .06$).

The analysis performed on NSW-1000 for the 1400-ms ISI condition only indicated that arrow direction, collapsed across cortical retions, approached significance only at the frontal region (p. < .07). Seperate regional analyses revealed a significant arrow direction effect only at central cortex ($p < 0.03$).

An analysis performed on NSW-1400 for the 1400-ms ISI condition, revealed that the arrow direction effect manifested in Fig. 21 across all cortical regions was not statistically significant.

## ERP EFFECTS OF SECONDARY INTEREST TO THE CURRENT STUDY

### 250-500 MS Measure (P300)

### Region

The comprehensive ANOVA performed on the average amplitude of the positive ERP deflection occurring in the 250-500 ms latency range revealed a main marginally significant regional [$F(3, 66) = 4.59$; $p < .05$]. The mean amplitude of the positive ERP wave, collapsed across arrow direction and all other factors, was largest at the parietal region (2.46 uv). It was followed in decreasing order at occipital (1.83 uv), central (1.63 uv) and frontal regions (1.50 uv). These slight differences are barely discernible in the positive ERP wave in this latency range in Fig. 2. Contrast analyses revealed no significant differences between the values obtained at at any combination of pairs of cortical regions (occipital vs parietal, central vs frontal, etc.). Although the main regional effect was marginal, the discernible differences across regions are consistent with the findings of others indicating that P300 tends to be of largest magnitude over parieto-central cortex (Hillyard, Courchesne, Krausz, and Picton, 1976; Squires, Petuchowski, Wickens, and Donchin, 1977; Ritter, Simson, and Vaughan, 1977; Vaughan and Ritter, 1977).

### Hemispheres

The absolute magnitude of the ERP in this latency range (P300) was significantly greater over the right (2.13 uv) than over the left (1.63 uv) hemisphere [$F(1, 22) = 17.77$; $p < .001$]. With careful observation, these hemispheric differences can be discerned in the ERPs of Fig. 6, although they are very small due to the compressed size of the microvoltage scale. The attainment of larger P300s over the left than over the right hemisphere have been reported in other studies (Hillyard and Munte, 1984; Harter Anllo-Vento, Wood, and Schroeder, 1988; Harter et al., 1989), but no studies were found which reported greater amplitude responses over the right hemisphere.

### Region by Hemisphere Interaction

The magnitude of the hemispheric differences were also dependent on the recording region [F(3, 66) = 7.33; p < .001]. The greatest hemispheric difference was obtained at the parietal region (0.90 uv), the difference progressively decreasing at central (0.47 uv), frontal (0.39 uv), and occipital regions (0.24 uv).

## Negative Slow Wave

### Region

#### NSW-600

The two comprehensive ANOVAs performed on NSW-600 involving between-group comparisons for the (A) 600- vs 1000-ms ISIs and the (B) 600-vs 1400-ms ISIs revealed significant main region effects in both instances. For (A), F(3,126) = 13.91; p <.0001. For (B), F(3, 126) = 9.37, p < .002. These effects are manifested in Fig. 14, wherein it can be seen that NSW-600 was leargest at central and smallest at occipital regions, when collapsed across either the 600- vs 1000-ms ISIs or the 600- vs 1400-ms ISIs.

The comprehensive ANOVA of NSW-600 involving a within-group comparison of the fixed 1000- vs the fixed 1400-ms ISI revealed no significant main regional effect. Thus, when collapsed across the 1000- and 1400-ms ISI conditions, the apparent smaller amplitude of NSW-600 manifested in Fig. 14

at occipital cortex, compared to other cortical regions, was not found to be statistically reliable.

### NSW-1000

The within-group ANOVA of NSW-1000 for fixed 1000- vs fixed 1400-ms ISI conditons, reflecting the greater amplitude of NSW-1000 (collapsed across the two ISIs) at parietal and central than at occipital and frontal regions (Fig. 14).

### NSW-1400

Consistent with the nearly equal magnitudes manifested in Fig. 15, no significant main regional effect was obtained for NSW-1400.

## Other Effects

In the comprehensive analyses involving five or six factors, an occasional four-, five, or six-way interaction emerged as being significant at the 0.05 level, and on even rarer occasions, at the 0.01 level. Although some of these interactions may be indicative of real effects, they were not predicted and do not lend themselves to meaningful interpretation within the context of this study. Some of the interactions involved the replication factor which, as previously noted, was produced by the random appearance of the target stimulus in the validly cued or invalidly cued visual field. Interactions involving this factor could only have been due to the occurrence of chance events having nothing to do with the variables manipulated by the experimenter.

No significant main gender effects were obtained in any of the analyses performed on the ERP measures. While a few significant interactions involving sex and one or more other variables occurred, the frequency of occurrence was consistent with that which would be expected by chance for an apriori alpha level setting of 0.03.

## REACTION TIME

A within group analysis of RTs obtained to target stimuli in the current study revealed a significant main ISI effect [F=(1, 42) = 5.92; p < .05], reflecting the fact that response time for the 1000-ms ISI (240.4 ms) was longer than for the 1400-ms ISI (236.8 ms). There also was a significant ISI x certainty interaction [F(1, 42) = 11.97, p < .01], reflecting a shorter RT under the certain (236.0 ms) than under the uncertain condition (244.8 ms) for the 1000-ms ISI with the values being slightly reversed under the certain (238.4 ms) and uncertain (235.3 ms) conditions for the 1400-ms ISI. No other significant effects were obtained.

Between-group statistical comparisons also were made between the RTs obtained for the 600-ms ISI in Keyes' thesis study to those obtained for the 1000- and 1400-ms ISIs under conditions of certainty in the current study. However, it should be kept in mind that the results of these analyses were not based on "pure" comparisons of ISI length, since the latency period within which the subject was required to respond in order to obtain a "hit" was 100 ms longer in the thesis study (400 ms) than in the current study (300 ms). The analysis comparing the thesis RT data to that obtained for the fixed 1000-ms ISI in the current study revealed a significant main effect [F(1,22) = 18.32, p < .001], the mean RT being considerably longer for the 600- (254.1 ms) than for the 1000-ms ISI condition (236.0 ms). The mean RT for the 600-ms ISI condition (254.1) also was significantly longer than that (238.4 ms) for the 1400-ms condition [F(1, 22) = 12.80, p < .001]. No other effects were significant.

## SUMMARY OF RESULTS

### Early ERP Effects

The earliest ERP component evoked by the arrow cue consisted of a deflection with a peak latency of approximately 140 ms. This deflection was of positive polarity at occipital cortex, gradually inverting in polarity more anteriorly to become distinctly more negative at frontal cortex. The next deflection peaked at about 180-200 ms. Its polarity was negative at occipital cortex, but it also gradually inverted in polarity to become clearly positive at frontal cortex.

These components were quantified by measuring the peak-to-peak difference in voltage between them at latencies of 130-140 and 170-180 ms respectively. A repeated-measures

ANOVA revealed a significant contra- vs ipsilateral arrow direction effect at the occipital region $(p < .01]$, along with a marginally significant certainty by sex interaction $(p < .05)$. A significant certainty effect was obtained at central $(p < .01])$ and frontal $(p < .01)$ regions, and marginally at the parietal region $(p < .05)$.. In each case, P1N1 amplitude was greater for the uncertain than for the certain condition. Significant hemisphere effects were obtained at central $(p < .01)$ and marginally at frontal $(p < .05)$ regions. At the central region P1N1 was greater for the right hemisphere, whereas at the frontal region it was greater for the left hemisphere.

## ERP Measures in 250-500 ms Latency Range

### Main Arrow Direction Effects and Interaction with Cortical Region

Graphic manifestations of arrow cue effects are presented in various formats in Figs. 2, 3, 4, and 5. As manifested in the figures and verified by statistical analysis, the polarity of a positive deflection ocurring during the latency interval of 250-500 ms was found to be relatively more negative over a given hemisphere when the arrow pointed to the contralateral than to the ipsilateral field. The average amplitude of the negative voltage manifested during the course of the 250-500 ms interval (CN-375) was significant as a main effect. A significant arrow direction by cortical region interaction was obtained, reflecting the fact that the greatest degree of contralateral negativity occurred over central cortex, the least amount over occipital cortex, with intermediate levels at parietal and frontal regions.

### Three-way Interaction Involving Arrow Direction, Cortical Region and Hemispheres

As revealed by a three-way interaction between arrow direction, cortical region and hemispheres, the magnitude of CN-375 was dependent on hemispheres as well as cortical region. As can be seen in Figs. 7 and 9, for the left hemisphere, the degree of contralateral negativity was greatest at parietal and least at frontal cortex, with generally greater negativity manifested posteriorily. For the right hemisphere, the voltage level for the contralateral arrow condition was relatively more positive posterioraly than for the ipsilateral condition. At progressively more frontal regions, the difference in polarity gradually shifted such that at frontal cortex the voltage level was relatively much more negative for the contra- than for the ipsilateral arrow condition, with generally greater levels of negativity manifested anteriorily. Despite the large apparent differences manifested at occipital, aprietal, and frontal regions in Fig. 9, separate regional analyses revealed no significant differences in degree of contralateral negativity between the two hemispheres for any cortical region.

### Two-way Interaction Between Arrow Direction and ISI Length

The major effects of length of the ISI on the magnitude of the 250-500 ms measure as a function of contra- vs ipsilateral arrow direction are depicted in DERP format in Figs 10 and in bar graph format in Fig 11.

Comprehensive between-group analyses involving comparisons of the 600-ms ISI with either the fixed 1000- or 1400-ms ISI intervals revealed that the contralateral negativity was greater for the 600- than for the 1000-ms ISI condition as well as for as for the 1400-ms condition 1400-ms ISI. In the latter case, separate regional analyses revealed significant differences at all but the frontal region. Statistical significance was attained only at the central region for the 600- vs the 1000-ms ISI comparison.

The interaction between arrow direction and ISI length for the fixed 1000- and 1400-ms ISI data, derived from a comprehensive repeated Measures ANOVA, did not quite reach statistical significance ($p < .07$). However, the nearly significant F-value is consistent with the overall trend reflected in Figs. 10 and 11 in which the contralateral negativity tended to be greater for the 1000- than for the 1400-ms ISI condition. Regional analyses indicated that the degree of contralateral negativity was significantly greater for the 1000- than for the 1400-ms ISI condition at occipital ($p < 0.01$) and parietal regions ($p < 0.02$), but not at the more frontal regions.

### Three-way Interaction of Arrow Direction with ISI Length (1000 vs 1400 ms) and Certainty of Length (Fixed vs Mixed Condition)

Although a comprehensive repeated measures analysis encompassing all the variables manipulated in the current study revealed a significant arrow direction by ISI length by certainty of length interaction ($p < 0.02$), followup contrast analyses indicated the differential effects of arrow direction for the two ISIs varied significantly across regions only between the occipital and parietal areas and there only marginally ($p < .04$). While, for the mixed condition, there was a tendency for the degree of contralateral negativity manifested in the DERPs to be smaller for the 1000- than for the 1400-ms ISI condition (Figs. 12 and 13), a comprehensive analysis of the data revealed that the difference between the two ISIs was only very marginally significant. Separate regional analyses revealed a significant difference only at the parietal region which also was very marginal ($p < .05$).

## ERP Comparisons Involving the NSW

### Effects of ISI Length

As manifested in Fig. 14, starting at about 500 ms, the rate of buildup in negative polarity (slope) of the NSW was greatest for the 600-ms ISI and least for the 1400-ms ISI. In the latency window of 550-650 ms, the amplitude of the NSW (NSW-600) was greatest for the 600-, intermediate for the 1000- and least for the 1400-ms ISI condition. Similarly, in the latency window of 950-1050 ms (NSW-1000), NSW amplitude was greater for the 1000- than for the 1400-ISI condition. The latency at which the NSW reached its peak amplitude for each ISI (peak latency) occurred at approximately the time the target stimulus was presented (600, 1000, or 1400 ms).

### NSW-600

Between-group analyses comparing the NSW-600 measure for the 600-ms ISI condition to that obtained for the 1000-ms ISI revealed a significant main ISI effect ($p < 0.001$). A similar main ISI effect was found for the 600- vs the 1400-ms ISI conditions ($p < 0.0001$). For the 600- vs 1400-ms ISI comparison, ISI length also interacted with recording region ($p < 0.02$), supporting the observation made from Fig. 14 that the difference in amplitude between the 600- and 1400-ms ISIs was considerably greater at parietal and central regions than at occipital and frontal regions. Contrast analyses revealed significantly greater amplitude differences at parietal ($p < 0.0001$) and central regions than at occipital cortex, and likewise, greater differences at these same two regions than at frontal cortex (p. <0001 in both cases). Regional analyses revealed significant differences in NSW-600 amplitude at all cortical regions for the 600- vs 1400-ms ISI conditions ($p < 0.001$ in every case) and at all regions except frontal cortex for the 600- vs 1000-ms ISI conditions ($p < 0.01$ in all three instances).

A repeated-measures comprehensive analysis of NSW-600 for the 1000- vs the 1400-ms ISI condition indicated a significantly greater amplitude for the 1000 than for the 1400 ISI ($p < 0.001$), as well as a marginally significant Region by ISI interaction (0.05). As manifested in Fig. 14, and bolstered by contrast and separate regional analyses, the interaction was largely due to the smaller, nonsignificant amplitude difference at occipital cortex, compared to the larger, statistically significant differences at all other regions.

### NSW-1000

As manifested in Fig. 14, a comprehensive analysis of NSW-1000 for the fixed 1000- vs the fixed 1400-ms ISI condition revealed that, collapsed across all cortical regions, the difference in NSW-1000 amplitude was statistically significant ($p < 0.001$). In addition to this main effect, there was a marginally significant Region by ISI interaction ($p < 0.05$). Contrast analyses established that the ISI effect was greater at both parietal ($p < 0.02$) and central ($p < 0.$ ) regions than at the occipital region, there being no other statistically significant regional differences. Separate regional analyses revealed a significant ISI effect at parietal ($p < 0.001$), central (p

$< 0.001$), and frontal ($p < 0.01$) regions, but not at the occipital region.

## Effects of Certainty of ISI Length as a Function of ISI Length (1000 vs 1400 ms)

A comprehensive repeated measures ANOVA encompassing the NSW-600 and NSW-1000 measures, and the 1000- and 1400-ms ISI lengths, revealed a marginally significant certainty by ISI interaction ($p < 0.04$), reflecting the negligible impact of the certainty factor on the combined magnitude of NSW-600 and NSW-1000 for the 1000-ms ISI in contrast to the readily observable impact for the 1400-ms ISI (Fig. 18).

A comprehensive analysis of both measures for the 1000-ms ISI condition only, revealed no main certainty effect, nor did the certainty factor interact with these two measures.

A comprehensive analysis encompassing all three measures (NSW-600, NSW-1000, and NSW-1400) for the 1400-ms ISI condition revealed a highly significant interaction between the three measures, collapsed across cortical regions, and the certainty factor ($p < 0.0001$). This analysis also revealed a marginally significant region by measure by certainty interaction ($p < 0.04$). Regional contrast analyses indicated that the pattern or profile of the certainty by measure interaction differed significantly between the occipital and parietal regions ($p < 0.01$), the occipital and central regions ($p < 0.01$), and the central and frontal regions ($p < 0.01$). No other regional comparisons were significant. Followup ANOVAs encompassing all three measures performed separately for each region revealed that the measure by certainty interaction was significant at occipital ($p < 0.05$), parietal ($p < 0.001$), central ($p < 0.0001$) and frontal ($p < 0.01$) regions. The differing profiles across cortical regions can be readily observed in Fig. 18.

A comprehensive analysis of NSW-600 for the 1400-ms ISI revealed a significant region by certainty interaction ($p < 0.03$). Also, a main certainty effect approached significance ($p < 0.07$). Separate regional analyses revealed that the greater amplitude for the certain than for the uncertain condition was significant at central ($p < 0.02$) and frontal regions ($p < 0.02$) but not at occipital and parietal regions. These effects can be observed in Fig. 18 by comparing the first two bars of each region.

A comparable analysis performed on NSW-1000 for the 1400-ms ISI revealed a main certainty effect ($p < 0.03$). Separate regional analyses revealed significant differences in amplitudes at parietal ($p < 0.03$), central ($p < 0.01$), and frontal regions ($F_{1,22}$ df = 7.43; $p < 0.02$). These effects are observable in Fig. 18 by comparing the middle two bars of each region.

A comprehensive analysis of NSW-1400, collapsed across cortical regions, for the 1400-ms ISI did not produce a significant certainty effect. Thus, the apparently larger amplitude of NSW-1400 amplitude for the certain than for the uncertain condition manifested in the NSW tracings of Fig. 15 and bar graphs of Fig. 18 did not prove to be statistically reliable.

## Effects of the Attention Manipulation (Contra- vs Ipsilateral Arrow Direction) as a Function of Cortical Region and ISI Length

### NSW-600

A comprehensive analysis of the NSW-600 data for the 600-vs the Fixed 1000-ms ISI condition revealed a significant arrow direction by region by ISI length interaction ($p < 0.01$). The pattern of this interaction is manifested in Fig. 19. However, followup regional analyses indicated that arrow direction interacted significantly with ISI length only at parietal cortex, and there only marginally ($p < 0.05$). Also, separate analyses of the parietal data for each ISI revealed no significant arrow direction effect for either the 600- or the 1000-ms ISI condition. Thus the apparent three-way interactive effects of arrow direction, region, and ISI length on the magnitude of NSW-600 may have been chance events.

A comprehensive analysis of the NSW-600 data for the 600-vs the fixed 1400-ms ISI condition exhibited a significant two-way interaction between arrow direction and ISI length ($p < 0.03$), as well as a significant three-way interaction involving arrow direction, ISI length, and cortical region ($p < 0.001$). These interactions are evident in Fig. 19. However, no significant contra- vs ipsilateral arrow direction effects were found to exist at any cortical region for either the 600- or the 1400-ISI condition.

A Repeated-measures ANOVA performed on NSW-600 for the 1000- vs 1400-ms ISI condition revealed no significant interactions involving arrow direction, region, and ISI, indicating that the slight differences manifested between contra- vs ipsilateral arrow direction in Fig. 19 for the 1000- vs the 1400-ms ISI conditions were not statistically reliable. This result, coupled with the overall results of the between-group analyses summarized above, suggests that the effect of arrow direction on the amplitude of NSW-600 was minimally dependent on specific combinations of region and ISI length, if at all.

### NSW-1000

In contrast to the results obtained for NSW-600, the repeated-measures ANOVA performed on the NSW-1000 amplitude data for the 1000- and 1400-ms ISI conditions revealed a main arrow direction (contra- vs ipsilateral) effect ($p < 0.002$). As manifested in Fig. 20, NSW-1000 was of consistently greater magnitude for the contra- than for the ipsilateral arrow at all cortical regions for both ISIs. Separate regional analysess encompassing both ISIs revealed that arrow direction had a significant effect at all cortical regions. There was no significant interaction between arrow direction and ISI length.

Based on an analysis of NSW-1000 for only the 1000-ms ISI condition, the amplitude of NSW-1000, collapsed across all regions, was significantly greater for the contra- than for the ipsilateral arrow condition, although marginally ($p < .05$). This effect is manifested in Fig. 20. Separate regional analyses revealed that the difference in magnitude for the two arrow direction conditions was significant at parietal ($p < 0.01$), central ($p < 0.04$) and frontal regions ($p < 0.02$), and approached significance at the occipital region ($p < 0.07$).

In an analysis of the amplitude of NSW-1000 for the 1400-ms ISI alone, the effect of arrow direction (manifested in Fig. 20) only approached significance ($p < 0.07$). Followup regional analyses revealed no significant differences, with only the occipital region approaching significance ($p < 0.06$).

NSW-1400

Although for the 1400-ms ISI, the mean amplitude of NSW-1400 as a function of arrow direction (manifested in Fig. 21) was slightly greater for the contra- than for the ipsilateral arrow condition at all cortical regions, an ANOVA encompassing all cortical regions revealed no significant effect.

### Summary of Arrow Direction Effects

In summary, the analyses involving arrow direction, region, and ISI length indicate that the arrow direction effects manifested in Figs. 19, 20, and 21 were significant only for NSW-1000 (Fig. 20). For this measure the effect of arrow direction, collapsed across the four cortical regions and two ISIs, was highly significant ($p < 0.002$). Also, the arrow direction effect, collapsed across both ISIs, was significant at every cortical region. Analyses of each ISI taken separately revealed a marginally significant arrow direction effect on NSW-1000 for the 1000-ms ISI ($p < 0.05$), but the effect only approached significance for the NSW-1400 ISI ($p < 0.07$).

## ERP Findings of Secondary Interest to the Current Study

### 250-500 MS Measure

The comprehensive ANOVA encompassing all variables manipulated in the current study revealed a marginally significant main region effect ($p < 0.05$) with respect to the absolute magnitude of the ERP falling within the 250-500 ms latency range of Fig. 2. However, contrast analyses revealed no significant differences between the values obtained at at any combination of pairs of cortical regions, suggesting that the marginally significant main regional effect may have resulted from chance variation.

The absolute magnitude of the ERP in this latency range was significantly greater over the right (2.13 uv) than over the left (1.63 uv) hemisphere ($p < 0.001$). Also, the magnitude of the hemispheric differences were dependent on the recording region ($p < 0.001$). The greatest hemispheric difference was obtained at the parietal region (0.90 uv), the difference progressively decreasing at central (0.47 uv), frontal (0.39 uv), and occipital regions (0.24 uv).

### Negative Slow Wave

Comprehensive ANOVAs performed on NSW-600 involving between-group comparisons for the 600- vs 1000-ms ISI and the 600-vs 1400-ms ISI revealed significant main region effects in both instances, reflecting the fact that NSW-600 was largest at central and smallest at occipital regions. An ANOVA of the same measure for the fixed 1000- vs the fixed 1400-ms ISI produced no significant main effect.

The within-group ANOVA of NSW-1000 for fixed 1000- vs fixed 1400-ms ISI conditions was significant, reflecting the greater amplitude of NSW-1000 (collapsed across the two ISIs) at parietal and central than at occipital and frontal regions (Fig. 13).

No significant main Regional effect was obtained for NSW-1400.

## REACTION TIME (RT)

A within group analysis of RTs obtained to target stimuli in the current study revealed a marginally significant main ISI effect ($p < .05$), reflecting the tendency for mean RT to be slightly longer for the 1000- (240.4 ms) than for the 1400-ms ISI (236.8 ms). There also was a significant ISI x certainty interaction ($p < .01$), reflecting a shorter RT under the certain (236.0 ms) than under the uncertain condition (244.8 ms) for the 1000-ms ISI, with the values being slightly reversed under the certain (238.4 ms) and uncertain (235.3 ms) conditions for the 1400-ms ISI. No other significant effects were obtained.

Between-group statistical comparisons also were made between the RTs obtained for the 600-ms ISI in Keyes' thesis study to those obtained for the 1000- and 1400-ms ISIs under conditions of certainty in the current study. In making these comparisons it was noted that the latency period within which the subject was required to respond in order to obtain a "hit" was 100 ms longer in the thesis study (400 ms) than in the current study (300 ms). The analysis comparing the thesis RT data to that obtained for the fixed 1000-ms ISI in the current study revealed a significant main effect ($p < .001$), the mean RT being considerably longer for the 600- (254.1 ms) than for the 1000-ms ISI condition (236.0 ms). The mean RT for the 600-ms ISI condition (254.1) also was significantly longer than that (238.4 ms) for the 1400-ms condition ($p < .001$). No other main effects were significant.

# CHAPTER 4

# DISCUSSION

## ERP MEASURES PRIOR TO 250 MS (P1N1)

### Effect of Contra- vs Ipsilateral Arrow Direction

The significant contra- vs ipsilateral arrow direction effect obtained at occipital cortex for the P1N1 measure ($p < 0.01$) is consistent with the observation by Harter and associates (Harter, et al. 1989) that the earliest significant attention-related effect occurred between 180-200 ms at the posterior region of the cortex. Although the measure used in the current study was an occipital P100/N200 peak-to-peak measure, in contrast to a baseline-to-occipital N200 measure used by Harter et al., the two measures were functionally the same, since no attention-related effect on P100 *per se* was observed in either of the two studies. That is, only the N200 peak was affected by arrow direction in both studies.

It is therefore concluded that the occipital P1N1 results obtained in the current study lend further support to the earlier conclusion by Harter et al. that the earliest ERP indication of a differential neural response related to the attentional information contained in the arrow cue begins at about 200 ms and is localized in the occipito-parietal region. This conclusion is compatible with the commonly held notion that early ERP components occurring prior to 200 ms reflect the sensory-perceptual stage of processing in which the physical properties of the stimulus are analyzed (references, incl. Hillyard, et al., 1995, Mangun, 1995). Until this initial stage of analysis has been completed, it would not be possible for the attentional system to accurately switch and focus attention at the designated location. Therefore, as was the case, one would not expect these early sensory processing components to be affected by the directional information contained in the arrow cue.

## Other Effects

The greater degree of negativity obtained for occipital N1P1 for the uncertain than for the certain ISI length suggests that the general arousal level of the subjects was higher when performing under conditions of uncertainty. Eason et al. (1969) demonstrated years ago that the experimental manipulation of general activation level and alertness through variations in the task demands placed on the subject alters the amplitude of early ERP components, including both P1 and N1. Since it took twice as long to collect the data for the uncertain than for each of the certain conditions (see Methods, pp. 32-33) in this study, the demands placed on the subjects were clearly greater while performing under conditions of uncertainty.

The significant contra- vs ipsilateral arrow direction effect obtained at occipital cortex for the P1N1 measure ($p < 0.01$) is consistent with the observation by Harter and associates (Harter, et al. 1989) that the earliest significant attention-related effect occurred between 180-200 ms at the posterior region of the cortex. Although the measure used in the current study was an occipital P100/N200 peak-to-peak measure, in contrast to a baseline-to-occipital N200 measure used by Harter et al., the two measures were functionally the same, since no attention-related effect on P100 per se was observed in either of the two studies. That is, only the N200 peak was affected by arrow direction in both studies.

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It is therefore concluded that the occipital P1N1 results obtained in the current study lend further support to the earlier conclusion by Harter et al. that the earliest ERP indication of a differential neural response related to the attentional information contained in the arrow cue begins at about 200 ms and is localized in the occipito-parietal region. This conclusion is compatible with the commonly held notion that early ERP components occurring prior to 200 ms reflect the sensory-perceptual stage of processing in which the physical properties of the stimulus are analyzed (references, incl. Hillyard, et al., 1995, Mangun, 1995).

The larger P1N1 amplitudes obtained at the central region for the right hemisphere have been observed in a number of ERP studies (Harter and Salmon, 1972; Hillyard, Hink, Schwent, and Picton, 1973; Picton and Hillyard, 1974). Larger amplitudes have been observed over the right hemisphere at other cortical regions as well. Depending on the type of stimuli used (e.g., verbal vs nonverbal) larger responses have also been observed over the left hemisphere (Riddoch and Humphreys, 1983). Since the hemispheric differences manifested by these early components were not of primary interest in this study they will not be considered further here.

### DP250-500 (CN-375)

As noted above, the first signs of neural engagement of an attentional mechanism in response to the direction of the arrow cue began at about 200 ms in the occipitial region. While this was the earliest sign of attention-related activity, the major portion of the ERP response which Harter and associates labelled "EDAN" (Harter, et al., 1989; Harter & Anllo-Vento, 1991; Keyes, 1991) fell in the latency range of about 250-500 ms after the presentation of the arrow cue. This was the same latency interval during which P300 occurred and upon which "EDAN" appeared to "ride," thereby causing P300 to be relatively more negative (i.e., of smaller amplitude relative to baseline) when the arrow cue pointed to the contralateral visual field. The contralateral negativity was interpreted as a manifestation of the neural processes involved in shifting attention to the cued visual field.

Having placed this interpretation on the contralateral negativity as to its functional significance, the observed negativity was assigned the label, "EDAN", an acronym for "early directing attention negativity". In the current study the contralateral negativity has been labelled "CN-375", rather than "EDAN". It is a purely descriptive label of the negativity which denotes the polarity (CN) and midpoint (375) of the 250-500 ms latency interval over which the negativity was observed.

The results obtained in the current study were highly consistent with those obtained by Harter and associates in previous studies (Harter et al, 1989; Harter & Anllo-Vento, 1991; Keyes, 1991). As they observed both in children and adults, the predominant part of the contralateral negativity occurred over a latency interval of 250-500 ms (CN-375) which "rode" on "P300". The negativity was observed at all cortical regions, and in agreement with earlier results, it was largest over central cortex and smallest at occipital cortex with intermediate levels at parietal and frontal regions (Figs. 1 and 4). The findings obtained in the current study constitute the third major replication of the "EDAN" phenomenon in the UNCG psychophysiology laboratory, once in children and twice in adults. The demonstrated replicability of the "EDAN" effect fulfils one of the primary objectives of the current study, and leaves little doubt as to the reliability of its existence.

Reseachers from two other laboratories, employing paradigms analogous to that used in the current study, have reported preliminary findings of attention-related contralateral negativities falling within the 250-500 ms range (Freeman-Hill and Mangun, 1993; Yamaguchi & Kobayashi, 1993). Freeman-Hill and Mangun reported greater contralateral negativities over fronto-central scalp sites in the latency range of 275-375 ms. Yamaguchi and Kobayashi reported contralateral negativities over occipito-temporal regions starting at 250 ms. More anteriorly the negativity began later in time and continued up to 500 ms. Collectively, these two studies constitute further substantiation of the contralateral negativity observed in the 250-500 ms range in the current study.

### Hemispheric Differences in CN-375 Amplitude

It should be recalled that a significant interaction was found between arrow direction, region and hemispheres, reflecting the fact that CN-375 was relatively greater over the left hemisphere than over the right at posterior cortical regions, whereas it was relatively greater over the right hemisphere at anterior regions (see Fig. 6). This differential hemispheric pattern suggests that the neural response to the attentional information contained in the arrow cue was relatively greater in the left than in the right hemisphere at occipital and parietal regions, but at progressively more anterior regions the magnitude of the response gradually shifted in favor of the right hemisphere. This finding was unexpected, and if it can be replicated, would seem to have important implications for the nature of the neural mechanism involved in shifting and focusing attention. Until the finding is replicated, however, it seems premature to speculate on why the attentional system would engage the two hemispheres differentially at posterior and frontal brain regions. The utility of such speculation is further questioned, given the fact that no significant differences in CN-375 amplitude between hemispheres were obtained at any cortical region, including occipital and frontal cortex where relatively large apparent differences were observed (Fig. 9).

In addition to the replicability issue, a question may be raised as to whether the significant interaction involving hemispheres may have been specific to the particular reference voltage against which the amplitude of CN-375 was measured. The selection of an appropriate reference voltage against which to quantify ERP components has been and continues to be a major problem in ERP research (Picton and Hink, 1974; Vaughan, 1974). Most researchers have adopted the convention of using the so called "resting" voltage at the time the stimulus to which the ERP response is time locked is presented. This "resting" baseline voltage typically has been defined as the average voltage level occurring either within 50-100 ms prior to stimulus presentation or within 50-100 ms after stimulus presentation (Mangun and Hillyard, 1987; Harter et al., 1989; Harter & Anllo-Vento, 1991; Hillyard et al., 1974; Mangun, 1995).

The reference voltage used in this study for quantifying CN-375, as well as the NSW components, was chosen in accordance with this convention, and consisted of the average voltage occurring within the first 60 ms after the presentation of the arrow cue. Since the mid-latency (30 ms) of the reference voltage preceded the onset latency of CN-375 by over 200 ms, it is possible that the differential CN-375 profiles manifested across cortical regions for the two hemispheres in Fig. 6 may have resulted in part from ERP differences between hemispheres which occurred prior to the onset of CN-375. This possibility takes on a certain degree of finite probability upon examination of the DERPs obtained for the two hemispheres in Fig. 8. Such examination reveals that the voltages do appear to have changed in opposite directions for the two hemispheres at each cortical region within the first 250 ms after presentation of the arrow cue. Furthermore, the degree of change appears to have varied across cortical regions. Had the reference voltage for measuring CN-375 been chosen at a latency interval closer to its onset (e.g., between 200-250 ms) the regional profiles manifested in Fig. 9 for the two hemispheres may have been more similar in appearance. The selection of a reference voltage is a perennial problem for ERP researchers, because the effect of a given experimental manipulation on the magnitude of an ERP component may vary with the criteria and procedures used in selecting the reference baseline.

Since a "resting" voltage baseline also was used by Harter et al. (1989) and Harter & Anllo-Vento (1991) in measuring contralateral activity associated with the arrow cue, an attempt was made to compare the differential regional profiles manifested in Fig. 9 to the hemispheric asymmetries associated with arrow direction which they had reported. Upon examination of their results, it became apparent that the "EDAN" measures derived for the two hemispheres in the children's data were not consistent with respect to contra- vs ipsilateral arrow direction. Their procedure involved subtracting the right arrow cue from the left arrow cue irrespective of the recording hemisphere. Thus, for the right hemisphere, subtraction of the right arrow cue from the left was equivalent to subtracting the ipsilateral (right) arrow cue from the contralateral (left) arrow cue as was done in the current study. However, for the left hemisphere, "EDAN" was derived by subtracting the contralateral (right) arrow cue from the ipsilateral (left) arrow cue, thus inverting the polarity of the measure for the left hemisphere compared to that obtained for the right hemisphere. The inversion of the polarity of "EDAN" across hemispheres appears to have been responsible for the significantly different asymmetries they reported.

Behavioral and biological studies employing a wide range of procedures and subject types have implicated the right hemisphere as being the dominant hemisphere for disengaging, shifting, and focusing attention, although there is evidence that both hemispheres are involved (Kinsbourne, 1987; Posner, 1995; Rafael & Robertson, 1995). The results summarized above do not mesh with expectations based on current knowledge of the neural basis of attention.

Based on the above comments, the most parsiminous conclusion to draw at this time would seem to be that the question of whether the attention-related process manifested by CN-375 varies across hemispheres at one or more cortical regions remains to be conclusively demonstrated.

## ISI Effects on CN-375 Amplitude

In the Statement of Purpose (pp. 24-25), it was postulated that variations in the length of the ISI should alter the demands placed on the attentional system when preparing to respond to a target stimulus. The shorter the ISI the greater should be the demand placed on the system. Differing demands placed on the attentional system by variations in ISI length could be manifested by (1) changes in the magnitude of the neural discharge involving the attentional system; (2) changes in the latency at which the discharge begins, peaks, and ends; or (3) by changes in both the amplitude and latency. Based on this postulation, it was hypothesized that, under conditions of certainty of ISI length, if the "EDAN" response (i.e., contralateral negativity) reflects the engagement of an attentional mechanism involving shifting attention to a different location, as proposed by Harter and associates (Harter, et al., 1989; Harter & Anllo-Vento, 1991), or the execution of any other attentional requirement such as spatial focusing, then the magnitude of the neural response should vary inversely with ISI length, its onset and offset latencies should vary directly with ISI length, and/or some combination of the two should occur.

The results obtained as a function of ISI length under conditions of certainty (shown in Figs. 10 & 11) were consistent with that part of the hypothesis which predicted that the magnitude of the response should vary inversely with ISI length. As depicted in the figures, the mean amplitude of CN-375 was largest for the 600- and smallest for the 1400-ms ISI condition at all scalp regions.

## ISI Effects on CN-375 Latency

While CN-375 amplitude was affected by ISI length in the manner described above, there was no discernible effect of this manipulation on either the onset latency or duration of the contralateral negativity measure. In fact, both the onset latency and duration of CN-375 was remarkedly constant under all experimental conditions. This constancy was readily observable in the DERPs of Fig. 10 wherein it could be seen that the onset and duration of the contralateral negativity wave was about the same for all ISIs and for all cortical regions.

The consistent onset latency and duration of the endogenous negativity evoked in the hemisphere contralateral to the visual field to which attention was directed suggests that the response was closely time-locked to the cueing stimulus. Irrespective of total preparation time (ISI length), this "reflex"-like response to the cue stimulus appears to have been activated at the earliest possible moment after the directional information contained in the arrow cue had been processed.

In view of this contant latency of response to the cue stimulus, regardless of ISI length, it appears the neural mechanism involving in shifting (and perhaps initiating the focusing of) attention is reflexly engaged at about the same point in time after presentation of the arrow cue regardless of the amount of time available for preparing to respond to the target stimulus. At least this appears to be the case for preparatory intervals varying over an 800-ms range (from 600 to 1400 ms). Once engaged, however, the magnitude of the latency-locked neural response associated with the directional information contained in the cue stimulus depends on the length of the preparatory interval.

### Central vs Peripheral Cuing

The reflex-like nature of CN-375 to the foveally-presented arrow cue is interesting in view of findings by both behavioral and neurological studies which have shown differences in the degree of automaticity found to exist when attention is directed to a peripheral location by means of a centrally (i.e., foveally) located cue vs a peripheral cue appearing at or near that location (Posner, et al., 1980; Posner & Cohen, 1984; Yantis & Jonides, 1990; Mangun, Hansen & Hillyard, 1987; Mangun & Hillyard, 1991; Mangun, 1995). The central cuing procedure (known as endogenous or symbolic cuing) is assumed to produce only voluntary shifts in attention, whereas the peripheral procedure (known as exogenous or sensory cuing) is thought to produce sensory-evoked involuntary shifts in attention (Posner & Cohen, 1984; Mangun, 1995). The constant-latency, reflex-like CN-375 responses elicited by centrally located arrow cues in the current study raises some question as to whether symbolically cued attentional shifts are totally voluntary acts as has been assumed to be the case (Mangun, 1995).

## Relations Between P300 and CN-375

It should be recalled that, one objective of the current study was to determine whether and to what extent the effects of ISI length on CN-375 might be yoked to the latency of P300. As was the case for CN-375, the latency of of P300 remained essentially invariant under all experimental conditions, including ISI length. Thus, CN-375, which "rode" on P300, occurred at essentially the same portion of the P300 waveform under all experimental conditions. Due to the latency invariance of both measures for all ISIs, no evidence was obtained to indicate that the latency and duration of CN-375 could be made to vary independently of P300. Thus, the possibility cannot be ruled out that they both reflect the same or closely related parallel processes which were set into motion by the directional information contained in the arrow cue.

## Components Comprising CN-375 and Their Scalp Distribution

Based on volume conduction theory (Nunez, 1986, 1987; Vaughan, 1974) and source location studies (Arezzo, Vaughan, Kraut, Steinschneider, & Legatt, 1986; Wood and Allison, 1981), the amplitude profile (Figs. 1, 3, & 9) obtained across cortical regions in the current, as well as in the previous studies by Harter and associates (Harter, et al., 1989; Harter & Anllo-Vento, 1991; Keyes, 1991), suggests that the neural activity associated with CN-375 was widely distributed across the cortex. The amplitude profile suggests further that the equivalent dipole source or sources responsible for the scalp-recorded contralateral negativity involved the activation of (1) a single dipole source comprised of a large cortical sheet of tissue extending across occipital, parietal, central, and frontal regions, (2) at least two dipole sources located considerable distances apart along the longitudinal axis of the brain, or (3) a deep source involving one or more subcortical structures (Nunez, 1981; Vaughan, 1974, 1982; Wood, 1981, 1982).

Without concomitant recordings of electrophysiological data with microelectrodes placed in local brain areas none of these possibilities can be ruled out. However, variations in the peak latency of CN-375 across cortical regions manifested in Figs. 2, 4, & 10, tend to favor the second possibility. Upon visual inspection of these figures, it appears that the latency at which the wave of contralateral negativity reached its peak varied across cortical regions. The peak latency occurred at about 300 ms at the occipital region and at 400 ms at the frontal region, with intermediate values occurring at parietal and central regions. Another possibility is that the wave of contralateral negativity was not comprised of a single peak which shifted in latency, but of two peaks (one occurring at a latency of about 300 ms and the other at 400 ms) whose relative amplitudes changed across cortical regions. Either of these possibilities suggest that CN-375 was comprised of more than one dipole generator. The most parsimonious possibility would be two dipole sources with peak activity levels occurring at 300 and 400 ms respectively, the first source being located in the occipito-parietal region and the second in the centro-frontal region in or near the frontal eye fields.

Assuming this two-dipole model has some degree of credibility, it seems at least plausible to speculate that the engagement of the attentional system in response to the arrow cue was initiated in the occipito-parietal region, with the locus of peak activity shifting to the frontal region within about 100 ms. To speculate a little further, the activation of the posterior dipole may have been associated with the initial stage of shifting attention, whereas activation of the frontal region in or near the frontal eye fields may have been associated with the completion of the attentional shift to the designated location and with the initial stages of focusing attention at that location.

### Summary Statement Involving CN-375

Although the details remain to be worked out, it is clear that in about 200-250 ms after the presentation of an arrow cue, one or more neural process(es) lasting for about 250 ms is/are set into motion in response to the directional information contained in the cue. This activity reflects an early processing stage in making the attentional adjustments required for maximal preparation to respond to a target stimulus. Although both the onset latency and duration of this early processing stage remain essentially constant, the magnitude of the neural activity associated with it is more intense for short than for long preparatory intervals. While the primary visual area of the occipital cortex is heavily involved in processing the sensory information contained in the arrow cue (Mangun & Hillyard, 1988; Mangun, 1995), the scalp distribution of CN-375 suggests that, once the sensory processing stage is over, the attentional information contained in the arrow cue is processed at higher levels involving associational cortex across all cortical regions. The amplitude of CN-375 is maximal at parietal and central regions, suggesting these regions are somehow involved in the initial stages of shifting and focusing attention. However, shifts in the peak latency of CN-375 across cortical regions suggest occipital and frontal associational areas may be focal points of involvement at certain points in time. Whether or not the two hemispheres are differentially involved in this early attention-related preparatory process remains to be conclusively demonstrated.

## NEGATIVE SLOW WAVE (NSW)

### Main Effects of ISI Length on NSW

Based on the premise that the time employed by a subject to prepare to respond to an impending target stimulus (TS) will vary in accordance with the amount of time available for becoming prepared, it was hypothesized (pp. 27-28) that if the negative slow wave (NSW), or "contingent negative variation - CNV" as it is sometimes called (McCallum, 1988), reflects cortical activity involving preparation to respond to a target stimulus (TS), then under conditions of certainty of ISI length, its rate of buildup (slope) and peak latency should vary inversely with the length of the ISI. Thus, at 600 ms latency, NSW amplitude should be greatest for an ISI length of 600 ms, smallest for a length of 1400 ms, and intermediate for a length of 1000 ms. Likewise, at 1000 ms latency, NSW amplitude should be greater for and ISI length of 1000 than for a length of 1400 ms.

The main effects of ISI Length on the amplitude of NSW, manifested in Fig. 14, and strongly supported by statistical analyses, clearly were in accord with the hypothesis and predictions stated above. The difference in slope as a function of ISI length during the initial phase of the NSW (between 400-500 ms) was very marked, as was the difference in average amplitude during the latency interval of 550-650 ms (NSW-600) for the three ISI lengths. The difference in average amplitude manifested during the 950-1050 latency interval (NSW-1000) between the 1000- and 1400-ms ISIs also was very marked. The slope and amplitude differences were most pronounced at parietal and central regions.

A plausible interpretation of these results, which is consistent with conclusions regarding the functional significance of the CNV (Ruchkin et al., 1986; McCallum, 1988), is that, once attention has been shifted in response to the arrow cue (as reflected by CN250-500), subjects adjust their rate of buildup in motivational, cognitive, and motor preparation needed to respond optimally to the TS in accordance with the amount of time available to prepare. Furthermore, the confirmation of _apriori_ predictions concerning the relation between ISI length and the NSW gives validity to the _apriori_ assumption on which the predictions were made that the rising slope and amplitude of the NSW at various points in time may be used as an index of the progressive buildup in cortical excitation and the peak level of activation associated with the preparatory process. [see McCallum, p.468]

### _Interaction of ISI Length with Certainty of Length_

To facilitate the discussion of the effects of the certainty manipulation on the NSW as a function of ISI length, it should be noted that the results discussed in the preceding section were limited to those obtained under conditions of certainty. That is, the length of the ISI interval remained fixed throught the data collection interval. When performing under such circumstances the subjects adjusted their rate of preparation, as reflected in the rate of buildup and peak latency of the NSW, to the total time available to prepare.

As proposed in the Introduction (pp. 28-30), when working under conditions of uncertainty, a different strategy would be required for optimal performance. That is, regardless of ISI length, the subject would need to be fully prepared to respond to the TS within the time interval allowed by the shortest ISI which could occur (1000 ms in the current study). On the assumption that most subjects would adopt this strategy the following predictions were made.

Prediction 1

Since the subject should be equally ready to respond to a TS presented at 1000 ms under both certain (Fixed) and uncertain (Mixed) conditions, the rate and degree of buildup in NSW amplitude occurring up to that point in time should be essentially the same. Thus, for the 1000-ms ISI condition, there should be no difference in the buildup of NSW amplitude as a function of certainty. However, for the 1400-ms ISI condition, there should be a difference in buildup as a function of certainty, since under the uncertain condition the subject should be fully prepared to respond by 1000 ms while under the certain condition full preparation would not be required until 1400 ms had passed. This prediction should be manifested in terms of an interaction involving ISI length and certainty of length for NSW amplitude measures up to 1000 ms (i.e., for NSW-600 and NSW-1000).

The graphic results depicted in Figs. 15-18 were consistent with this prediction, as were the findings from statistical analyses performed on the NSW-600 and NSW-1000 measures.

Prediction 2

An extension of the first prediction was that, for the 1400-ms condition, the differences noted in NSW amplitude at 1000 ms between the certain and uncertain conditions should have disappeared by 1400 ms, since subjects should have been fully prepared to respond under both conditions by that time. If an implicit P300 response marking the absence of the presentation of a TS at 1000 ms should "ride" on the NSW (Ruchkin & Sutton, 1978), thereby driving it in a positive direction just prior to the termination of the 1400-ms ISI, then NSW amplitude for the uncertain condition might be less than rather than approximately equal to that for the certain condition.

The empirical findings provide clear support for the predicted convergence of the NSWs obtained under certain and uncertain conditions during the last 400 ms of the 1400-ms ISI. As manifested in Fig. 14, the waves not only converged but crossed over about midway through the interval at all but the frontal region, resulting in a lower NSW amplitude for the uncertain than for the certain condition at 1400 ms (right panel of Fig. 15). A highly significant interaction was obtained between the three NSW amplitude measures (NSW-600, NSW-1000, and NSW-1400) and certainty, reflecting the shift from relatively greater NSW amplitudes at 600 and 1000 ms to an equal or lower amplitude at 1400 ms for the uncertain compared to the certain condition. Despite the significant interaction and the apparently lower amplitude for the uncertain condition at 1400 ms, no main certainty effect was obtained for NSW-1400 nor did certainty interact with cortical region.

Since the apparently lower amplitude manifested in NSW-1400 for the uncertain condition was not statistically different from that for the certain condition, the prediction that the amplitudes should be approximately equal at the end of the ISI remains plausible. If an implicit P300 was elicited which algebraically summed with the NSW to produce an apparent reduction in the amplitude of NSW-1400 for the uncertain condition, the reduction was not strong enough to reach statistical significance.

In conclusion, the effects of certainty of ISI length, in combination with the effects of variations in ISI length discussed in the preceding section, offer solid support for the hypothesis that, after attention has been shifted to the appropriate location in response to an arrow cue, the NSW reflects the engagement of cortical processes involved in becoming fully ready to respond to a target stimulus expected to appear at that location at a given point in time. If the exact time interval between the presentation of the stimulus cue and presentation of the target stimulus is known, the neural preparatory rate is adjusted to the length of the ISI. If the ISI is variable and unpredictable, the preparatory rate is adapted to the shortest interval at which the target stimulus might appear. Indirect support for this conclusion is provided in a CNV study by Ruchkin, et al. (1986). Having observed in a conventional CNV paradigm that the slope and peak latency of the CNV varied inversely with the length of the ISI, they concluded that the slow wave negativity reflects one or more cognitive processes involving expectancy, anticipation or "mental preparation" which builds up in accordance with the length of the preparatory interval.

## Effects of Arrow Direction (Directing Attention to the Contralateral vs the Ipsilateral Visual Field) on the NSW

### NSW-600 ("LDAP")

As was noted in the Introduction, Harter and associates (Harter, et al, 1989; Harter & Anllo-Vento, 1991) observed in children that the contralateral negativity occurring in the 250-500 ms range was immediately followed by a wave of contralateral positivity which lasted until about 700 ms. This wave of positivity "rode" on the slow negative wave which peaked at about 700 ms. The positivity was most pronounced at occipital cortex, becoming progressively less so more anteriorly. Harter, et al. interpreted the positivity as reflecting "neural priming" over the visual cortical area of the hemisphere lying contralaterally to the cued visual field. The positivity was labelled "LDAP", an acronym for "late directing attention positivity."

In Keyes' masters thesis study with adults (Keyes, 1991; Harter & Anllo-Vento, 1991), "LDAP" was minimally present at occipital cortex and totally absent at central and frontal regions, raising some question as to the replicability of the "LDAP" effect in adults and its manifestation of "cortical priming" as proposed by Harter and associates.

In the thesis study, "LDAP" was derived by first obtaining the voltage differential between the levels manifested at 440 and 640 ms (P440N640), and then subtracting the value obtained for the ipsilateral arrow cue from that obtained for the contralateral cue. In order to compare the "LDAP" results reported in the thesis to those obtained in the current study, the thesis data were remeasured so as to derive an NSW-600 (averaged across 550-650 ms) comparable to that used in the current study. As was the case for the earlier measure used in the thesis study, the effect of arrow direction on NSW-600 derived from that study was not statistically significant. Furthermore, the observable difference, although nonsignificant, was in a direction opposite to that of "LDAP", NSW-600 being relatively more <u>negative</u> when the arrow pointed to the contra- than to the ipsilateral visual field.

The reader is reminded that the effects of arrow direction on NSW-600 for the 600-ms ISI employed in the thesis study, along with the effects obtained for this same measure for the 1000- and 1400-ms ISIs used in the current study, were presented graphically in Fig. 19 and described on pages 72-73. A slight degree of contralateral negativity was observable at occipital and parietal regions for the 600-ms ISI condition, in contrast to a detectable amount of contralateral positivity at these same regions for the 1000- and 1400-ms ISI conditions. These apparent differences in the magnitude and polarity of "LDAP" for the 600- vs the 1000- and the 1400-ms ISIs were associated respectively with a significant two-way interaction involving arrow direction and ISI length and a three-way interaction involving arrow direction, ISI length, and cortical region. However, separate analyses performed for each ISI revealed no significant contra- vs ipsilateral arrow direction effect at any cortical region. Based on these results, it would appear that if "LDAP" exists in adults, its amplitude is so small that its existence remains to be reliably demonstrated.

The lack of convincing evidence for the existence of an "LDAP"-like response in adults, based on results obtained in two successive experiments involving a total of 44 subjects, contrasts sharply with the evidence obtained in previous studies from three large samples of children (Keyes & Eason, 1994; see Fig 1 of this document). Not only was a greater degree of positivity manifested over a given hemisphere when the arrow cue pointed to the contralateral field, the degree of positivity was directly related to the reading capacity of the children.

The factors responsible for the asymmetrical buildup in positivity over the contralateral hemisphere in children are presently unknown. Since the basic paradigm used in both the children and adult studies demanded the differential focusing of spatial attention in order to meet performance requirements, it seems unlikly that the asymmetry observed in the children's ERPs in the 500-700 ms latency range was indicative of "cortical priming" related to focusing attention, as originally proposed by Harter and associates (Harter, et al., 1989 Harter & Anllo-Vento, 1991).

Further research is needed first to determine whether "LDAP" can be replicated in other groups of children, and if so, to determine what may be its functional significance, if any, in preparing to respond to a TS cued to appear at a specified location in space. One approach would be to run several groups of children ranging in age from approximately nine to eighteen years while varying such parameters as ISI length, certainty of length, performance incentive, and time allowed within which to respond to the TS.

### NSW-1000 and NSW-1400

Although there were no significant effects of arrow direction on the NSW in the 550-650 latency range, there was a significant effect 400 ms later. That is, NSW-1000 was found to be significantly more negative, as a main effect, for the contra- than for the ipsilateral arrow condition (collapsed across 1000- and 1400-ms ISIs and cortical region). This main effect was manfested in Fig. 20 wherein NSW-1000 was noticably more negative for the contralateral condition for both ISIs and at all cortical regions. Separate regional analyses, collapsed across the two ISIs, indicated the greater contralateral negativity manifested in Fig. 20 was significant at all cortical regions. Regional analyses for each ISI separately revealed significant differences at all but the occipital region (which approached significance) for the 1000-ms ISI; however, no significant differences were obtained for the 1400-ms ISI. Although a relatively greater degree of negativity associated with the contralateral arrow cue also was observed for NSW-1400 (Fig. 21) at all cortical regions, no statistically significant main arrow direction effect was obtained.

Despite the highly significant main attentional effect (p. < .002), the extremely small magnitude of the differences manifested in Fig. 20 coupled with the failure to demonstrate a significant effect for the 1400-ms ISI alone signifies that the statistically significant effects obtained for the 1000-ms ISI should be interpreted cautiously. Acknowledging this, the greater NSW amplitude manifested for the contralateral arrow condition at the time the TS appeared adds another small bit of evidence to the substantial body of evidence which currently exists in support of the view that the NSW (or "CNV") reflects, among other things, a selective attention process (McCallum, 1988; McCallum & Walter, 1968; Ruchkin, et al., 1986; Tecce & Scheff, 1969; Tecce & Hamilton, 1973).

## REACTION TIME

### Effects of ISI Length

#### Within-Group Effects

A repeated-measures ANOVA of RT measures obtained for the 1000- and 1400-ms ISIs under certain and uncertain conditions revealed a main ISI effect, reflecting the fact that RTs were slightly longer for the 1000- (240.4 ms) than for the 1400-ms ISI (236.8) length ($p < 0.05$). Even though the difference reached statistical significance, the reaction time for the 1000-ms ISI was only 1.5% longer than that for the 1400-ms ISI, bringing into question the functional significance of the difference as well as its replicability.

The fact that the RT data were essentially the same for the two ISIs is consistent with the fact that ERP measures obtained at a latency of 1000 ms were about equal in magnitude to those obtained at a latency of 1400 ms. Since

ISI length had little effect, if any, on either the behavioral or electro-physiological measures, it is reasonable to conclude that the subjects were about equally well prepared to respond to target stimuli appearing at either 1000 or 1400 ms after the cueing stimulus.

There also was a significant ISI x certainty interaction ($p < 0.01$), reflecting a shorter RT under the certain (236.0 ms) than under the uncertain condition (244.8 ms) for the 1000-ms ISI, with the values being slightly reversed under certain (238.4 ms) and uncertain (235.3 ms) conditions for the 1400-ms ISI. This interaction is inconsistent with the rationale expressed in the Introduction (pp. 30-31), and with the findings obtained for ERP measures NSW-1000 and NSW-1400. That is, under conditions of uncertainty, in order to perform optimally, subjects should have been equally prepared to respond to target stimuli by 1000 ms regardless of ISI length (1000 or 1400 ms). If so, the amplitude of NSW-1000 should have been about the same for both the certain and uncertain conditions. This was observed to be the case. For the 1400-ms ISI condition, even though subjects were not expected to be as ready to respond to a TS presented at 1000 ms under conditions of certainty than under conditions of uncertainty, they were expected to be equally prepared to respond at 1400 ms latency. No significant differences were obtained for NSW-1400 as a function of certainty, thus indirectly supporting this expectancy. Therefore, no rational explanation can be offered as to why RT covaried with ISI length other than to suggest that it may have been a chance phenomenon.

Between-Group Effects

The between-group analysis comparing the thesis RT data to that obtained for the Fixed 1000-ms ISI in the current study revealed a significant main effect (< 0.001), the mean RT being longer for the 600- (254.1 ms) than for the 1000-ms ISI condition (236.0 ms). Also, the mean RT for the 600-ms ISI condition (254.1) was significantly longer than that (238.4 ms) for the 1400-ms condition ($p < 0.001$).

These results are in direct contradiction with those which were obtained for ERP measures CN-375 or NSW-600. For both of these measures larger amplitudes were obtained for the 600-ms ISI than for either the 1000- or 1400-ms ISI lengths.

In attempting to reconcile the apparent conflict between the behavioral and electrophysiological findings, it should be recalled (pp. 36-37) that the latency period within which the subject was required to respond in order to obtain a "hit" was 100 ms longer in the thesis study (400 ms) than in the current study (300 ms). Thus, the length of the latency period which produced a "hit" covaried across the two studies with ISI length. Although the outcome was not predicted, it turns out to be the case that reaction time responses to target stimuli were affected to a much greater extent by the length of the latency period for registering a "hit" than by the length of the ISI. In marked contrast, the electrophysiological measures of preparatory activity which preceded the occurrence of the target stimulus were affected more by ISI length than by the length of the latency period for acquiring a "hit."

Although it has been established that both physiological and behavioral measures reflect to some degree the combined effects of the sensory-perceptual, attentional, motivational, and motor systems involved in preparing to respond to a target stimulus (McCallum, 1988), the results reported here suggest that the physiological measures preceding the occurrence of the TS predominantly reflect the degree of involvement of the sensory-perceptual, attentional and motivational systems in the preparatory process; whereas the behavioral measure (RT) predominantly reflects the level of preparedness of the motor system.

The execution of an RT response to a TS cued to appear in a given visual field engages the motor system in a serial manner involving several sequential steps, some of which are clearly independent of the preparatory processes reflected in the electrophysiological measures which preceded the TS. Approximately 50-100 ms prior to the presentation of the TS, cortical "premotor" cells are activated which, in turn, "prime" pyramidal motor cells which innervate the muscles involved in the RT response (Evarts, 1984; Rizzolatti, 1983; Oakley & Eason, 1990). This motor "priming" process probably contributes to the buildup of the "readiness potential" which can be recorded at the scalp over motor cortex just prior to the overt response (Kornhumber & Deecke, 1965). Upon presentation of the TS, after some delay, the "primed" pyramidal cells located in motor cortex discharge, the magnitude and latency of the discharge being dependent on the degree of premotor "priming" (Evarts, 1984). The pyramidal cell discharge crosses at least one neural synapse, with some delay, to activate the skeletal motor nerves which in turn, with some delay, activate the myoneural junction. With further delay, muscle fiber units elicit a discharge which results in the contraction of the muscle group involved in making the appropriate movement for opening or closing a circuit. Even after the movement has begun, the time required to make or break the circuit may vary considerably, depending on the ballistic characteristics of the movement, the tension on the response key, and the size of the gap that must be traversed in order for the key to make contact in the event a switch closure is required (Bartlett, 1963; Bartlett, 1968).

These sequential steps, taken as a whole, involve several degrees of freedom that can produce variability and delay in RT responses which occurs after and is largely independent of the variability contained in electrophysiological measures preceeding the presentation of the TS. Therefore, it should not be surprising that behavioral and neurophysiological responses fail to correspond in a one-to-one manner, particularly when one type of response precedes the occurrence of the TS and the other follows it.

Based on the results summarized above, it is likely that the length of the latency period within which the subject was allowed to respond markedly affected the motor preparatory process at one or more of the levels noted above. Regardless of the length of the ISI, it may be the case that subjects learn very quickly the amount of motor preparation required to respond to a TS within the time allowed, and they adapt their motor readiness level so as to meet the criterion. They may be able to regulate this simply by voluntarily varying the amount of tension placed on the participating muscle group at the time the TS is presented.

On the other hand, perceptual, attentional and motivational preparedness may be more closely linked to the time interval ensuing between the presentation of the cue stimulus and the presentation of the target stimulus. If the attentional and sensory-perceptual processing systems are not fully prepared to process the presentation of the target stimulus cued to appear at a specified location at a given point in time, the subject might fail to perceive its occurrence entirely or perceive it after so much delay that insufficient time would be left to meet the response criterion even if the motor system were in the appropriate state of readiness for doing so.

This *posthoc* speculation could be readily subjected to experimental test by systematically varying ISI length between the CS and TS, along with the latency period allowed for responding to the TS, and noting their effects on electrophysiological measures which precede the TS in conjunction with RT measures to the TS.

# CHAPTER 5

## SUMMARY

### PURPOSE AND HYPOTHESES

This study examined the electrophysiological correlates of the preparatory processes intervening between the presentation of an attention-directing arrow cue and the presentation of a target stimulus. It constitutes an extension of earlier work conducted by Harter and associates concerning attentional mechanisms in children (Harter, et al., 1980; Harter & Anllo-Vento, 1991) and in adults (Keyes, 1991). In order to study the attentional aspect of the preparatory process engaged in prior to the presentation of an imperative stimulus, Harter et al. employed a paradigm in which a peripherally presented target stimulus followed by 600 ms a foveally presented arrow cue directing attention to the right or left visual field. The subject was required to respond to the target stimulus within a designated time period if it appeared in the cued field. No response was required if the stimulus appeared in the uncued field.

Two major findings emerged in the children'S studies. Approximately 250-500 ms after the presention of the arrow cue the polarity of the P300 component of the ERP was relatively more negative for a given hemisphere when the arrow pointed to the contralateral visual field. Harter and associates interpreted this contralateral negativity as a neurophysiological indicant of the process of shifting attention to the peripheral visual field directed by the arrow cue. This negativity was labelled "EDAN" for "early directing attention negativity." A little later in time (about 500-700 ms after presentation of the arrow cue) the ERP wave became relatively more positive when the arrow pointed to the contralateral field. This contralateral positivity, labelled "LDAP" for "late directing attention positivity" was interpreted as an indication of "cortical priming" in the hemisphere contralateral to the cued visual field in preparation to process target stimulus (TS) information from that field. An "EDAN" effect was similarly observed in adults, but and "LDAP" effect was found to be minimal or absent.

The present study addressed a number of questions growing out of the Harter, at al. studies concerning the replicibality, generalizability, and functional significance of their findings. Specific questions addressed were: (1) whether the "EDAN" and "LDAP" effects could be replicated in a second group of adults; (2) whether they could be obtained for ISI lengths other than 600 ms, and if so, (3) whether their magnitude and/or latency would vary with ISI length and degree of certainty of ISI length; (4) whether the "EDAN" effect could be dissociated from the P300 component; and (5) whether "LDAP", if found to exist, could be dissociated from the negative slow wave (NSW) upon which it was found to ride in the Harter, et al. studies.

In view of the continuing controversy as to whether the "CNV" wave reflects cortical activation associated with such psychological processes as motivation level, general arousal or alertness, and selective attention (McCollum, 1988), another purpose of the study was to determine whether the NSW, which has the physical characteristics of a "CNV" wave, would be influenced by arrow direction, as well as by ISI length and certainty of length.

Several apriori hypotheses and predictions were tested. Based on the postulate that variations in the length of the preparatory interval should alter the engagement of the motivational (arousal) and attentional systems, it was hypothesized that: (1) if "EDAN" reflects the early engagement of the attentional system in response to the arrow cue then, when the subject is certain of ISI length on a given trial, the peak amplitude of "EDAN" should vary inversely with ISI length while its onset latency and duration should vary directly with ISI length. (2) If the P300 wave of the raw ERPs, upon which "EDAN" "rides", reflects neural processing related to determination of the direction to which the arrow cue signals a shift in attention, and if the shifting process is contingent upon the completion of this process, then the onset and duration of P300 should be affected in the same manner by ISI length as was predicted for "EDAN" above.

(3) If "LDAP" is a reliable correlate of "cortical priming" in the hemisphere located contralaterally to the signalled visual field, as proposed by Harter, et al., then, when certain of ISI length, the onset latency, duration, and amplitude of "LDAP" should vary with ISI length. (4) If the neural processes responsible for "LDAP" modulate the same neural processes responsible for the generation of the NSW component of the raw ERP waveforms, then the onset and peak latencies of this CNV-like wave should closely parallel the onset and duration of "LDAP" as a function of arrow direction and ISI length. (5) If the NSW reflects variations in motivation level, general arousal or alertness, then when working under conditions of certainty of ISI length, the rate of buildup in negativity (slope) of the NSW should vary inversely with ISI length. If an "LDAP" should be found to occur at these longer latencies, its amplitude and duration should parallel that of the NSW. (6) When uncertain of ISI length, to maximize performance the subject should be prepared to response at the earliest time the target stimulus could appear. Thus, no differences should be observed in the rate of buildup and amplitude of the NSW during the shortest ISI interval in which the target stimulus could occur. (7) Reaction time responses to target stimuli should vary inversely with the amplitude of the NSW at the time the target stimulus appears.

## Method

Each of the 24 subjects participated in three data recording episodes involving four conditions with respect to ISI. Episode A was comprised of a Fixed 1000-ms ISI condition; B consisted of a Fixed 1400-ms ISI condition; and C involved two conditions consisting of Mixed (randomly presented) 1000- and 1400-ms ISI conditions. The order in which the three episodes were presented to each subject was systematically varied across blocks of six subjects in the following manner: ABC, ACB, BAC, BCA, CAB, and CBA. This sequence was repeated four times.

The subjects were seated at a table in a sound-attentuated and electronically shielded room. At the onset of each trial, a foveally presented arrow cue directed the subject to attend to a specified location in the visual field to which it pointed. After either 1000 or 1400 ms following arrow onset, depending on the ISI condition, a 5-mm square target stimulus (TS) appeared randomly in the right or left visual field at an angular distance of 8 degrees. When a TS appeared in the cued visual field (relevant target condition), the subject was required to respond as quickly as possible by lifting his/her index fingers of each hand simultaneously from a response key, and the reacton time was registered by the computer. On each trial the subject received feedback as to whether he/she responded correctly.

In preparing for ERP recording, an electrode placement cap was placed firmly on the subject's head. Electrode gel was then inserted into each electrode cup by means of a syringe, and the resistance was reduced to 10,000 ohms or less.

Recordings were obtained from conventional electrode positions O1, O2, P3, P4, C3, C4, F3, and F4. All were referenced to yoked earlobes. An electrode placed near the lower-left corner of the left eye detected eye movements and blinks. Those exceeding the voltage acceptance criterion were automatically rejected by the computer, and were not included in the averaged ERPs.

Electrical activity was amplified with Grass AC amplifiers with high and low half-amplitude frequency filter settings of 100 and 0.1 Hz respectively. The amplified signals were digitized, recorded, and averaged with a computer. Each averaged ERP was based on a minimumum of 24 presentations of the arrow cue for each experimental condition. Left hemisphere averages to right arrow cues and right hemisphere averages to left arrow cues were combined to form the data base for the contralateral arrow condition. The two hemisphere averages for the ipsilateral arrow cue were likewise combined to form the data base for the ipsilateral condition.

A "resting" baseline voltage consisting of the average voltage manifested during the first 60 ms after presentation of the arrow cue was used as the reference voltage against which to quantify ERP components.

All statistical analyses were performed with the 1990 version of the BMDP Repeated Measures ANOVA model (BMDP 2V). This program automatically applied Greenhouse-Geisser and Huynh-Feldt corrections to all F-values involving more than two factors (i.e., more than one degree of freedom).

As was to be expected, a substantial number of significant effects involving higher order interactions among the factors manipulated in the two studies were significant. Although some of these higher order interactions probably reflected the complexities of brain function, the significant findings emphasized in the Results Section were limited to issues most closely related to the objectives, hypotheses, and apriori predictions stated in the Introduction.

## Major Findings and Conclusions

### P1N1

The amplitude of the P1N1 component, which peaked at about 180-200 ms, was found to be greater over a given hemisphere of the occipital cortical region when the arrow pointed to the contralateral visual field. This was the earliest indication of differential processing related to the directional information contained in a foveally-presented arrow cue, and is considered a confirmation of the earlier conclusion drawn by Harter, et al. (1988) that the engagement of the attentional system is initiated about 200 ms after the attention directing stimulus is presented.

CN-375 and "EDAN"

During the occurrence of a positive ERP deflection (P300) extending over a latency interval of 250-500 ms, the polarity of the wave during this interval was relatively more negative over the hemisphere located contralaterally to the visual field to which the arrow cue pointed. The average amplitude of this contralateral negativity (CN-375) was found to be statistically significant, and consititues a replication of the "EDAN" effect ("early directing attention negativity") observed by Harter and associates in both children and adults (Harter, et al., 1988; Harter & Anllo-Vento, 1991; Keyes, 1991).

The amplitude of CN-375 varied inversely with ISI length, thus confirming one of the predictions. Even though knowledge of ISI length influenced the intensity of the contralateral negativity occurring in the 250-500 ms latency range, the onset latency and duration of the negativity was not affected by ISI length. This suggests that the initial engagement of the attentional system by an arrow cue is a reflex-like response, the magnitude of which can be modulated by knowledge of preparation time whereas the timing of the response to the arrow cue is insensitive to the amount of preparation time. Since the latency of both CN-375 and P300 remained invariant as a function of ISI length it was not possible to assess the degree of independence, if any, between these two measures. Thus, the possibility cannot be ruled out that they both reflect the same or closely related parallel processes which were set into motion by the directional information contained in the arrow cue.

The contralateral negativity was observed at all cortical regions, and in agreement with earlier results, it was largest over central cortex and smallest at occipital cortex with intermediate levels at parietal and frontal regions. The amplitude profile suggests further that the equivalent dipole source or sources responsible for the scalp-recorded contralateral negativity involved the activation of (1) a single dipole source comprised of a large cortical sheet of tissue extending across occipital, parietal, central, and frontal regions, (2) at least two dipole sources located considerable distances apart along the longitudinal axis of the brain, or (3) a deep source involving one or more subcortical structures. Without supplementary data based on other recording procedures such as microelectrode recordings in animal models and PET and MRI recordings in humans, none of these possibilities can be ruled out. The shift in peak amplitude of CN-375 from 300 ms at occipital cortex to 400 ms at frontal cortex suggests that at least two dipole sources were involved.

A significant interaction was found between arrow direction, region and hemispheres, reflecting the fact that CN-375 was relatively greater over the left hemisphere than over the right at posterior cortical regions, whereas it was relatively greater over the right hemisphere at anterior regions. Since the "resting" level voltage was used as the reference voltage for measuring CN-375, there is a possibility the interaction was produced in part by ERP changes occurring prior to the onset of CN-375. Had the reference voltage for measuring CN-375 been chosen at a latency interval closer to its onset (e.g., between 200-250 ms) the three-way interaction may have been less pronounced and possibly nonexistent. The attention-related hemispheric differences observed in this study could not be compared to those observed by Harter et al., since these investigators subtracted the right arrow condition from the left arrow condition for both hemispheres, thereby inverting the polarity of the contralateral negativity for the left hemisphere. Should the three-way interaction be shown to be replicatable, it has important implications for the differential involvement of the two hemispheres in shifting and focusing attention. As things now stand, the question of whether the attention-related process manifested by CN-375 varies across hemispheres at one or more cortical regions remains to be conclusively demonstrated.

### NSW

While the onset latency of the NSW was time-locked to the arrow cue, under conditions of certainty of ISI length, both the rate of amplitude growth and the latency at which the NSW wave peaked were tied to the length of the ISI. This finding, which contrasts sharply with the reflex-like response obtained for CN-375, suggests the rate of amplitude growth and peak latency of the NSW was under voluntary control and that it was a manifestation of cortical activation associated with increased behavioral arousal and alertness generated by the subject in preparation to respond to the target stimulus at the expected time of presentation. This finding and conclusion provides support for the apriori hypothesis stated in the introduction and also for the position that the "CNV" reflects variations in alertness, among other things.

Under conditions of uncertainty as to ISI length, the amplitude of the NSW for the uncertain 1000-ms condition was essentially the same as that for the certain 1000-ms condition. For the 1400-ms ISI condition NSW amplitude was greater for the uncertain than for the certain condition up to 1000-ms. For the remaining 400 ms the two waves converged, resulting in approximately equal (insignificantly different) amplitudes at 1400 ms. On 1400-ms ISI trials performed under conditions of uncertainty, there was no clear indication of an implicit P300 response evoked by the non-occurrence of a target stimulus at 1000 ms. These findings were in accordance with the hypothesis that subjects adopt a preparatory strategy which enables them to perform satisfactorily under the conditions imposed by the task situation, and that they voluntarily adjust their level of alertness in accordance with the task requirements. It is concluded that NSW amplitude reflects the degree of cortical activation associated with this preparatory process.

As was the case in Keyes thesis study, no clear evidence for the existence of a wave of contralateral negativity ("EDAN" or CN-375) being followed by a wave of contralateral positivity ("LDAP"), as Harter et al. observed in children's data, was found in the current study. NSW-600, which was derived from the middle one-third of the latency interval from which "LDAP" was derived, did not differ significantly as a function of arrow direction at any cortical region. Since no "LDAP" effect was observed in adults, the apriori hypothesis that "LDAP" modulates the same neural processes responsible for the generation of the NSW could not be tested.

Considering the inability to show the existence of an "LDAP" in adults in two different studies, in conjunction with the fact that the paradigm used in both the children and adult studies demanded the differential focusing of spatial attention in order to meet performance requirements, it seems unlikly that the "LDAP" observed in the children's ERPs was indicative of "cortical priming" related to focusing attention, as originally proposed by Harter and associates. (Harter, et al., 1989 Harter & Anllo-Vento, 1991).

Although there were no significant effects of arrow direction on NSW-600 (or "LDAP"), there was a significant effect 400 ms later. That is, for the 1000-ms ISI condition, NSW-1000 was larger for the contra- than for the ipsilateral arrow condition at all cortical regions except the occipital. No significant differences were manifested in NSW-1000 for the 1400-ms ISI condition. Although NSW-1400 also was larger for the contra- than for the ipsilateral arrow cue, no significant arrow direction effect was obtained. These findings, as a group, were interpreted as providing another piece of evidence, although tentative, in support of the view held by a substantial number of ERP researchers that the "CNV" reflects a selective attention process, among other things (McCallum, 1988; McCallum & Walter, 1968; Ruchkin, et al., 1986; Tecce & Scheff, 1969; Tecce & Hamilton, 1973).

## Reaction Time

Even though a marginally significant difference in reaction time was obtained between the 1000- and 1400-ms ISI conditions, RT being slightly shorter for the 1400-ms ISI (3.6 ms or 1.5%), the difference was so slight that its replicability is open to question. Furthermore, the nearly identical reaction times for the two ISIs paralleled the nearly identical NSW amplitudes obtained at 1000 ms for the 1000-ISI condition and at 1400 ms for the 1400-ms ISI condition under conditions of certainty. Thus, both the behavioral and physiological observations are consistent with the conclusion that the subjects were about equally well prepared to respond to target stimuli under both ISI conditions.

RTs were shorter under the certain (236.0 ms) than under the uncertain condition, the opposite being the case for the 1400-ms ISI condition. This interaction was inconsistent with the findings obtained for ERP measures NSW-1000 and NSW-1400 as well as with <u>apriori</u> predictions. No rational explanation can be offered for the unexpected interaction other than to suggest that it may have been a chance phenomenon.

The mean reaction time obtained for the 600-ms ISI in Keyes' thesis study was longer than that obtained for either the 1000- or 1400-ms ISI in the current study. These differences, which were highly significant, were in apparent contradiction to larger NSW-amplitudes having been obtained for the 600-ms ISI than for either the 1000- or 1400-ms ISI lengths. It was concluded that the apparent contradiction was a consequence of the longer time interval allowed for obtaining a "hit" in the thesis study (400 vs 300 ms). It was suggested that the electrophysiological events occurring within the interstimulus interval may largely reflect preparatory processes required for quick detection and perceptual pocessing of the spatial location information associated with the target stimulus, whereas RTs reflect the degree of motor preparedness required to perform within the time period allowed for making a satisfactory response (a "hit") to the target stimulus.

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# APPENDIX

## LIST OF FIGURES

Figure 1. Grand averaged ERPs and DERPs for children and adults indicating effects of arrow direction relative to the recording hemisphere (contra- vs ipsilateral) on ERP components occurring at varying latencies during the course of the arrow - target interstimulus (ISI) interval.

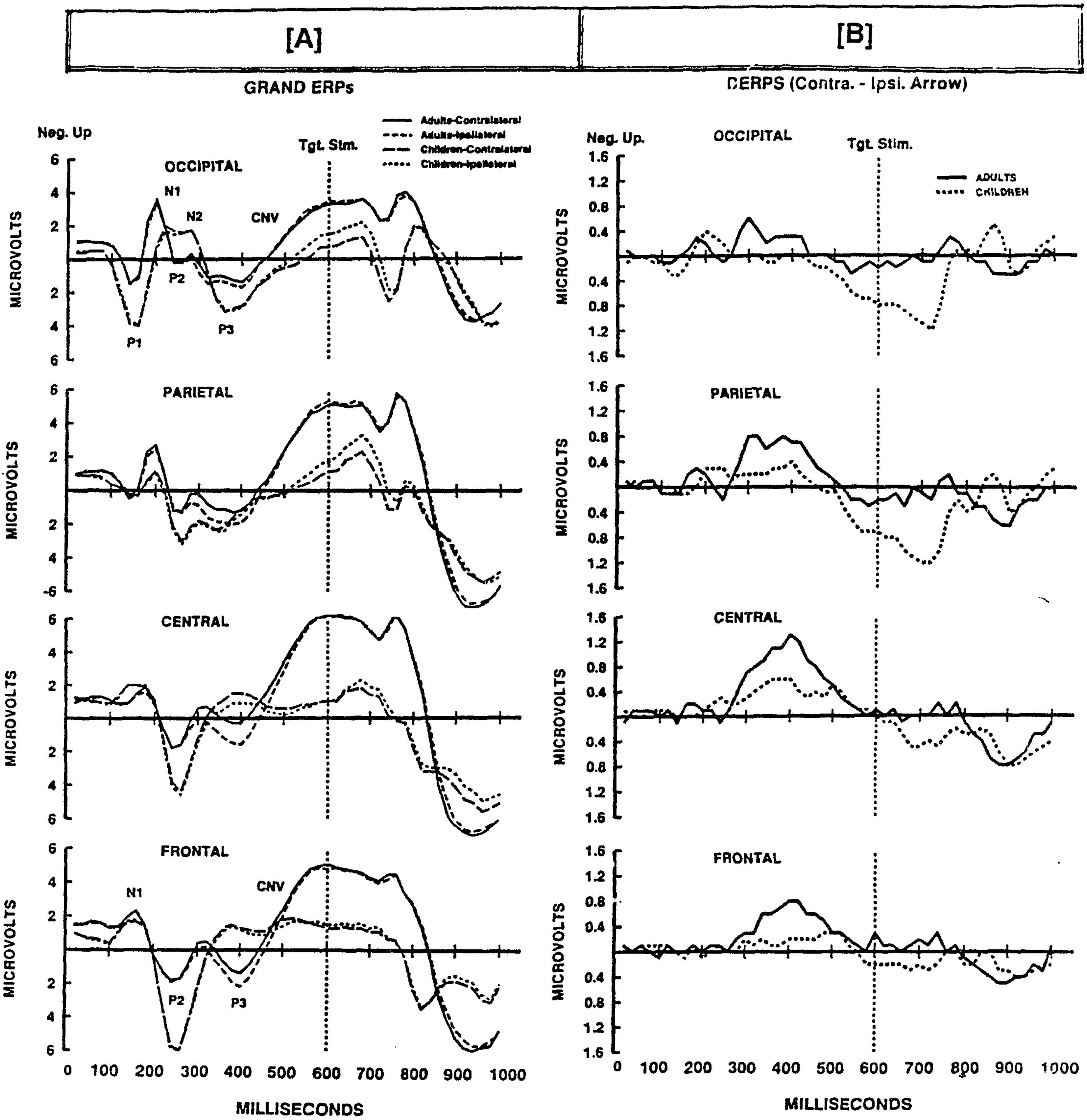

[A]
GRAND ERPs
Neg. Up
Tgt. Stm.
Adults-Contralateral
Adults-Ipsilateral
Children-Contralateral
Children-Ipsilateral
OCCIPITAL
N1
N2
CNV
P1
P2
P3
PARIETAL
CENTRAL
FRONTAL
MICROVOLTS
6
4
2
2
4
6
0
100
200
300
400
500
600
700
800
900
1000
MILLISECONDS
[B]
CERPS (Contra. - Ipsi. Arrow)
Neg. Up.
Tgt. Stim.
ADULTS
CHILDREN
1.6
1.2
0.8
0.4
0.4
0.8
1.2
1.6

Figure 2. Grand ERPs obtained to the onset of the arrow cue plotted as a function of arrow direction (contra- vs ipsilateral arrow relative to recording hemisphere). The ERP data have been collapsed across all other experimental conditions.

# GRAND ERPs AS A FUNCTION OF CONTRALATERAL VS IPSILATERAL ARROW DIRECTION

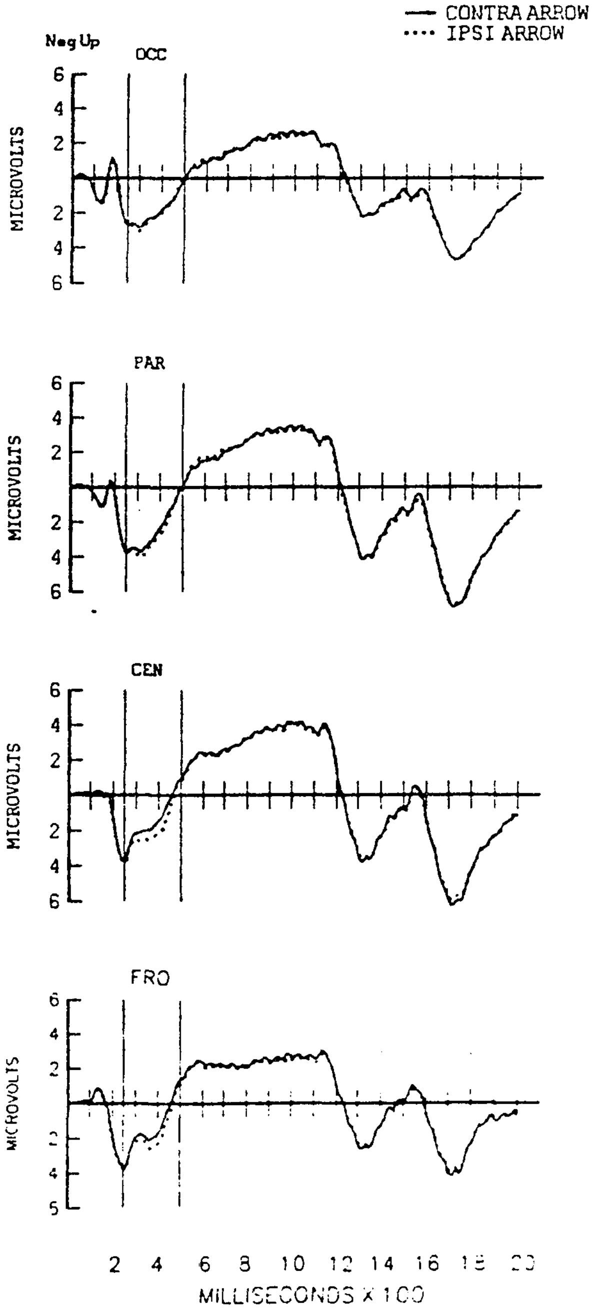


Figure 3. Effect of contra- vs ipsilateral arrow direction relative to recording hemisphere on the average amplitude of the ERP in the 250-500 ms latency range. The data have been collapsed across all other experimental conditions.

AV. AMP. OF P250–500 AS A FUNCTION OF CONTRA– VS IPSILATERAL ARROW DIRECTION

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

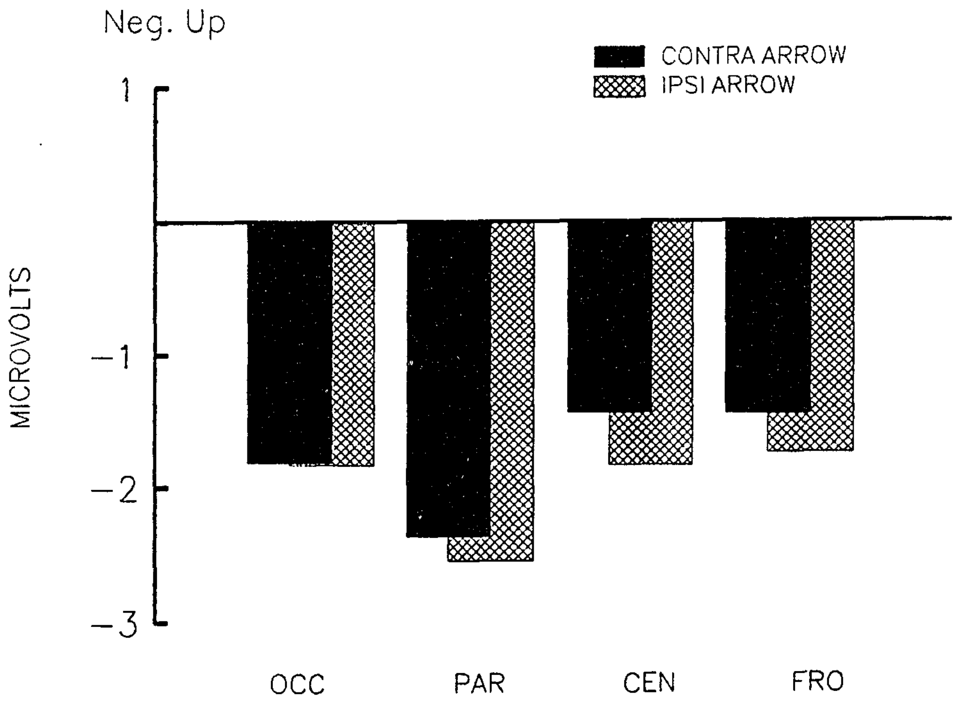


Figure 4. Effect of contra- vs ipsilateral arrow direction relative to recording hemisphere as manifested in the difference potentials (DERPs) between the two arrow direction conditions. The data have been collapsed across all other variables.

## GRAND DERPS (CONTRA MINUS IPSI ARROW DIR).
## (COLLAPSED ACROSS ALL VARIABLES)

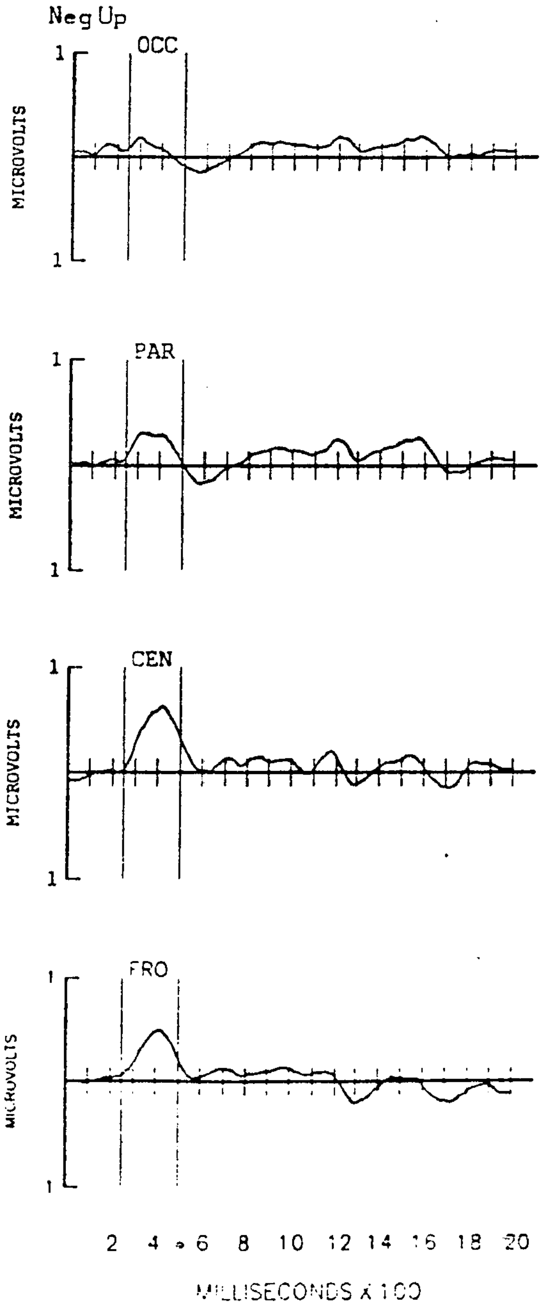


Figure 5. Effect of contra- vs ipsilateral arrow direction relative to the recording hemisphere on CN-375 (average amplitude of the DERPs in the 250-500 ms latency range). The data have been collapsed across all other experimental conditions.

DERPS (CONTRA VS IPSI) BY REGION

(COLLAPSED ACROSS ALL OTHER VARIABLES)

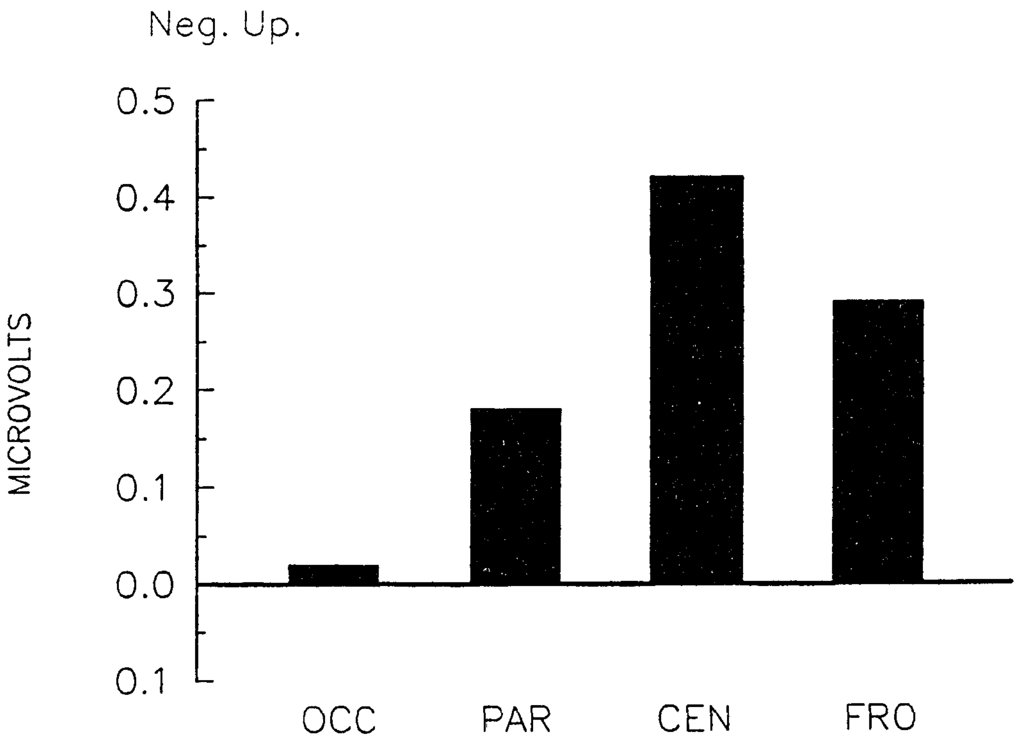


Figure 6. Grand ERPs obtained to the onset of the arrow cue plotted as a function of arrow direction (contra- vs ipsilateral arrow relative to recording hemisphere) and hemispheres. The ERP data have been collapsed across all other experimental conditions.

# GRAND ERPS AS A FUNCTION OF ARROW DIRECTION (CONTRA. VS IPSI.) AND HEMISPHERES.

(COLLAPSED ACROSS ALL OTHER CONDITIONS.)

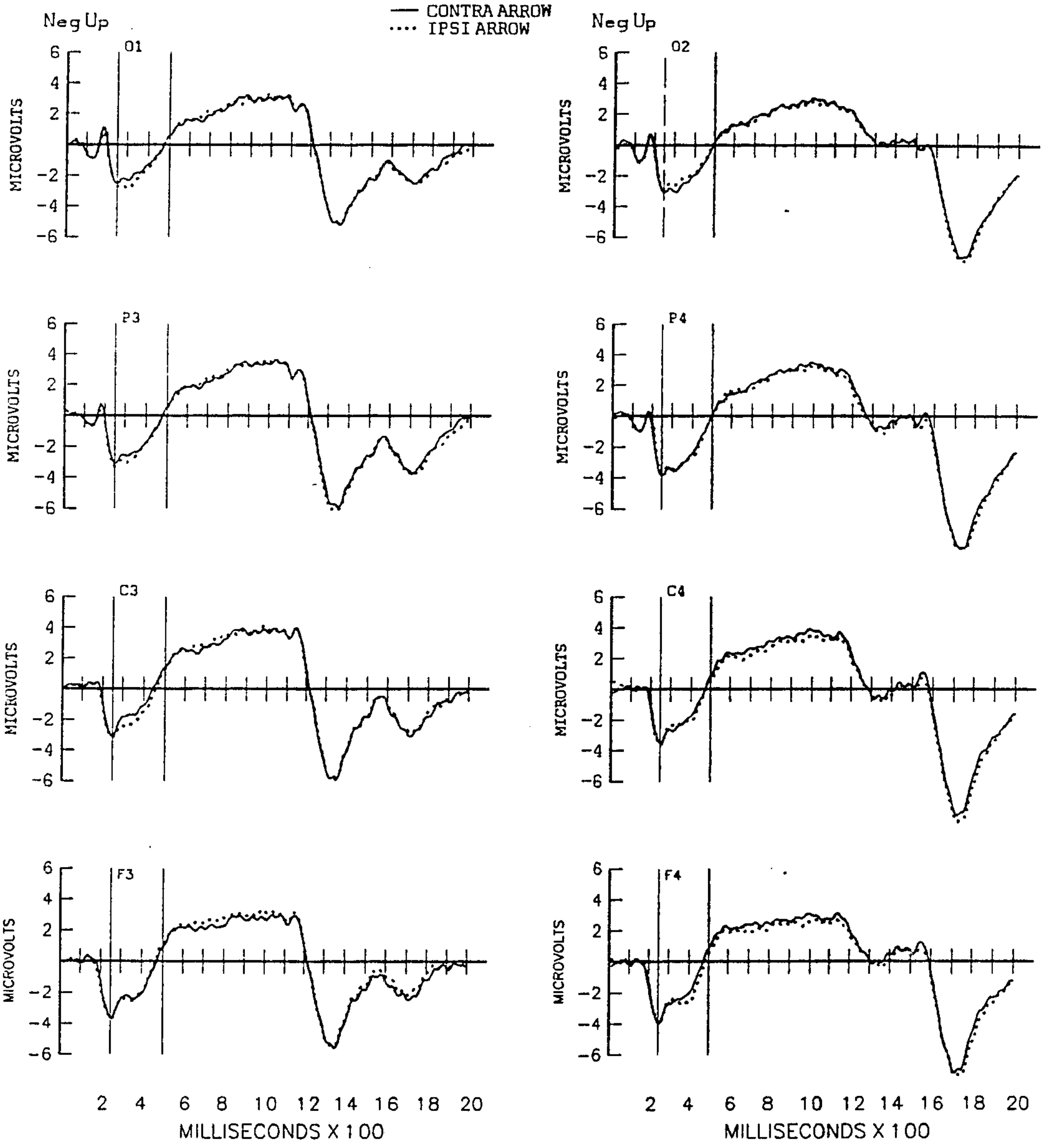


Figure 7. Effect of contra- vs ipsilateral arrow direction and hemisphere from which recordings were obtained on the average amplitude of the ERP falling within the 250-500 ms latency range. Data have been collapsed across all other experimental conditions.

AV. AMP. OF P250–500 AS A FUNCTION OF CONTRA– VS IPSILATERAL ARROW DIRECTION AND HEMISPHERES

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

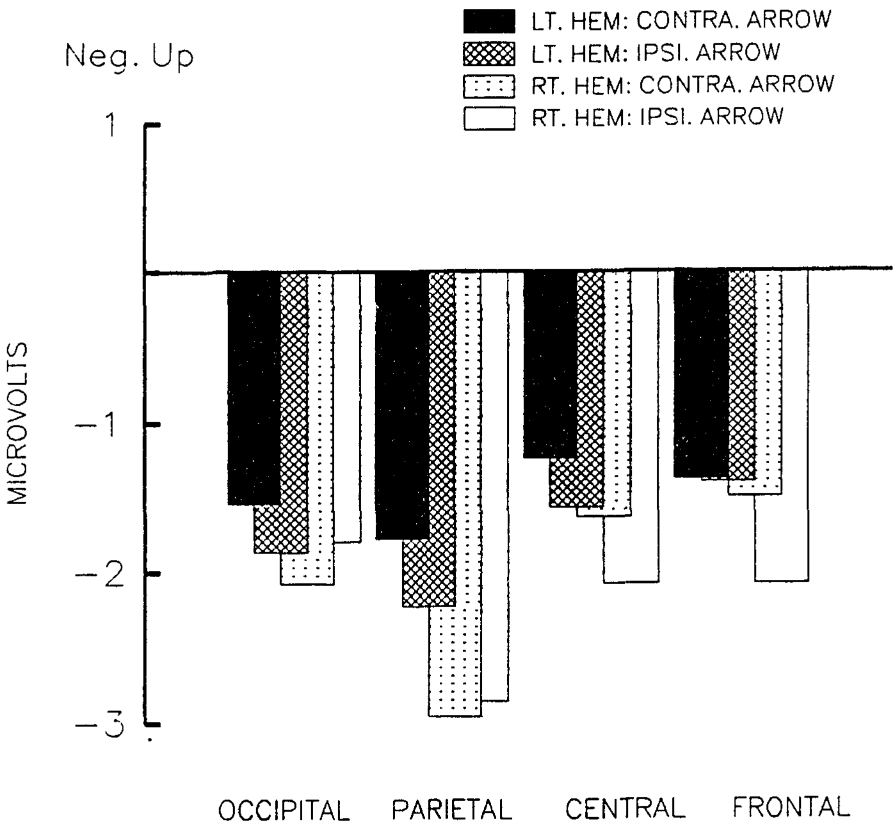


Figure 8. Effect of contra- vs ipsilateral arrow direction and hemisphere from which recordings were obtained as manifested in the difference potentials (DERPs). The data have been collapsed across all other variables.

## GRAND DERPs (CONTRA MINUS IPSI ARROW DIR) PLOTTED BY HEMISPHERES.

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

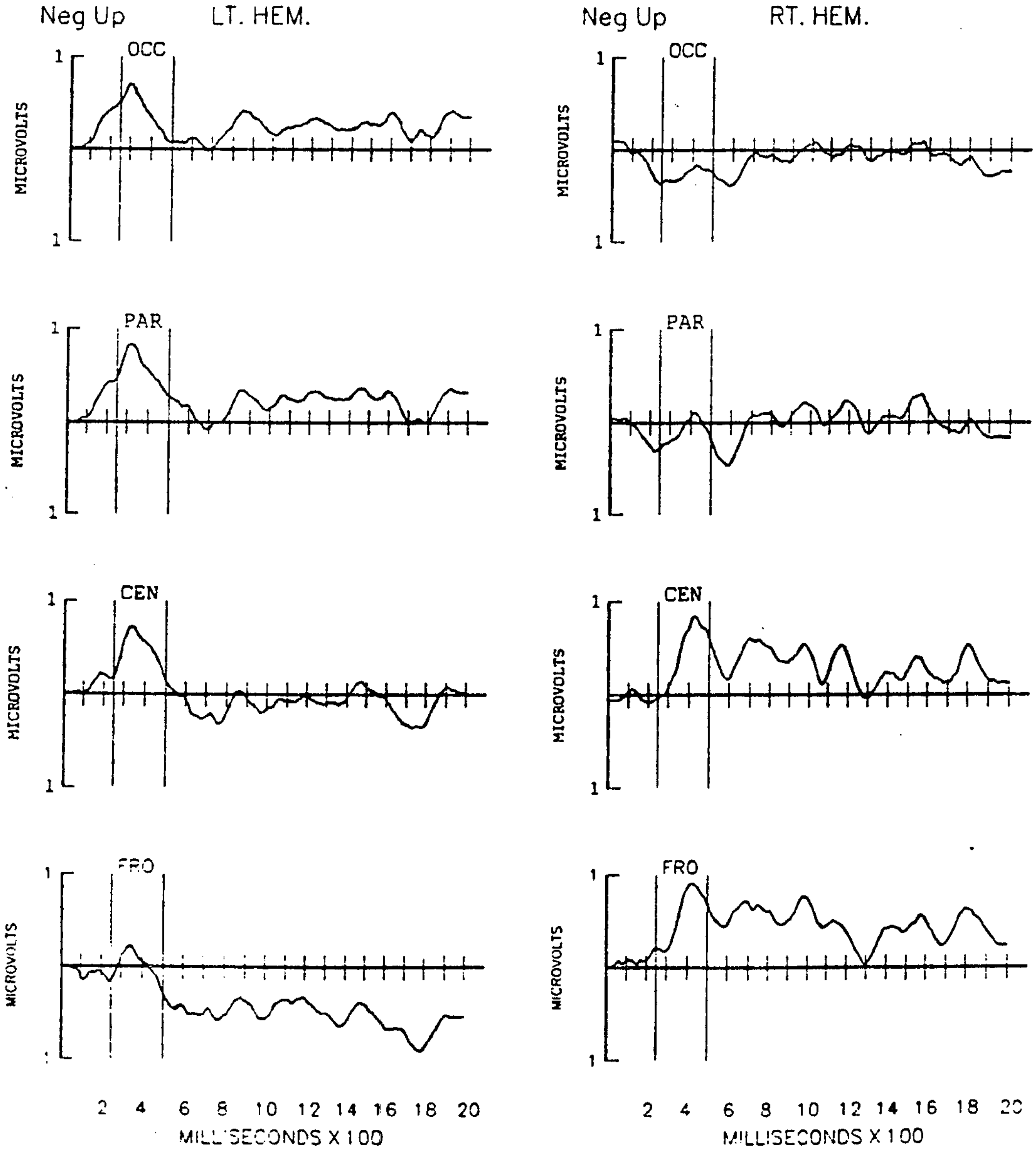


Figure 9. Effects of contra- vs ipsilateral arrow direction and hemisphere from which recordings were obtained on CN-375 (average amplitude of the DERPs in the 250-500 ms latency range). The data have been collapsed across all other variables.

AV. AMP. OF DERPs IN LAT. RANGE OF 250–500 MS
PLOTTED BY HEMISPHERES AND REGION
(COLLAPSED ACROSS ALL OTHER CONDITIONS)

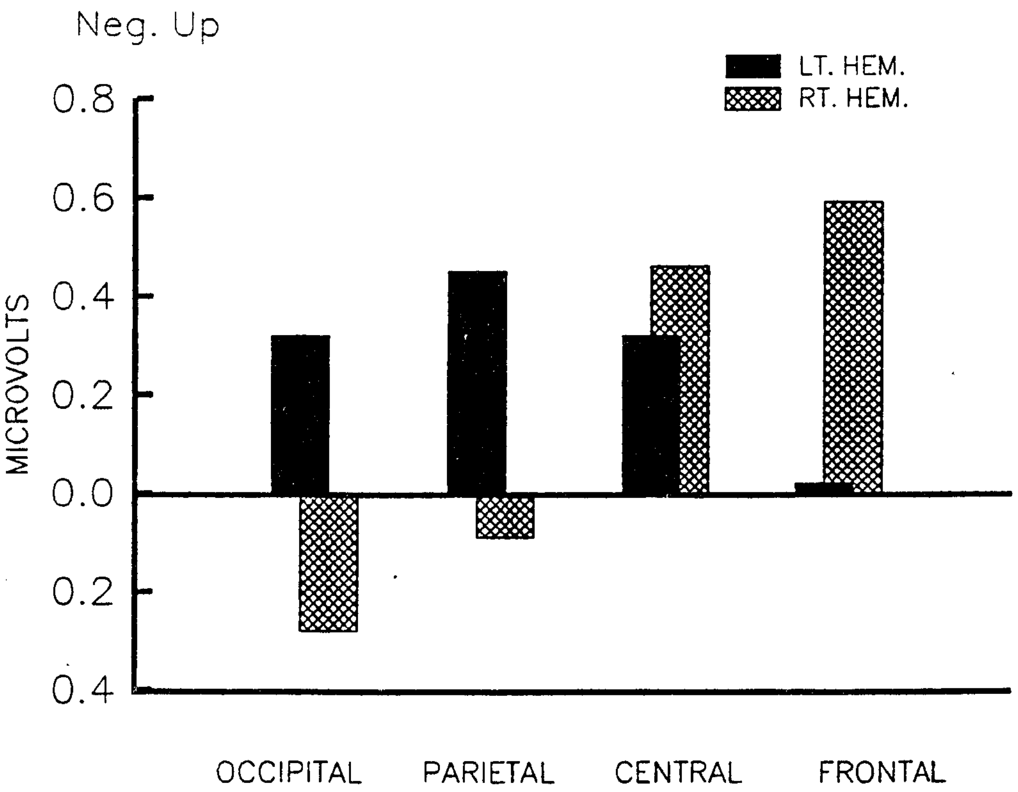


Figure 10. Effect of contra- vs ipsilateral arrow direction as manifested in the DERPs plotted as a function of ISI length. Data have been collapsed across all other variables.

# GRAND DERPS FOR CONTRA VS IPSI ARROW CUES AT FIXED 600–, 1000–, AND 1400–MS ISIs

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

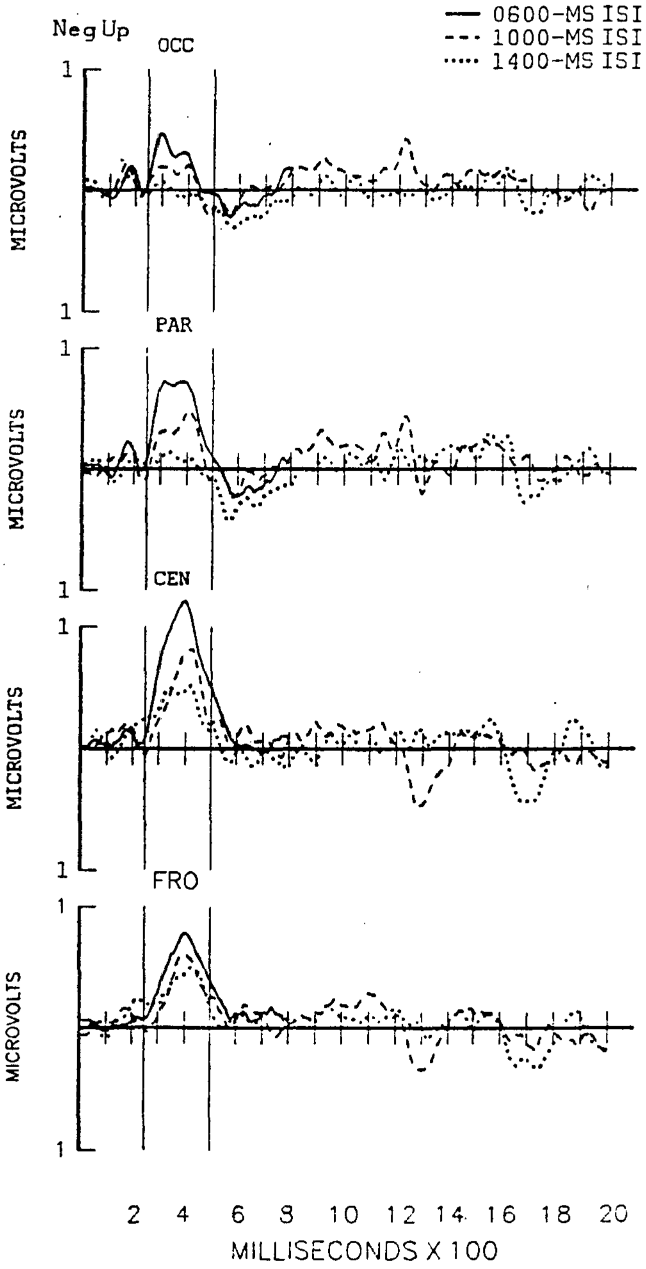


Figure 11. Effect of contra- vs ipsilateral arrow direction on CN-375 (average amplitude of the DERPs in the 250-500 ms latency range) as a function of ISI length. Data have been collapsed across all other variables.

MEAN AMPLITUDE OF DERPs IN 250–500 MS RANGE PLOTTED AS A FUNCTION OF ISI.

(COLLAPSED ACROSS ALL OTHER VARIABLES)

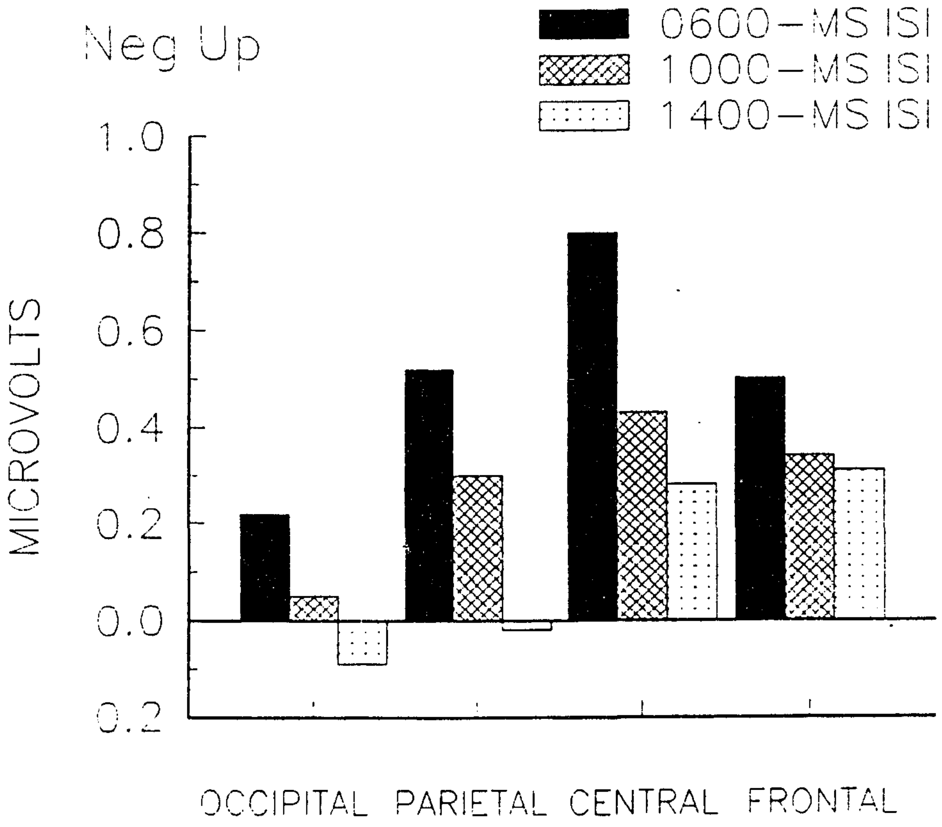


Figure 12. Effect of ISI length and certainty of length on the magnitude of the DERPs in the 250-500 ms latency range. Data have been collapsed across all other variables.

GRAND DERPs (CONTRA MINUS IPSI ARROW DIR) PLOTTED
BY ISIs (1 000 VS 1 400 MS) AND CERTAINTY (FIXED VS MIXED).

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

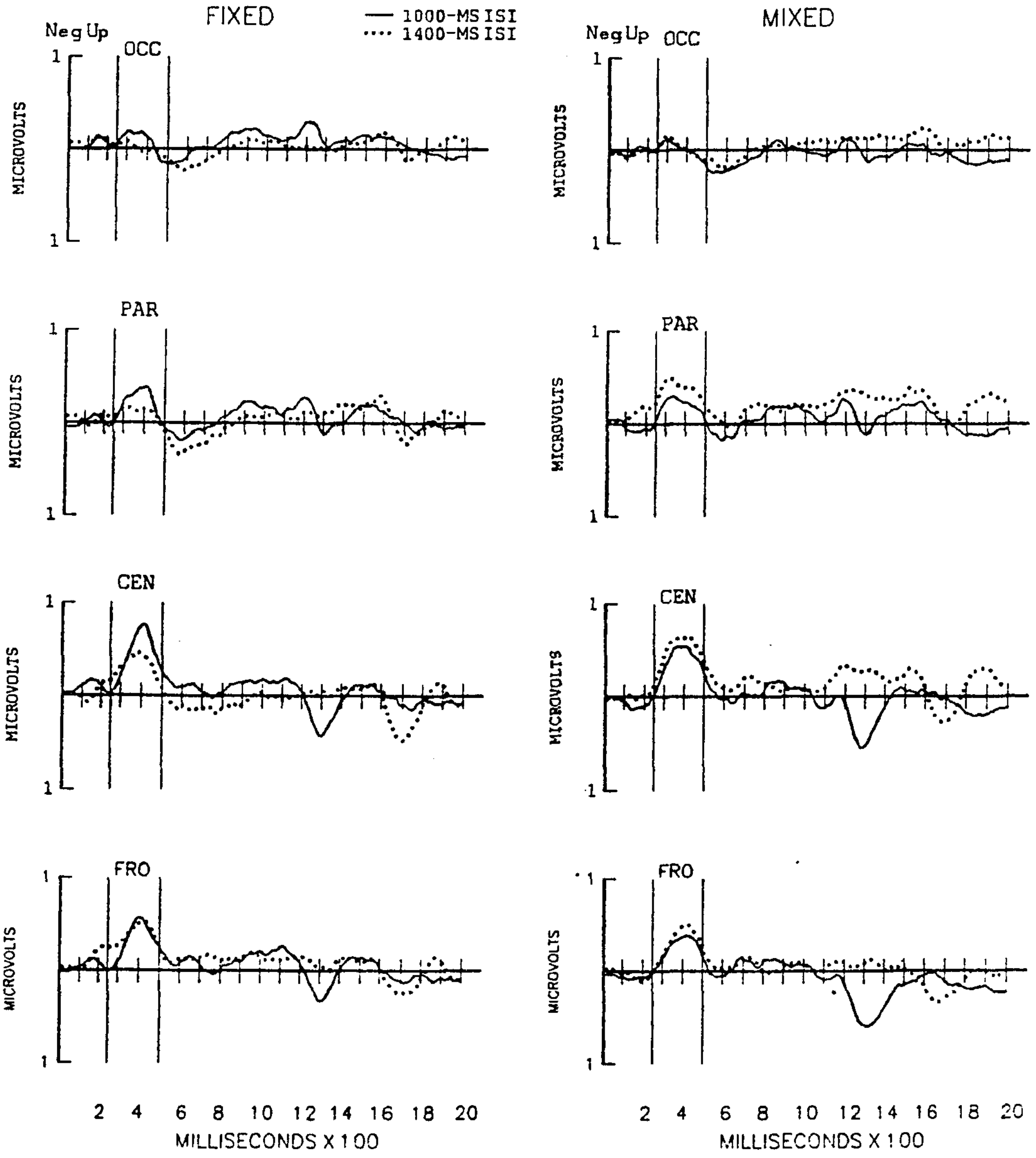
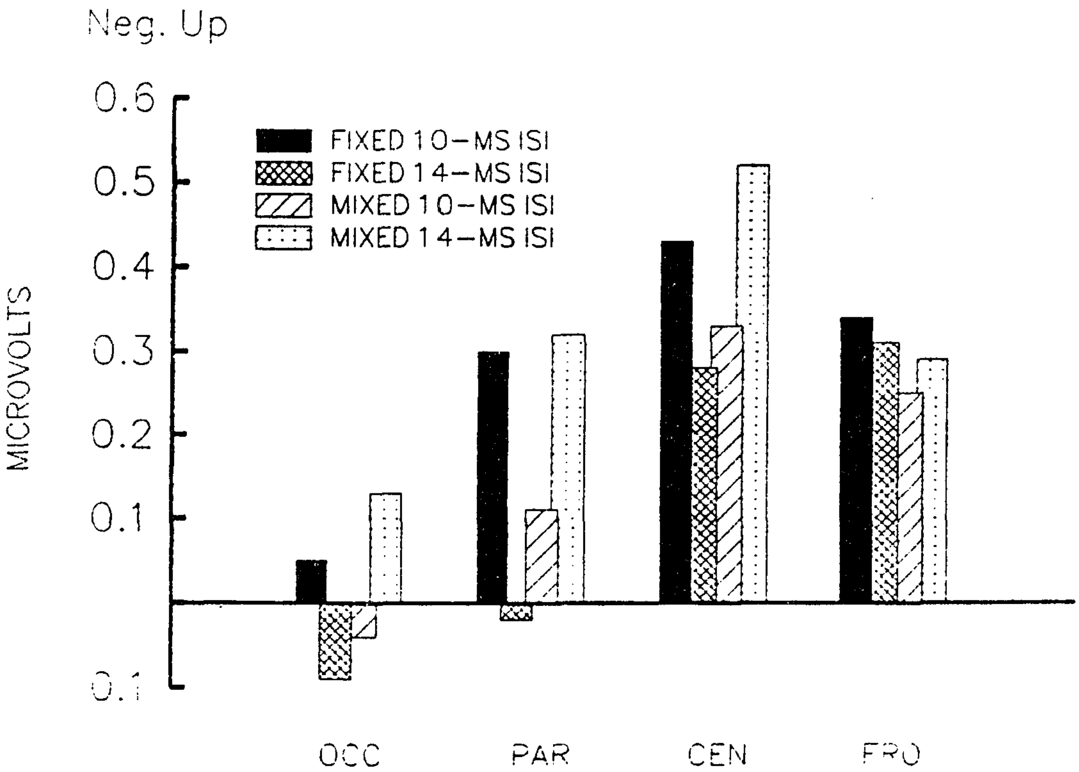


Figure 13. Effect of ISI length and certainty of length on CN-375. Data have been collapsed across all other variables.



DERPs (CONTRA VS IPSI) FOR 250–500 MS MEASURE AS A FUNCTION OF FIXED AND MIXED ISI DURATION.

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

Figure 14. Grand ERPs for Fixed ISI data plotted as a function of ISI length. Vertical lines identify the midpoints of the latency intervals at which the negative slow wave (NSW) was quantified. Data have been collapsed across all other variables.

GRAND ERPS FOR FIXED ISIs OF
600, 1000, AND 1400 MS
(COLLAPSED ACROSS ALL OTHER CONDITIONS)

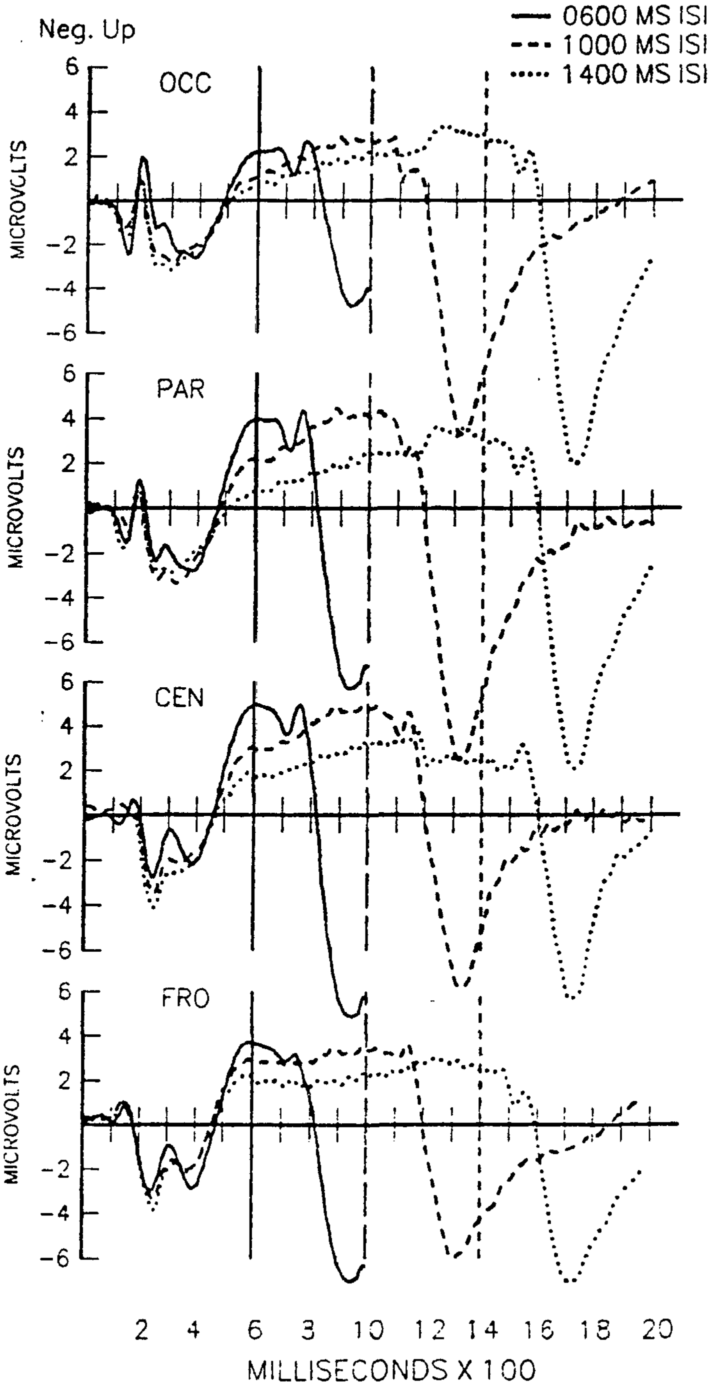


Figure 15. Grand ERPs plotted as a function of ISI length and certainty of length. Data have been collapsed across all other variables.

# EFFECT OF CERTAINTY OF ISI LENGTH ON ERPs FOR 1000– AND 1400–MS ISIs

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

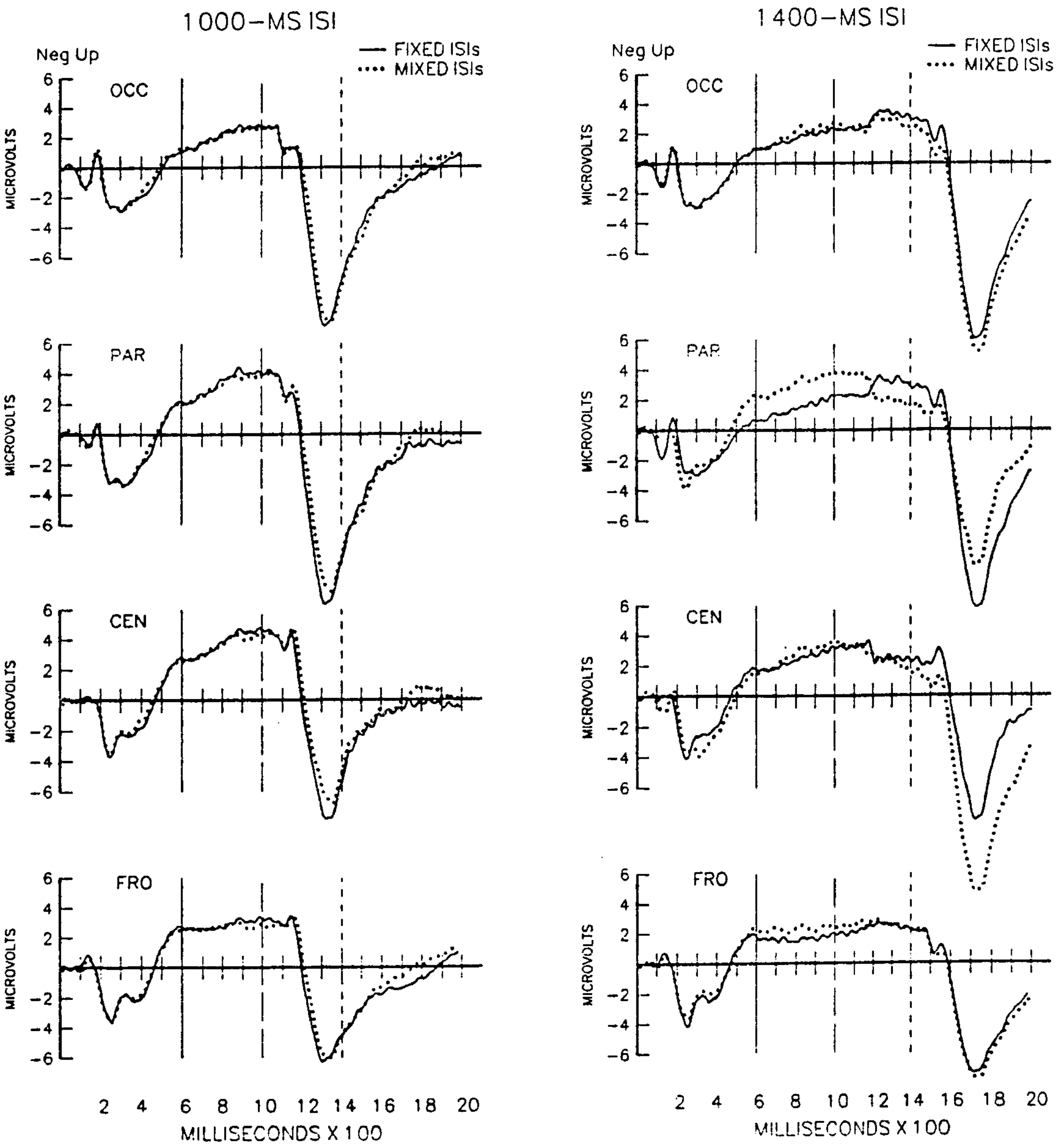


Figure 16. Grand ERPs plotted as a function of ISI length and certainty of length. The ERPs are the same as those in Fig. 15, except they have been rearranged such that the two ISI lengths have been superimposed. Data have been collapsed across all other variables.

# EFFECT OF ISI (1 000 VS 1 400 MS) ON ERPs UNDER FIXED VS MIXED CONDITONS.

(COLLAPSED ACROSS ALL OTHER CONDITIONS)

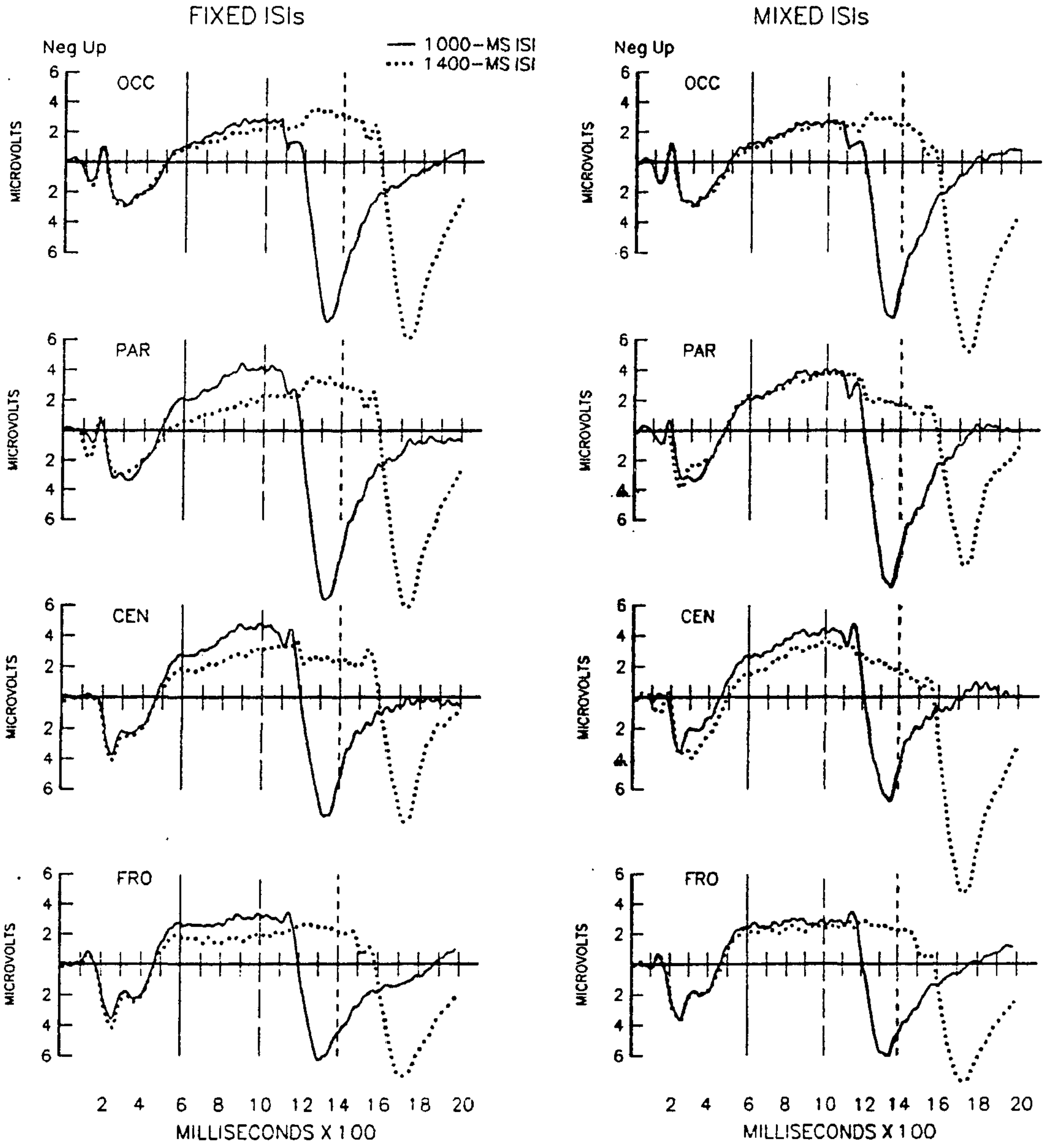


Figure 17. Effect of certainty of ISI length on the NSW-600 and NSW-1000 measures for the 1000-ms ISI. Data have been collapsed across all other variables.

AV. ERP AMP. AT 550–650 AND 950–1 050 MS AS A FUNCTION OF
CERTAINTY (FIXED VS MIXED) FOR THE 1 000–MS ISI CONDITION.
(COLLAPSED ACROSS ALL OTHER VARIABLERS)

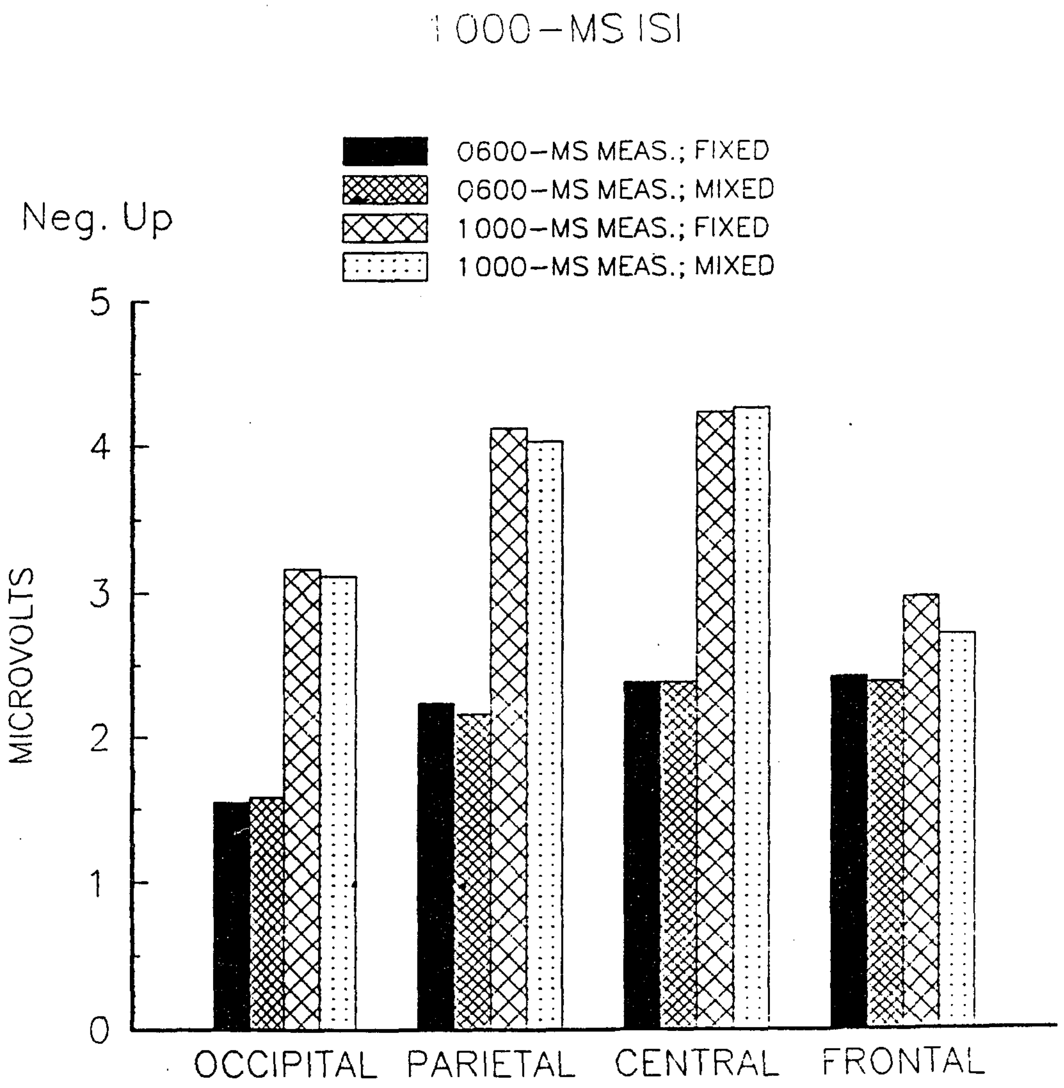


Figure 18. Effect of certainty of ISI length on NSW-600, NSW-1000, and NSW-1400 for the 1400-ms ISI condition. Data have been collapsed across all other variables.

AV. ERP AMP. AT 550 - 650, 950 - 1050 AND 1350 - 1450 MS AS A FUNCTION OF CERTAINTY (FIXED VS MIXED) FOR THE 1400 - MS ISI CONDITION.

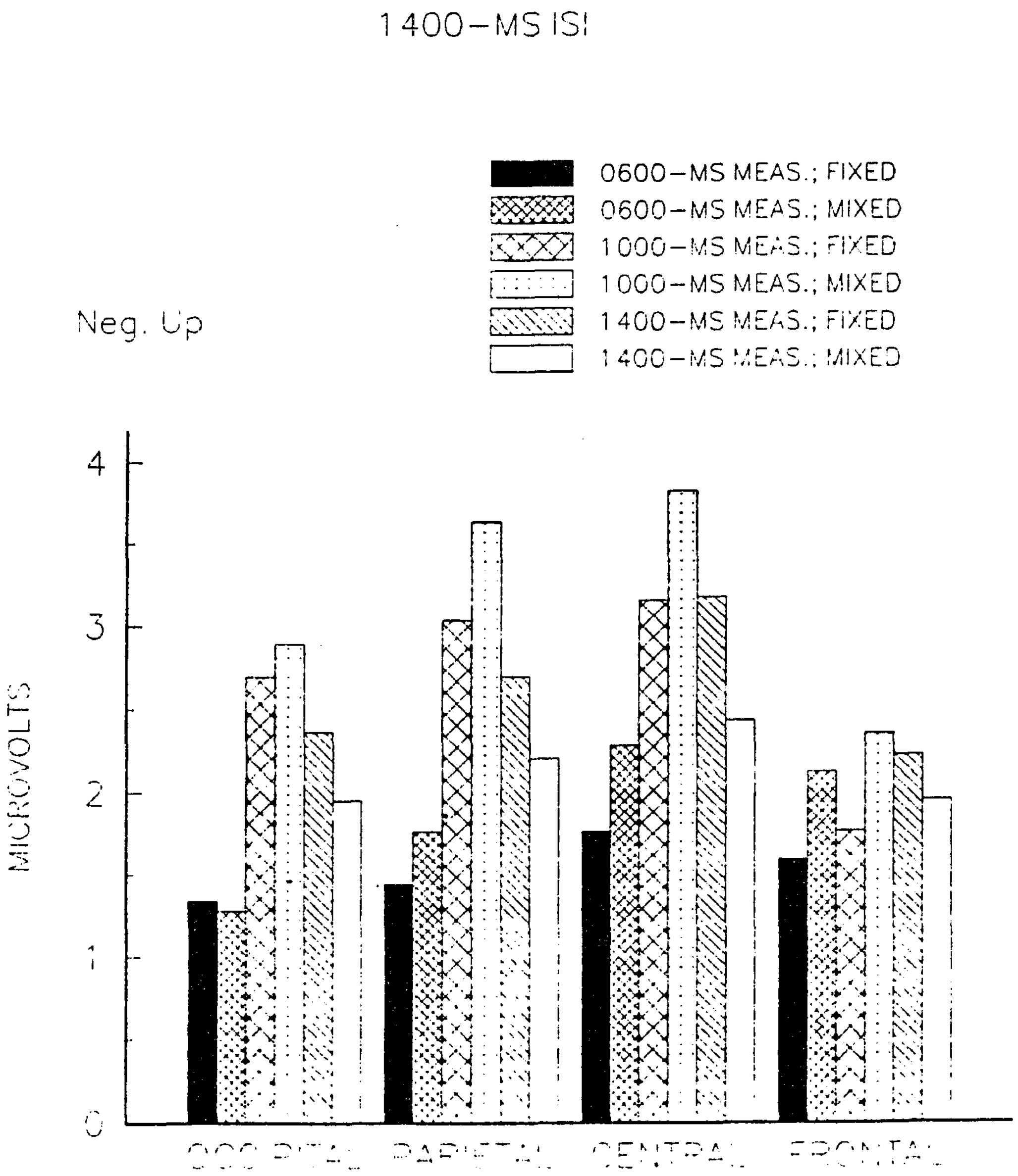


Figure 19. Effect of arrow direction on NSW-600 for each of the three ISI conditions. Data have been collapsed across all other variables.

AV ERP AMP AT 550–650 MS AS A FUNCTION OF
ISI AND ARROW DIRECTION (CONTRA VS IPSI.).

(COLLAPSED ACROSS ALL OTHER VARIABLES)

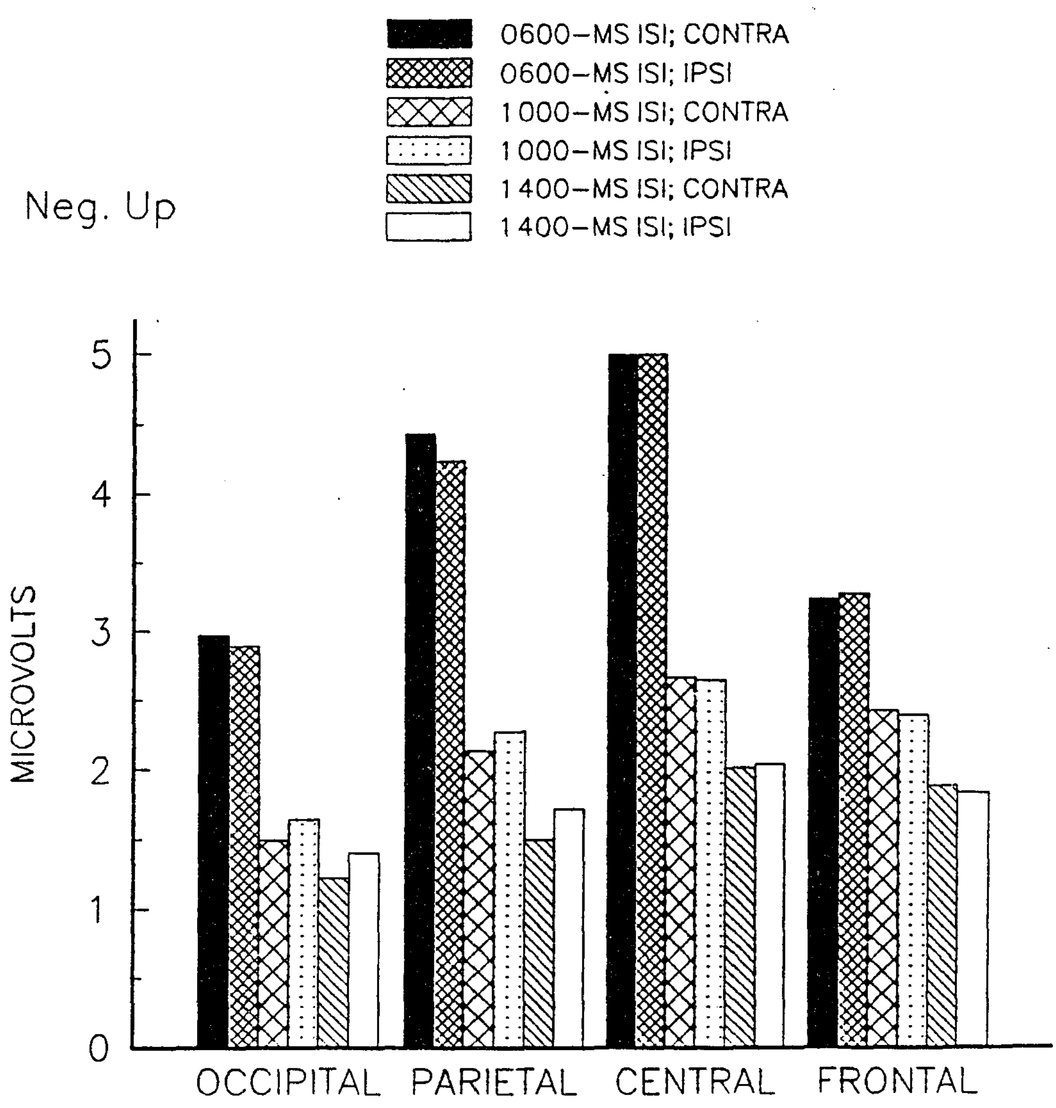


Figure 20. Effect of arrow direction on NSW-1000 for the 1000- and 1400-ms ISI conditions. Data have been collapsed across all other variables.

AV ERP AMP AT 950–1050 MS AS A FUNCTION OF
ISI AND ARROW DIRECTION (CONTRA. VS IPSI.).

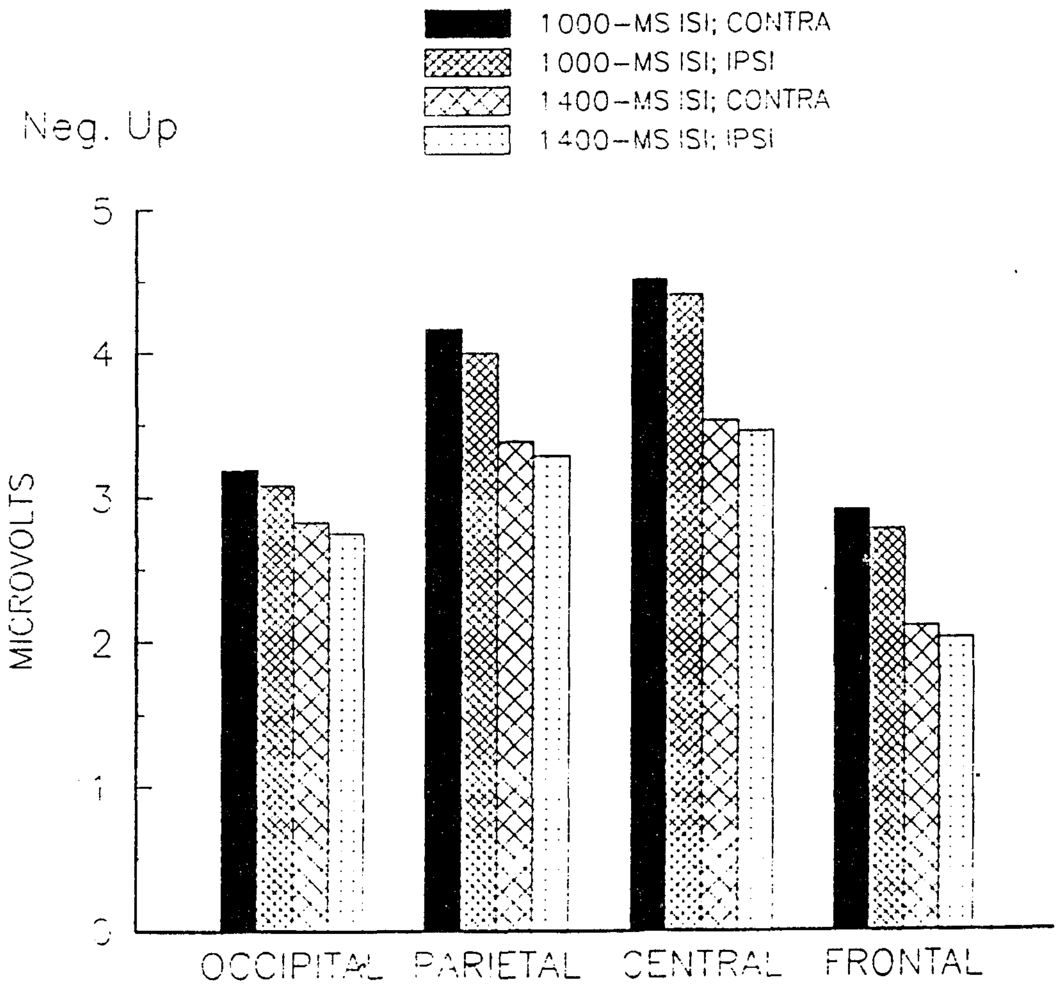


Figure 21. Effect of arrow direction on NSW-1400 for the 1400-ms ISI condition. Data have been collapsed across all other variables.

AV ERP AMP AT 1350–1450 MS LATENCY AS A FUNCTION OF ISI AND ARROW DIRECTION (CONTRA. VS IPSI.).