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THE EFFECTS OF STIMULUS UNCERTAINTY ON THE PUPILLARY DILATION RESPONSE AND THE VERTEX EVOKED POTENTIAL IN MAN

by

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11-16-1971
date

Chairman of Examining Committee

12/1/71
date

Executive Officer

Supervisory Committee

The City University of New York

To my wife, Bert, who never once asked me when I would be finished.

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ABSTRACT

EFFECTS OF STIMULUS UNCERTAINTY ON THE PUPILLARY DILATION RESPONSE AND THE VERTEX EVOKED POTENTIAL IN MAN

Advisor: Dr. Gad Hakerem

Peak pupillary dilation, the late positive component (P_3) of the auditory evoked potential, and slow baseline shifts, were recorded simultaneously and studied as a function of degree of stimulus uncertainty. All responses were averaged using a Computer of Average Transients. Degree of stimulus uncertainty was manipulated by varying the probability of occurrence of two stimuli from 20 to 80 percent probabilities of occurrence

N_1-P_3, an overall measure of evoked potential amplitude, and peak dilation amplitude decreased monotonically as a function of the rareness of event occurrence. This relationship held for N_1-P_3 in both uncertain (S̲ guessed the identity of the upcoming stimulus) and certain (S̲ was told the identity of the upcoming stimulus) conditions, but only in the uncertain condition for peak dilation.

Contingent Negative Variation (CNV) and pupillary slope (pre-stimulus events) did not vary as a function of probability in either condition. Contrary to Karlin's (1970) and Naatanen's (1970) arguments, no relationship between CNV amplitude and evoked potential amplitude was found.

All response measures differed markedly in amplitude between certain and uncertain conditions. N_1-P_3 and peak dilation were larger in the uncertain than in the certain condition. CNV was more negative in the uncertain condition than in the certain condition, and pupillary slope exhibited more dilation in the uncertain than in the certain condition.

Results for probability manipulation were interpreted in terms of Sokolov's (1963) theory of the orienting reflex. Findings for the effects of uncertainty were interpreted as indicative of greater arousal associated with the uncertain condition.

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CHAPTER I

INTRODUCTION

The recent psychophysiological literature is replete with investigations of pupillary motility that were sparked by Hess's (1965) initial findings. A separate body of literature, dealing with the effects of psychological variables on the averaged evoked potential recorded from scalp leads, has also become extensive. Investigations in the latter area have been facilitated by the average response computer, which extracts small, time-locked signals from the high-amplitude, background noise. In conjunction with the electronic, infared pupillograph, the use of the average response computer has been shown by Hakerem and his colleagues (Hakerem, 1967; Hakerem and Sutton, 1966; Levine and Hakerem, 1969) to be a powerful tool in the study of the effects of psychological variables on the pupillary response.

Both evoked potential and pupillary responses are similarly affected by experimental variables, such as "task relevance" (Sheatz and Chapman, 1969; Simpson, 1969), and stimulus uncertainty (Levine and Hakerem, 1969; Sutton, 1968). However, no attempt has been made to record both response processes simultaneously. Stimultaneous recording of averaged peripheral measures and the averaged evoked potential should yield information about temporal and amplitude relationships between central and peripheral responses. The current evidence comes only from separate investigations of averaged evoked potentials and averaged pupillary responses.

Recent experimentation has shown that stimulus uncertainty has remarkably similar effects on a number of physiological systems (Levine and Hakerem, 1969; Higgins, 1971; Lovibond, 1969; Pratt, 1970; Sutton, 1968). Its effects on the auditory evoked potential recorded from vertex were first systematically studied by Sutton and his colleagues (Sutton, Braren, John, and Zubin, 1965; Sutton, Tueting, Zubin, and John, 1967). Their investigations demonstrated that the third positive component (P_3) of the averaged evoked potential, which peaks at about 300 milliseconds, was related to the significance of the stimulus to the subject. P_3 was present and of large amplitude in the evoked potential to stimuli whose occurrence resolved uncertainty but was absent or of minimal amplitude when the subject knew in advance which stimulus was to be presented. Except for its latency, P_3 appeared to be independent of the sensory characteristics of the stimulus.

In a more recent experiment, Tueting, Sutton, and Zubin (1971) were able to quantify the relationship between degree of uncertainty and P_3 amplitude. Degree of uncertainty was varied by manipulating the probability of occurrence of high- and low-pitched clicks. S was told the stimulus probability and asked to guess what the next stimulus in a series would be (uncertain condition). In the control condition, S was told what the next stimulus would be (certain condition). The results showed that the amplitude of the P_3 component was an inverse function of the relative probability of the outcome of S's prediction--the lower the probability, the larger the amplitude of

P_3. P_3 was markedly reduced in amplitude in the certain condition for all probability manipulations.

Levine and Hakerem (1969) modified the experimental design of Sutton and his colleagues (1965; 1967) to investigate the effects of stimulus uncertainty on pupillary diameter. They found that the pupil reacts to uncertainty in the same manner as the P_3 component of the evoked potential. Dilation amplitude was larger in the uncertain condition for all Ss, and was reduced in amplitude or absent in the certain condition. Pratt (1970) demonstrated that pupillary dilation amplitude increased linearly as a function of stimulus uncertainty.

Hakerem and Sutton (1966) compared the effects of instructing Ss to report or not report whether a threshold level light was seen. In the "report" condition averaged pupillary dilation continued beyond the occurrence of the light; in the "no report" condition, the dilation levelled off. In a second experiment, averaged responses for the "seen" trials showed a definite dilation. Averaged curves for the "not seen" trials and for trials in which no discrimination was required produced small dilations not substantially different from "blank" trial averages, in which the stimulus energy was one-tenth that of the threshold stimulus. Similar results, in which dilation was larger when the S was required to make a decision, have been obtained by Simpson and Hale (1969). Presumably, the differences between these curves reflected differences in the degree of vigilance required for the two tasks.

An analysis of P_3 by Ritter and Vaughan (1969) produced results comparable to those of Hakerem and Sutton (1966). In their experiment, the signal stimulus was a tone burst, 5 db lower than the non-signal stimulus. Averaged evoked responses to detected stimuli contained a prominent late positive component (LPC or P_3), while averaged evoked responses to non-detected signals and non-signals had similar waveforms, but contained no late positive component. These authors concluded that the late positive component was a "correlate of central processes for cognitive evaluation of stimulus significance" (p. 328).

Both Paul (personal communication) and Hillyard, Squires, Bauer, and Lindsay (1971) have studied P_3 in a signal detection paradigm and have demonstrated a close correspondence between S's perceptual reports and P_3 amplitude. Paul found detected signals evoked P_3 amplitudes that were considerably larger than non-detected signals. The averaged evoked potential recorded in the Hillyard et al. (1971) experiment contained a large, late pos tive wave (P_3) only when the signal was correctly detected. P_3 was either absent or markedly attenuated in the averaged responses to undetected signals , falsely-reported signals, or correctly-reported non-signals.

Lovibond (1969) has found faster GSR habituation to stimuli of which the S was certain. Higgins (1971) has found faster heart rate acceleration to stimuli with a low probability of occurrence. These findings coupled with those for the pupil (Levine and Hakerem, 1969; Pratt, 1970), would suggest that an increase in sympathetic activity occurs in response to stimuli whose occurrence is uncertain. This evidence, when considered in conjunction with that of Tueting et al. (1971) and those experimental paradigms in which the P_3 component and pupillary dilation reacted similarly, lead one to the conclusion that both are mediated by some common neurophysiological mechanism.

Contingent Negative Variation

Grey Walter and his co-workers (Walter, Cooper, Aldridge, McCallum, and Winter, 1964) were the first to report the development of a slow, negative baseline shift in the averaged EEG occurring between the presentation of two stimuli which had been associated in a classical conditioning paradigm. Walter called this shift the contingent negative variation (CNV), since its development was contingent upon the association of the two stimuli (S_1 and S_2). He has also referred to it as an expectancy or "E-wave", since it does not occur after S_2 is no longer presented, and is reduced in amplitude if the probability of S_2 occurrence is reduced. Both Walter et al. (1964), and McAdam (1969) have shown that when CNV occurs, the cortex is in an increased state of excitability.

CNV has been considered indicative of arousal, due to its appearance under experimental conditions designed to increase S's arousal or activation level (e.g., Connor and Lang, 1969; Low, Coats, Rettig and McSherry, 1967). Recent investigations have shown CNV amplitude sensitive to changes in S's attentional state (Hillyard et al., 1971; Tecce, 1971; Wilkinson and Haines, 1970). Tecce's model considers arousal "a hypothetical process that energizes behavior uselectively...and does not involve the directional, associative functions of attention" (p. 13). In support of this model Chiorini (1969) has also implicated slow, negative potential shifts in diffuse activation of the cortex. Caspers (1963) has studied slow potential changes in animals and has demonstrated a close correspondence between behavioral signs of arousal and negative potential shifts. Although the exact relationship between the CNV and these steady potential shifts is not known, these results are suggestive of a common mediating mechanism.

The amplitude of P_3, pupillary dilation, and CNV have been related to "significance" of the stimulus for S. CNV ends with a positive-going process at about 300 msec. following S_2. This resolution time corresponds to most reports of P_3 latency. Thus, as Donchin and Smith (1970) point out, CNV and P_3 may be two aspects of the same process. For example, in the Levine and Hakerem (1969) study, S had to wait one second in order to determine if he would receive an additional click. This additional click informed him as to the correctness of his pretrial prediction. It has recently been confirmed by Hakerem, (personal communication) that a CNV developed between the first clicks S received and the additional click that he waited for in order to confirm or disconfirm his guess.

Karlin (1970) and Naatanen (1967, 1970) have argued that the frequency response of the amplifier be lowered to enable the experimenter to record slow baseline shifts as well as evoked potential. They cite studies of the effects of selective attention on averaged evoked potentials, in which relevant and irrelevant stimuli have alternated in such a way that S can accurately predict when the relevant stimulus is going to occur (e.g., Naatanen, 1967, 1970; Donchin and Cohen, 1967; Donchin and Smith, 1970). As the usual finding in these studies has been the enhancement of P_3 only to stimuli which are task relevant, Karlin (1970) has argued that S can "gear his readiness to the interval so that on the average his readiness for relevant stimuli will be greater than for irrelevant stimuli"(p. 124). Naatanen (1967, 1970) defines CNV as the "preparatory cortical activation" which accounts for the enhancement of the evoked potential under task relevant conditions, because when relevant and irrelevant stimuli were randomly presented, no evoked potential enhancement occurred. However, when they were alternated at regular intervals, evoked potential enhancement occurred only to the relevant stimuli. CNV also occurred only prior to the regularly alternated relevant stimuli. Donchin and Smith (1970) have also found P_3 enhancement in the presence of CNV which only occurred prior to the relevant stimulus.

This argument has initiated a great deal of controversy (e.g., Donchin and Cohen, 1969; Naatanen, 1969a, 1969b), as well as conflicting results. It has been reported that when differential preparation is precluded, evoked potential enhancement still occurs (Koppel, Wittner, and Warrick, 1969; Eason, Harter, and White, 1969). Donald and Goff (1971) have also been able to dissociate the two within the same experimental context.

Tueting (1968) did not employ a long time-constant EEG recording technique and therefore could not see slow, baseline shifts. In her experiment S received a warning signal followed by a specified time interval, after which the stimulus was delivered. A CNV would have been expected to develop within that interval, but since the stimuli were random by trial and therefore could not have been accurately predicted, CNV could not have accounted for the effect of probability on the evoked potential. Nevertheless, in view of the growing body of experimental data dealing with the CNV and the evoked potential, the importance of the relationship between these two brain processes cannot be overlooked.

The Present Experiment

The purpose of the present experiment is to reveal the relationship between CNV, P_3, and pupillary dilation. They will be studied as a function of degree of stimulus uncertainty, which will be produced, as in the Tueting(1968; Tueting et al., 1971) study, by varying the probability of occurrence of two stimuli. Four probabilities of occurrence for each stimulus will be used: 20, 40, 60 and 80 percent. Each probability will be run under certain and uncertain conditions. It is expected that the evoked potential data will replicate Tueting's (1968) findings--P_3 increases in amplitude as stimulus uncertainty increases.

It has been suggested that CNV is affected by the probability of events (Low, Borda, Frost, and Kellaway, 1966; Walter et al., 1964, 1966, 1968). However, the effect of probability on CNV is not a well-established relationship (see Hillyard and Galambos, 1967). In Walter's paradigm, the occurrence or non-occurrence of S_2 was not predicted by guessing. While in a guessing paradigm (McAdam, Knott, and Rebert, 1969), the results showed increased CNV amplitude for an uncertain event, probabilities were not manipulated. Therefore, no prediction with respect to the relationship between CNV amplitude and probability could be made. The effect on CNV amplitude when the S is guessing in a probability situation (as in the present experiment) will demonstrate the effects of probability manipulation on CNV amplitude, as well as provide data on the relationship between CNV and the evoked potential.

CNV, the tonic process has been considered a measure of arousal or activation (e.g., McAdam, 1969), while the evoked potential (specifically the late components), the phasic process, has been considered necessary for the mediation of short-term attentional shifts (Jenness, personal communication). Tonicity measures of pupillary activity are the pre-stimulus initial diameter (Dureman and Sholander, 1962; Lowenstein and Loewenfeld, 1950) and somewhat analagous to CNV, the pre-stimulus pupillary slope. The phasic component is peak dilation due to psychosensory stimulation.

The phasic processes of both responses have been implicated as components of the orienting reflex (Ritter, Vaughan and Costa, 1968; Sokolov, 1963). Further, mediation of tonic and phasic processes has been relegated to two different central nervous system mechanisms: 1) tonic, ascending reticular activating system 2) phasic, diffuse thalamic activating system (Lindsley, 1960). The present experiment may provide information on the functional significance of the dichotomy of the tonic and phasic processes.

The present experiment seeks answers to the following questions: What is the effect of degree of uncertainty on the covariation of CNV, P_3, and pupillary dilation? Are CNV and pre-stimulus pupillary slope sensitive to the probability of stimulus occurrence? Does the same quantitative relationship found between P_3 amplitude and probability hold for pupillary dilation?

CHAPTER II

METHOD

The equipment and general procedure were designed to obtain and store averaged pupillary responses, averaged evoked potentials, and averaged baseline shifts to experimental contingencies in a guessing situation. Data were monitored on-line as a check on the recording and analysis procedure, and were stored on magnetic tape for later retrieval and averaging.

Subjects

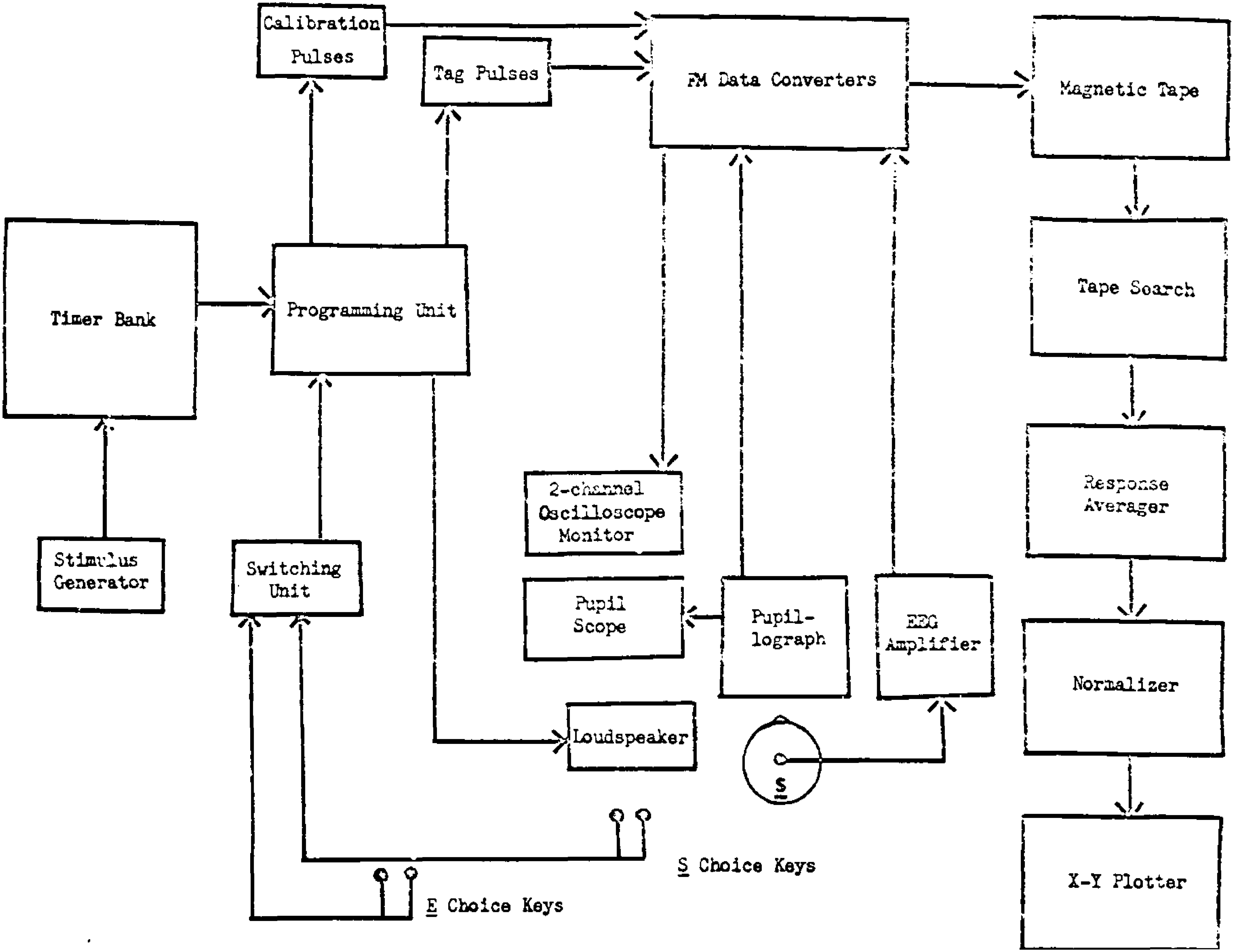
Six males and two identical female twins served as Ss. They were paid at the rate of $2.50 per hour, and were obtained by advertising in college placement offices.

Equipment

Figure 1 is a schematic diagram of the equipment. S was seated comfortably in a completely darkened, sound-damped chamber, which was electrostatically shielded using copper mesh.

Programming. The experimenter (E) sat outside the experimental chamber facing a programming and switching unit of local design, and a Tektronix Type 561 dual-beam oscilloscope, on which both EEG and pupil could be monitored. The programming unit enabled E to inter-connect a series of timers (accuracy ± 1 percent) in order to generate a trial

Figure 1. Simplified block diagram of the equipment used in the experiment.


Calibration Pulses
Tag Pulses
FM Data Converters
Magnetic Tape
Tape Search
Timer Bank
Programming Unit
Response Averager
2-channel Oscilloscope Monitor
Stimulus Generator
Switching Unit
Pupil Scope
Pupil-lograph
EEG Amplifier
Normalizer
Loudspeaker
S
S Choice Keys
E Choice Keys
X-Y Plotter

sequence. The switching unit enabled E to program either of the two stimuli. By pressing one of two choice keys S indicated his guess. These keys were connected into the switching unit, and generated electronic tagging pulses which identified his guess as either correct or incorrect. In this way, a maximum of four trial contingencies could be generated and identified: S was correct or incorrect in his guess of either of the two stimuli.

Stimuli. The stimuli were two double clicks that differed in the length of their inter-click-interval. The clicks, of .5 msec. duration, were obtained by a capacitor discharge, then were amplified (amplifier of local design) and attenuated (Hewlett-Packard attenuator, model number 350D) to approximately 60db above threshold (for one normal S), and delivered through a speaker two and one-half ft. above S's head. Preliminary testing with two pilot Ss, using an ascending and descending method of limits, established a difference of 6 msec. in inter-click-interval as necessary for these Ss to perceive the two double clicks as unequivocally different. Therefore, one inter-click-interval was fixed at 2 msec. ("single" click), and the other at 8 msec. ("double" click). When the two stimuli were randomly presented in a 50/50 probability paradigm in both certain and uncertain conditions, they produced averaged evoked potential waveforms and averaged pupillary dilations which did not differ significantly with respect to amplitude or latency in the two pilot Ss employed.

Extraneous stimuli were masked by constant noise generated by an air-conditioning unit, exhaust fans located in the S's chamber, and the pupillograph drum. Ambient noise, as measured by a Bruel and Kjaer Precision Sound Level Meter (Type 2203) was determined to be 65db SPL on Scale A.

Choice keys. The choice keys were two microswitches (Honeywell model number 7A1HL) placed one inch apart into a strip of plywood, approximately one ft. to the right of S, and at a level which allowed him to be comfortable when resting his right arm. The left key represented the "single" click, and the right key the "double" click. To aid S in remembering his choice, a single bar was placed permanently on the key representing the "single" click, and two bars were placed on the key representing the "double" click. The force necessary to close the switch was approximately one ounce through one centimeter.

Pupillograph operation. The instrument used was the Loewenstein-Lowenfeld electronic pupillograph (Loewenstein and Lowenfeld, 1958), as described by Hakerem (1967). A mechanically-controlled spot of infrared light scans a one and one-half in. wide, and a three-quarter in. high area with a twelve-line, sixty cycle per sec. raster. The image of this raster is projected on to the iris of the right eye. The infrared light scan is either reflected by the iris and sclera, or absorbed by the pupil. The reflected light scan from S's eye is picked up by a lens system and is directed to the sensitive surface of a photomultiplier. When the infrared scan moves across the iris, it is reflected and there is a voltage output from the photomultiplier. When the scan moves into the pupil, the light is absorbed by the eye and the voltage output drops to zero. Since the speed with which the scan moves in the raster is known, the width of the resulting square wave is proportional to the length of the pupil sector it has crossed. The widest square wave, the diameter of the pupil, is detected by the instrument and converted into a proportional DC voltage. A diameter measurement of the pupil is thus obtained 60 times per sec.

Calibration of Averaged Pupillary Amplitude

A calibration pulse equivalent to 8 mm. of pupil, was laid down on tape at the beginning of each trial. This was done in order to obtain a precise, absolute value of pre-stimulus pupil size (i.e., initial diameter), so that the averaged pupillary response could be compared to the calibration pulse. The resolution of this system permits the detectability of pupil diameter changes of the order of 0.01 mm. in an averaged curve of 50 trials (Hakerem, personal communication).

EEG Amplification

One channel of EEG data was amplified by a Cyber amplifier (model number J1). The amplifier passed all signals within a frequency range of .016 to 50 cycles per sec. The amplifier gain was calibrated with a sine wave of known voltage at the input, and adjusted at the output of the amplifier to produce a gain of 10,000. The band pass characteristics of the amplifier meant that slow changes (i.e., baseline shifts) in activity could be examined. The calibration of the amplifier was checked prior to the beginning of running of the experiment, and twice during the seven-month period of data collection.

Calibration of Averaged Evoked Potential Amplitude

A calibration pulse, equivalent to 30 uV of signal, was deposited on tape at the beginning of every trial. The averaged evoked potential was compared to this pulse in order to obtain an absolute measure of response amplitude.

Data Storage, Retrieval, and Averaging

The pupil signal, EEG and calibration pulses passed through the FM data converters (Mnemetron model number LC) where their analog voltages were converted into frequency code and deposited on tape. To check on the proper functioning of the equipment, E was able to monitor the summing by the Computer of Average Transients (Mnemetron model CAT 400A) of both EEG and pupil signals "on line" for a limited number of experimental categories.

During analyses, the data were played back from tape at 15 in. per sec., a speed eight times faster than that at which it was recorded. When retrieving the data from tape, the FM data converters changed the data back to continuously graded voltages. E was able to obtain the particular contingency of interest by programming the tape search system with a set of diodes, thus determining which binary coded tag pulse would initiate a sweep of the memory registers of the average response computer. The sweep speed used was 500 msec. (4 sec. of real time), producing a dwell time of 1.25 msec. per register.

The response averager was necessary, since both pupillary and EEG time-locked signals often occur in "noise" that is larger in voltage than the signal itself. The noise component increases proportionate to the square root of N, while the signal voltage continues to grow proportionate to N. Since the resultant data in CAT were sums, averages were obtained by passing the summed output of each memory register through a passive network, whose resistance could be varied as a function of the number of trials. The resultant averaged response was then plotted on a Mosely X-Y plotter (model number 135M).

Electrode Placement

The EEG was recorded from a vertex lead, C_z according to the ten-twenty system (Jasper, 1958). Other investigators (e.g., Low et al., 1966; Tueting, 1968; Vaughan and Ritter, 1970; Walter et al., 1964) have shown CNV as well as P_3 to be maximal in amplitude at this placement. While there is still some controversy as to whether or not eye movements contribute to CNV genesis (see, for example, Cohen, 1969; Hillyard and Galambos, 1969; Low et al., 1966), eye movements were monitored with one of the output scopes of the pupillograph, and those trials which contained eye movements or blinks were eliminated.

Beckman standard biopotential skin electrodes (model # 330421) were used. These electrodes are non-polarizing and highly resistant to movement artifact. They contain a silver/silver chloride pellet within a plastic casing. The scalp area was cleaned with acetone in order to remove the outer layer of dead epidermis cells. Beckman electrode paste was squeezed into the electrode reservoir in order to facilitate ion flow from the dermis to the silver/silver chloride pellet. The electrode was then secured to the scalp by applying Mallinckrodt collodion around the edges of the electrode with a hypodermic syringe. Drying was facilitated with the use of a hair dryer. Resistances greater than 10,000 ohms were not accepted and the procedure was repeated. The reference electrode on the right earlobe was a miniature model of the Beckman standard electrode (model # 650399). For the earlobe placement, Beckman adhesive collars were used. The neck electrode, which was used to ground the S, was also placed using a Beckman adhesive collar.

Placement of Subject in the Recording Chamber

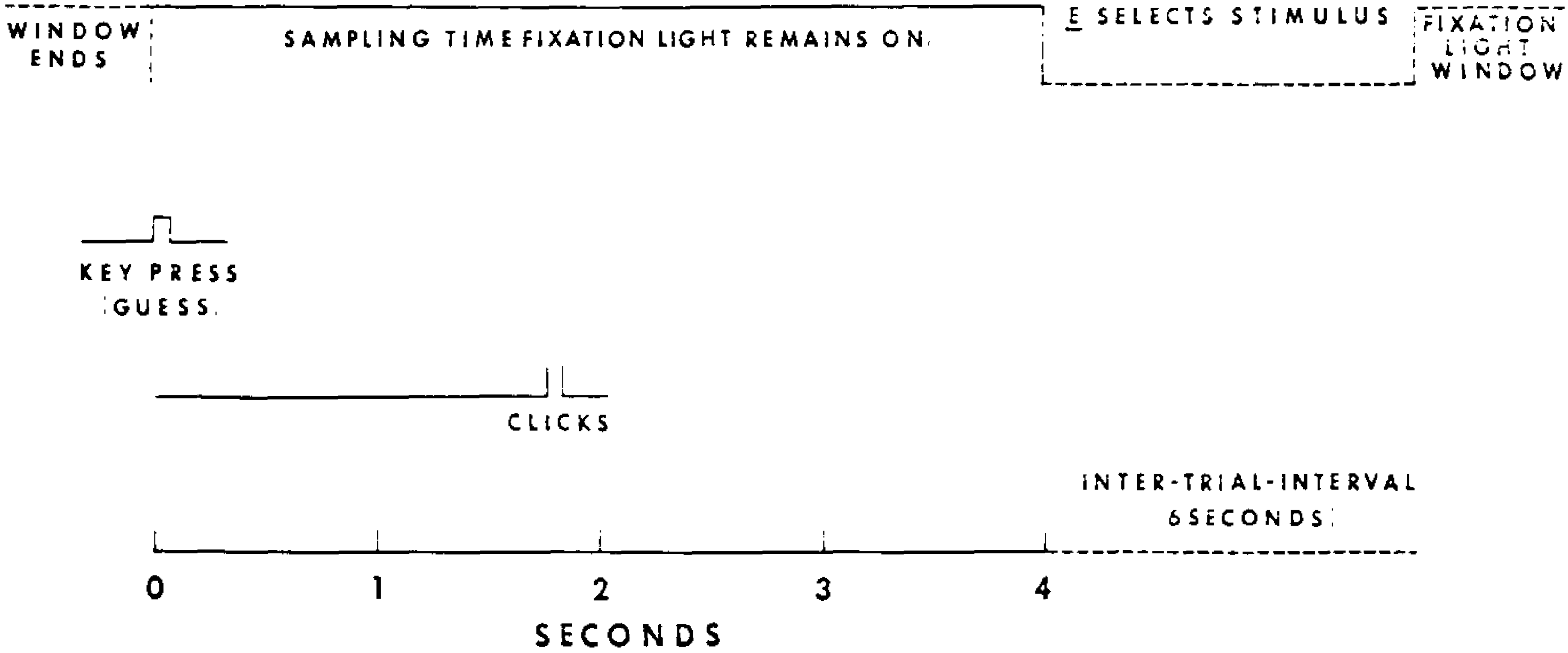
After placement of electrodes, resistances were checked. S was seated on a modified dental chair stationed in front of the pupillograph. E then adjusted S so that his eyes were at the correct level for pupillary data recording. The electrode leads were attached to the preamplifier unit, which was a small, portable unit placed securely on S's shoulder.

Trial Procedure

The decision was made not to require a motor response to the occurrence of the clicks due to the possible confounding effects of a motor potential developing between the key press and the click stimulus (Deecke, Scheid, and Kornhuber, 1969; Gilden, Vaughan, and Costa, 1966). Furthermore, it has been shown that CNV development does not require a motor response (Donchin, Gerbrandt, and Leifer, 1970), although the usual finding has been that the amplitude of CNV is lessened without a motor response (Low *et al.*, 1966; Walter, 1966).

Blinking has been a problem in all pupillary research (whether mentioned in the literature or not). In the present experiment, an attempt was made to reduce blinking to a minimum by leaving the choice of initiating the experimental sequence to S. This was accomplished by giving S adequate time to ready himself in position before he made his key press, by providing S with a four sec. time period (shown in Figure 2 as the "fixation light window")within which he could press one of the choice keys. If S felt uncomfortable or had the urge to blink, or adjust himself in any way, he simply did not press the key until he was ready. If S failed to press the key within that time, E simply recycled the trial by triggering the fixation light. In addition, Ss were told to

Figure 2. Schematic diagram of events in the trial sequence. The fixation light brightened, indicating to S̲ that he had 4 sec. (fixation light window), within which to ready himself and then press one of the two choice keys, in order to indicate his guess, which was either confirmed or disconfirmed when the stimulus was delivered 1.78 sec later. Sampling time began with the key press and lasted 4 sec. The inter-trail-interval began with the end of sampling time, and ended 6 sec. later when the fixation light brightened.



SEQUENCE OF EVENTS IN TRIAL

"blink themselves out" by consciously forcing themselves to blink during the inter-trial-interval, in order to suppress the tendency to blink during actual sampling time. This procedure worked well throughout the experiment. Only about one percent of the trials could not be used because of blinking.

In both certain (_S_ knew in advance which stimulus he would receive - _E_ told _S_ during the intertrail interval), and uncertain (_S_ did not know which stimulus would occur) conditions, _S_ initiated all trial events by pressing one of the choice keys. Prior to _S_'s key press, a dim red fixation light at optical infinity brightened, indicating to _S_ that he was to go into position in the biteboard. _S_ viewed the fixation light with his left eye, while actual measurement was made on the pupil of the right eye. From the time the fixation light brightened, _S_ had a total of four sec. within which he had to ready himself in position, fixate the light, and press one of the choice keys. With his press, _S_ initiated a series of timers which caused a control pulse, tag pulses (indicating the experimental contingency), and calibration pulses for both EEG and pupil to be deposited on tape. The stimulus, either confirming or disconfirming _S_'s guess, was delivered 1.78 seconds following the press. The fixation light was programmed to dim after sampling time was over, and this served as a cue to _S_ that the trial was over. After _S_ came out of position, he told _E_ (by means of an intercom) the stimulus he had guessed, and the stimulus that actually occurred. This was done to insure that _S_ correctly identified the stimuli. These events are schematically presented in Figure 2.

The inter-trial-interval was fixed at six sec. Since _S_ could press at any time within the four-second window, the maximum inter-stimulus interval was 14 secs.,and the minimum was 10 secs. These inter-stimulus-interval times insured that there would be no confounding effects due to recovery processes in the vertex auditory evoked potential (see Davis, Mast, Yoshie, and Zerlin, 1966).

Probability Programs

Five probability programs were employed during the course of the experiment. The programs were composed using random numbers generated by computer to assign single or double in order to obtain the desired probability. After assignment of the trials to single or double, the probabilities were made exact with the use of a random number table. On Day 1, S received a 50/50 program (50% "single" -S- and 50% "double" -D- click) composed of 300 uncertain trials, and 150 certain trials. This was divided into three sections of 100 uncertain and 50 certain trails each.

On Days 2 through 5, 4 programs were used: 20% S/80% D, 40% S/60% D, 60% S/40% D, 80% S/20% D. Each uncertain program consisted of 500 trials, and each certain program of 200 trials. Each uncertain program was broken down into four equal sections of 125 trials each, and the certain programs into four equal sections of 50 trials each, one for every day of running.

General Procedure

Each S participated in the experiment for 5 days. Day 1 served as both a means of familiarization for S, and as a means of data collection for E. S had a number of activities to master on Day 1, each of which served to make the remaining 4 days of running easier for both S and E. Since S was run in complete darkness, he had to be able to move in and out of position in the biteboard easily and without excessive movement. At the same time, S had to learn to fixate and maintain fixation for a four to five second period without blinking. S had to learn to press the key with a minimum of pressure, and to report to E what he had guessed, and which stimulus he had actually received. All of this had to be accomplished in a smooth sequence. For a naive S, this turned out to be a moderately difficult task, although all Ss became proficient after the first day.

Stimuli were presented in blocks of 25, with short rests between blocks. Probability programs were presented in sessions lasting about 50 min., with half-hour rests between sessions. The two certain blocks were presented to S first, followed by five uncertain blocks for each session (on Day 1, each session consisted of 2 certain and 4 uncertain blocks). The sessions were counterbalanced over each of the four days with the use of a 4 x 4 Latin Square. Therefore, each of the programs appeared as the first, second, third, or fourth session once in the four days. E used a different Latin Square for each S, in order to assign programs to sessions. The actual Latin Squares used for each S appear in Table 1.

Instructions

Instructions for the 50/50 condition were read on Day 1, and appear below. On days 2 through 5, S was simply reminded of the general procedure and the probabilities involved.

> This experiment is designed to measure the electrical activity of your brain and the movements of your pupil under different conditions. There will be three sessions of about 50 min. each, separated by half-hour rest periods.
> You will be presented with two types of stimuli. One will be a single click (demonstrate single click), the other will be a double click (demonstrate double click). Both types of click will be presented in blocks, or groups of trials of approximately 6 min. in length. There will be a short rest between blocks.
>
> For each session, the first 2 blocks will be

TABLE 1

Counterbalancing Procedure

Subject WC	ABCD
	BADC
	CDAB
	DCBA
Subject PK	BDCA
	DBAC
	CADB
	ACBD
Subject BR	CABD
	ABDC
	DCAB
	BDCA
Subject SP	DABC
	BDCA
	ACDB
	CBAD
Subject SS	ADCB
	CBDA
	BCAD
	DABC
Subject MK	DBCA
	CABD
	BDAC
	ACDB
Subject GB	ADCB
	DBAC
	CABD
	BCDA
Subject CB	CDBA
	DCAB
	ABDC
	BACD

Code: A= 20% single/80% double
B= 40% single/60% double
C= 60% single/40% double
D= 80% single/20% double

CERTAIN. This means that you will know in advance which stimulus will be presented, because I will tell you (through the intercom) whether a single or a double click will be presented. You will then press the appropriate key (demonstrate key press), so that you are sure you know what the next stimulus will be. 1.8 sec. after you press the key, the stimulus will be presented.

The last 4 blocks of each session will be UNCERTAIN. For these blocks, I will not tell you what the next stimulus will be. Instead, you will guess, by pressing one of the choice keys (demonstrate), which stimulus will be presented next. For example, if you predict double, and a double click occurs, you will be right; if the single click occurs, you will be wrong. After each trial is over, I want you to tell me the stimulus you predicted would occur, and the stimulus that actually did occur. I will tell you the number of trials you predict correctly, and the number you predict incorrectly at the end of each uncertain block.

All 3 sessions today will have 50% single clicks,and 50% double clicks. These frequencies were predetermined by the use of a computer generated, random number table, and will, therefore, be exact only in the long rung. Therefore, any particular block may not have exactly 50% single and 50% double clicks.

After the fixation light brightens, you must go into position in the bite board and fixate the light. You will have 4 sec. within which to do this and to press one of the keys indicating what you predict the next stimulus will be. Your press on the key should be as light as possible, and made with your index finger. 1.8 sec. following your press, the stimulus will be presented. After you press, it is extremely important for you not to move for a 4 sec. period. It is during this period that your pupillary and brain activity are being recorded. Moving includes blinking, moving the head, moving your eyes, moving the body, gasping, and coming out of the bite board too soon. If you must move, DO NOT PRESS THE KEY. When the fixation light dims, this is your signal that the trial is over and you may come out of position and report to me which stimulus you guessed and which you received. Once you have pressed the key, you MUST NOT MOVE until 4 sec. have elapsed. Please do not count signals at any time.

Data Analysis

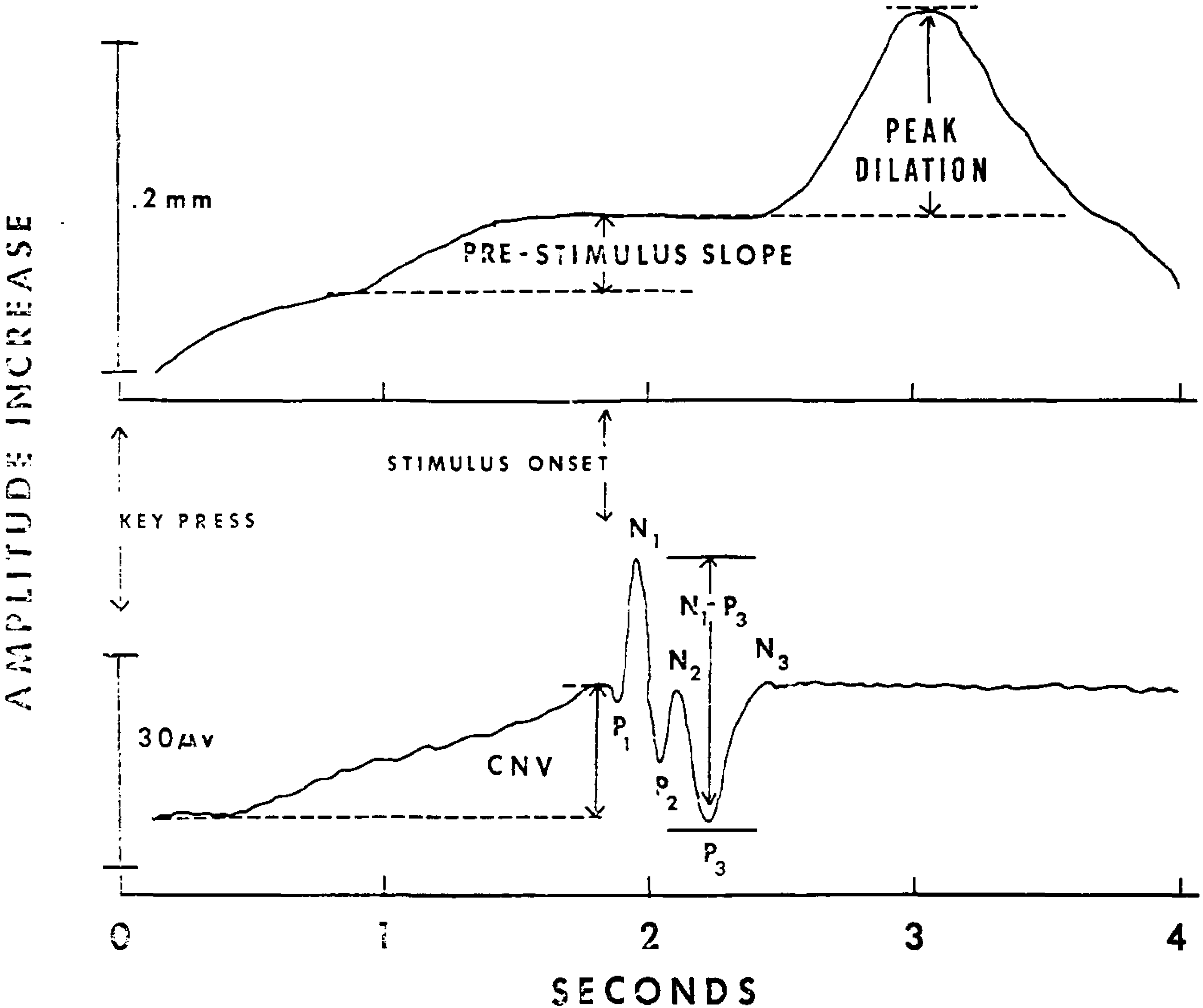
Each of the response components will be considered separately. Figure 3 presents schematic evoked potential and pupillary data. The components that were measured are labelled for each response. CNV is a slow component, and so is prestimulus pupillary slope, whereas the evoked potential and peak dilation are fast components.

Negative shift (CNV). Due to the method by which the data were recorded, it was necessary to deposit the calibration pulses at the beginning of sampling time. Because of this, data measurement for an X-Y readout could not be accomplished until a point 180 msec. following S's press (i.e., a time interval corresponding to the length of the calibration pulse). In order to measure CNV, a baseline was drawn through the averaged activity of this 160 msec. time period, peak negativity was determined, and CNV amplitude was defined as the height, in microvolts, from baseline to this peak. If the basefline shifted in a positive direction, the same procedure was followed, and peak positivity was determined.

Evoked potential. Establishment of a baseline is an arbitrary procedure. Further, since maximal CNV amplitude usually occurred at a point where a baseline would normally be established (prior to stimulus onset), this point could not be used as a baseline due to the fact that it did not represent a "resting" level. Therefore, all measurements were made peak to peak. Five components were measured and subjected to statistical analysis: P_1-N_1, N_1-P_2, P_2-N_2, N_2-P_3, and P_3-N_3. An overall measure of evoked potential activity, N_1-P_3, was also used(see Jenness, 1970 and Ritter et al., 1968).

If a component was difficult to identify, then the best averaged

Figure 3. Schematic diagram illustrating the components which were measured for pupillary and evoked potential data. Dotted lines represent baselines drawn to establish amplitudes for pre-stimulus pupillary slope, CNV, and peak dilation.


AMPLITUDE INCREASE
.2 mm
PEAK
DILATION
PRE-STIMULUS SLOPE
STIMULUS ONSET
KEY PRESS
N_1
$N_1 - P_3$
N_2
N_3
P_1
P_2
P_3
30µv
CNV
0
1
2
3
4
SECONDS

response (which clearly showed all components) for any given S was consulted, and the component in question was identified using this averaged response. In some cases, particularly when S was right in predicting the low-frequency event, N_2 was absent or just barely identifiable. In this case, latency, in conjunction with other waveforms for the S in which the component appeared, was used to locate this component.

Pupillary data measurement. Pilot data had demonstrated the existence of three pupillary "components": the first of these was a dilation peaking at about 900-1000 msec. following the key press (press dilation); the second was a slow component, which began to either rise (dilation) or fall (constriction) following the peak of the press dilation; and the third was a fast component, produced by the reception of the stimulus. The first component did not differ across conditions (certain versus uncertain), and was most certainly due to the motor movement invoied in the key press (Simpson and Paivio, 1966). The second component did differ as a function of conditions, and was therefore measured in the main experiment. In order to measure this component, a baseline was drawn through the peak of the press dilation, and the height, in mm. from that averaged baseline to a baseline drawn through averaged pupillary activity at stimulus onset was determined. This was called pre-stimulus pupillary slope. Peak dilation was measured in mm. from a baseline drawn at stimulus onset to the peak of the dilation. In addition, initial diameter measurements, were obtained for each averaged pupillary response.

Probability effects. Figure 4 presents a hypothetical sequence of stimuli and guesses for a 10 trial 80% S/20% D probability program. Listed below each trial's stimulus and guess is the outcome that resulted. The bottom half of the figure presents the 2x2 probability table, in which

Figure 4. Hypothetical sequence of stimuli and guesses and resulting 2x2 probability table for a 10 trial 80/20 program, in the uncertain condition.

TRIAL	1	2	3	4	5	6	7	8	9	10
STIMULUS	S_A	S_A	S_A	D_B	S_A	S_A	S_A	D_B	S_A	S_A
GUESS	$S_{A'}$	$S_{A'}$	$S_{A'}$	$S_{A'}$	$S_{A'}$	$D_{B'}$	$S_{A'}$	$D_{B'}$	$S_{A'}$	$S_{A'}$
OUTCOME	A'A HIT	A'A HIT	A'A HIT	A'B MISS	A'A HIT	B'A MISS	A'A HIT	B'B HIT	A'A HIT	A'A HIT

STIMULUS

		80% S	20% D	
GUESS	S	OUTCOME PROBABILITY CELL $\sum$ A'A HIT	$\sum$ A'B MISS	$\sum$ A' - 80% GUESS AVERAGED RESPONSE
	D	$\sum$ B'A MISS	$\sum$ B'B HIT	$\sum$ B' - 20% GUESS AVERAGED RESPONSE
		$\sum$ A - 80% STIMULUS AVERAGED RESPONSE	$\sum$ B - 20% STIMULUS AVERAGED RESPONSE	

the trials that were summed to obtain a particular averaged response contingency are indicated. In this example, S probability matched. Figure 4b shows the 3 ways in which the data was analyzed: 1) as a function of stimulus probability (Σ A and Σ B), which E generated; 2) as a function of guessing probability (Σ A' and Σ B') which S generated; and 3) as a function of the interaction of the above two probabilities, or the outcome probability (Σ A'A, Σ A'B etc.). The values bracketed in the table are the probabilities that correspond to each summed response. An amplitude measure for all evoked potential components and for peak dilation was obtained for each type of probability represented in the 2x2 table. CNV and pre-stimulus pupillary slope amplitudes were obtained for stimulus and guessing probabilities. Amplitudes corresponding to stimulus and guessing probabilities were obtained by weighting the outcome probability amplitudes by their cells Ns across rows or columns.

Since there were two stimuli, probability functions were obtained for both. The data to be presented were averaged across the two stimuli, since statistical analyses had shown that the two stimuli produced similar functions. Therefore, the 20% right outcome amplitude is the mean value of the 20% single right and the 20% double right. In the same way, the 20% stimulus amplitude is the average value of the 20% single amplitude and the 20% double amplitude.

Variability estimates. Estimates of variability were obtained by averaging all the even-numbered trials and all of the odd-numbered trials separately. This was done for N_1-P_3, CNV, and peak dilation.

The absolute difference between the amplitude of the odd averaged response and the even averaged response was used as an estimate of the variability of the averaged response for the total number of trials. The estimates were averaged across the two stimuli. Odd minus even estimates were computed for averaged responses as a function of stimulus, guessing and outcome probability.

Statistical analyses. The main statistical analysis employed was a slope analysis (Fleiss, personal communication). A slope term from regression analysis was obtained for each S, for every evoked potential component, N_1-P_3, peak dilation, pre-stimulus slope, and CNV. Slope terms were obtained for the regression of these amplitudes on stimulus probability and outcome probability (both hits and misses) in the uncertain condition. These slope terms were averaged across Ss, and the resultant mean slope tested for significant departure from zero slope. The test performed was a t-test, which if significant indicated that the slope term differed significantly from zero, and that mean amplitude was a monotonic function of the particular probability involved.

In the analysis of sequential averages for the 80% hit situation, Friedman two-way analyses of variance (Siegel, 1956) were used to test whether or not amplitudes varied significantly as a function of time. Since each S's sequential average was based upon a different number of trials, it was felt that a non-parametric technique would be best, due to the fact that some of the assumptions of parametric analysis of variance would not be met.

Finally, since this experiment employed a repeated measures design (each S serving as his own control), t-tests for correlated means (Guilford, 1965) were employed to test the significance of differences between amplitudes and latencies in the certain and uncertain conditions, and between right and wrong outcomes for both amplitudes and latencies.

CHAPTER III

RESULTS

Response Description

The identification of averaged evoked potential components is from Davis et al. (1966) and Tueting (1968). Figure 5 presents both pupillary and evoked potential data for one S in both certain and uncertain conditions.

P_1 was the first positive component and occurred with an average latency of 48 msec. N_1 was the first negative component and peaked at about 100 msec. P_2 occurred at a latency of 200 msec., N_2 at 230, P_3 at 320 and N_3 at 430 msec. Some Ss showed a fourth positive component, but P_4 was so variable both within and between Ss, that it was not studied further.

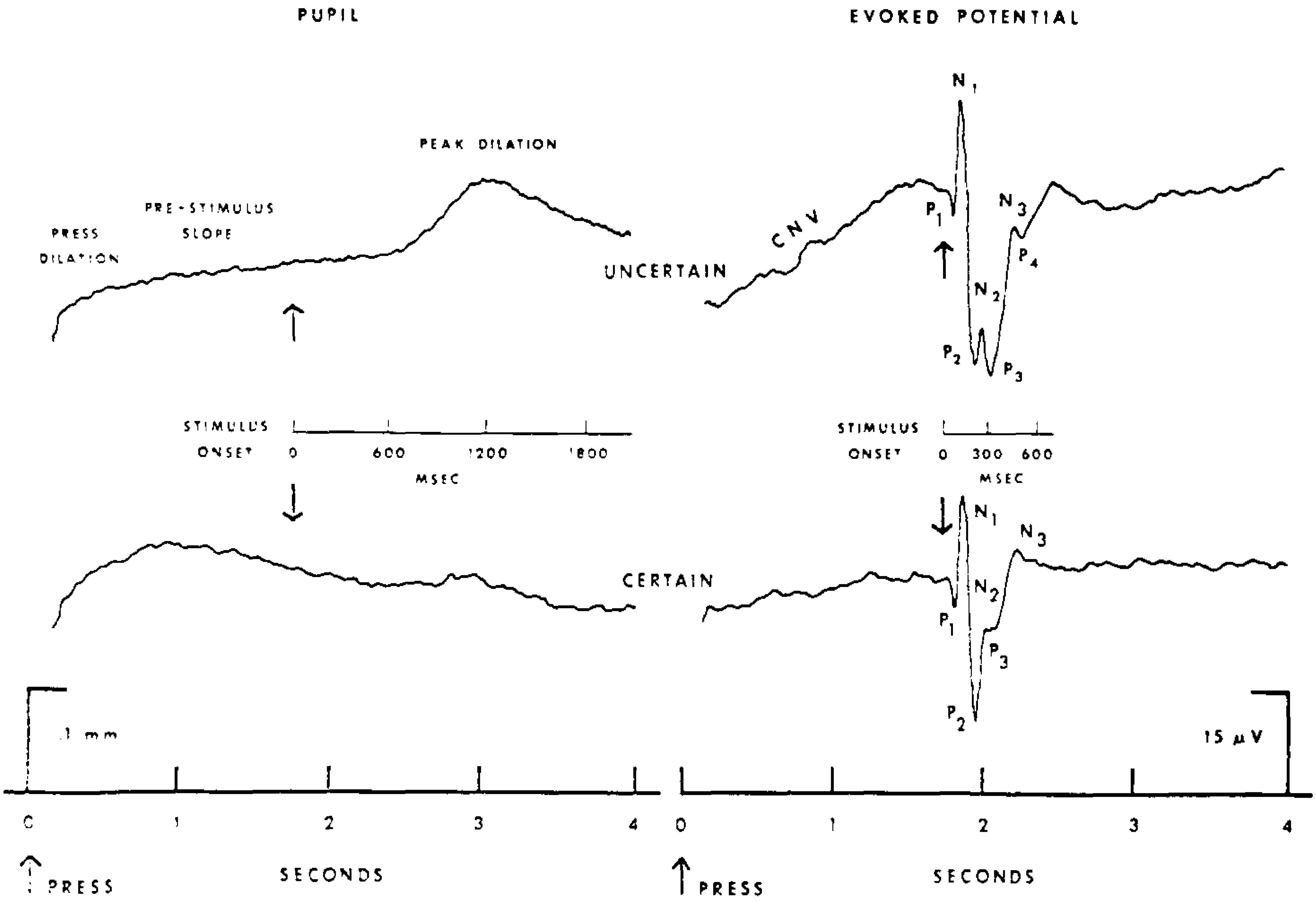
Six Ss produced slow negative DC shifts (CNV) fairly consistently following their key press, one S showed no CNV activity at all, and another showed only positive shifts of a few microvolts in amplitude. In those Ss that produced CNV, it appeared to begin with a latency of approximately 50-100 msec.

The pupillary response also consisted of a series of components. Following the key press, all Ss showed a dilation peaking at approximately 1000 msec.(after the press). This dilation varied in both amplitude and shape between Ss, but was remarkably consistent within an S. Following this initial dilation, the pupil either continued to dilate, constricted,

Figure 5. Averaged pupillary and evoked potential responses for subject BR. Time zero on the heavy time line represents the point when S pressed the choice key. Time zero on the inserted time line represents stimulus onset. Calibration for each response is shown. Both sets of data are for the 80% stimulus probability.

80 % STIMULUS

BR 6/70



or remained at a steady level (depending upon the S) until stimulus onset, after which the pupil dilated with a latency of from 600-800 msec., and reached peak dilation at 1200 msec.

Certain Versus Uncertain Conditions and Effect of Probability

All data will be presented as both individual and group functions, averaged across the eight Ss.

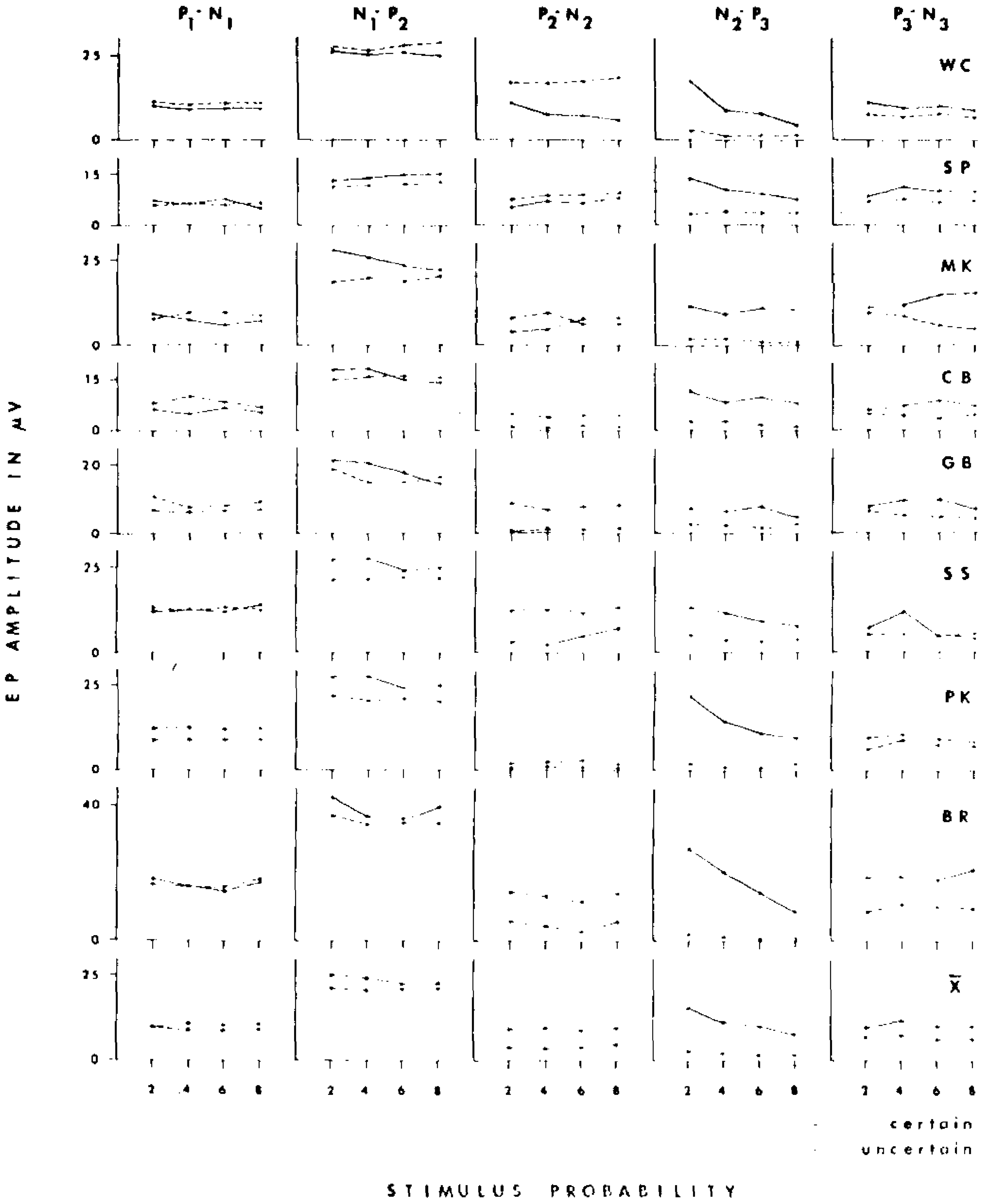
The uncertain condition produced two functions, one for stimulus probability and one for guessing probability (i.e., S's guessing rate). Both of these functions will be presented for all evoked potential components and for peak pupillary dilation.

Evoked potential findings. Figure 6 demonstrates the effect of stimulus probability on five evoked potential components. For 4 of the components, functions for the certain condition were generally of smaller amplitude compared with their uncertain counterparts. The P_2-N_2 component, however, yielded the opposite result for all Ss, larger amplitude in the certain than in the uncertain condition.

T-tests for correlated means were run for each stimulus probability point to test the significance of the difference between certain and uncertain mean amplitudes for all components of the evoked potential. For N_1-P_2, N_2-P_3, and P_3-N_3 the uncertain condition produced larger amplitudes than the certain condition with t-values for each probability significant at the .05 level, with the exception of N_1-P_2 at the 60 and 80 percent points, where no difference was found. The certain condition produced larger amplitudes than the uncertain condition for P_1-N_1 and P_2-N_2, except for the 20 percent point for P_1-N_1, where there was no difference.

N_1-P_2 and N_2-P_3 produced inverse slopes that differed significantly

Figure 6. Five averaged, peak to peak evoked potential components in certain and uncertain conditions, plotted as a function of stimulus probability.


P_1-N_1
N_1-P_2
P_2-N_2
N_2-P_3
P_3-N_3
WC
SP
MK
CB
GB
SS
PK
BR
$\bar{X}$
0
25
15
20
40
2
4
6
8
EP AMPLITUDE IN μV
STIMULUS PROBABILITY
certain
uncertain

from zero, and indicated that both components decreased monotonically as a function of stimulus probability. For the certain condition, only N_2-P_3 produced a negative slope, which though significant was much less steep than its uncertain counterpart (mean slope for the uncertain condition was -12.34; for the certain condition -1.34).

Figure 7 presents the same five evoked potential components as a function of *S*'s guessing rate. N_2-P_3 again produced a significant negative slope ($p<.05$), as did P_3-N_3 ($p<.05$), but N_1-P_2 did not.

Figure 8 shows the effect of both stimulus probability and guessing probability on CNV and N_1-P_3. The difference between certain and uncertain functions are clearly marked for all *Ss*. These differences were again tested at each probability point by employing t-tests for correlated means. All uncertain N_1-P_3 amplitudes were significantly larger than their certain counterparts at all probability points ($p<.01$). CNV was significantly more negative at all probability points ($p<.05$) in the uncertain than in the certain condition.

All *Ss* produced negative slope values of approximately the same magnitude. The mean slope for the regression of N_1-P_3 on stimulus probability was -18.99 ($p<.001$), and of N_1-P_3 on guessing probability was -14.67 ($p<.001$). The slope for N_1-P_3 was also significant in the certain condition, although of a much smaller nagnitude (mean slope was -3.46, p .05).

To determine whether any of the three CNV functions (stimulus probability in the certain and uncertain conditions, and guessing probability in the uncertain condition) were affected by probability, slope analyses were employed. In no case, did any of these analyses yield a statistically significant value.

With respect to the individual plots of CNV and N_1-P_3, an important

Figure 7. Five averaged evoked potential components plotted as a function of guessing probability in the uncertain condition.

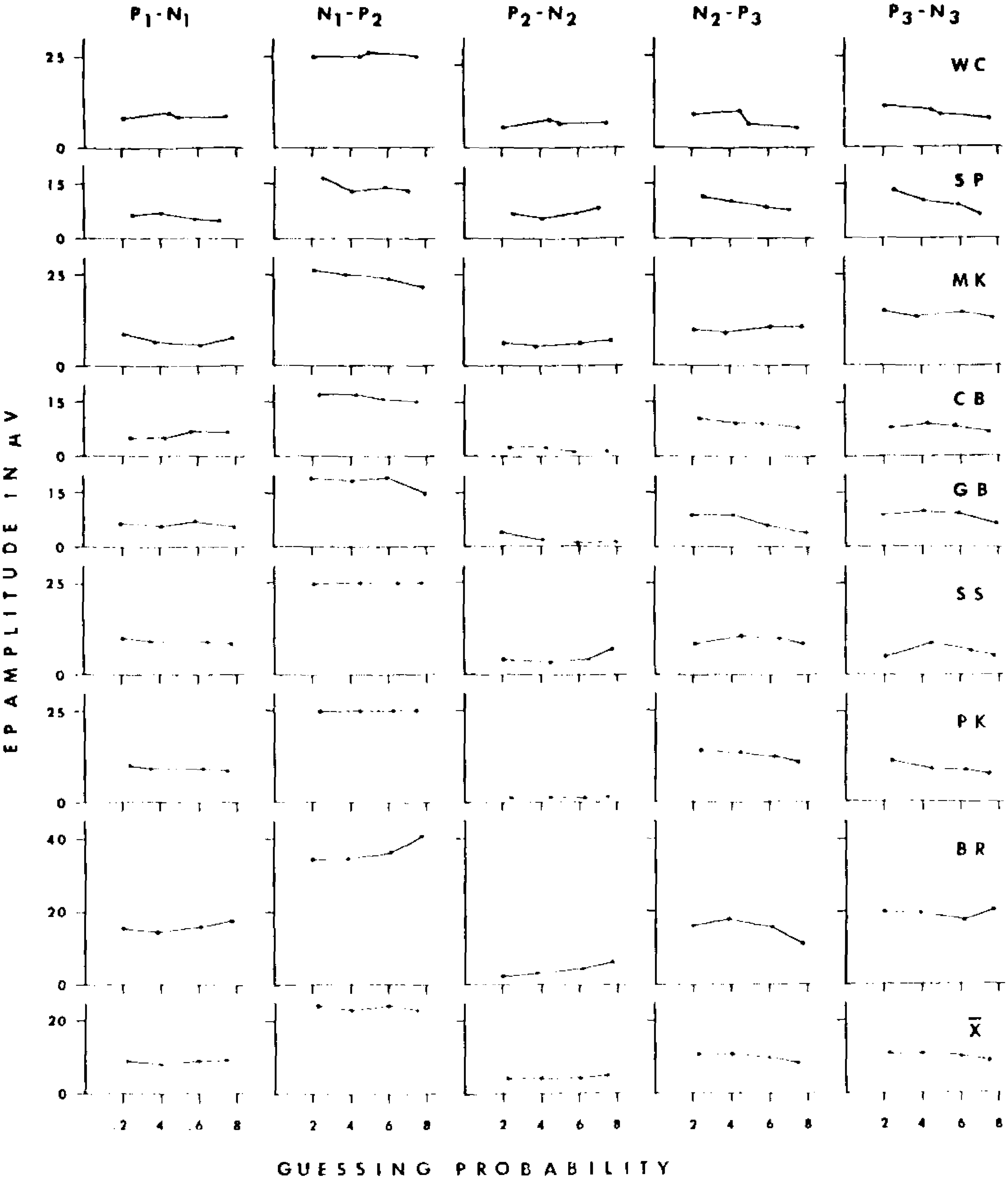
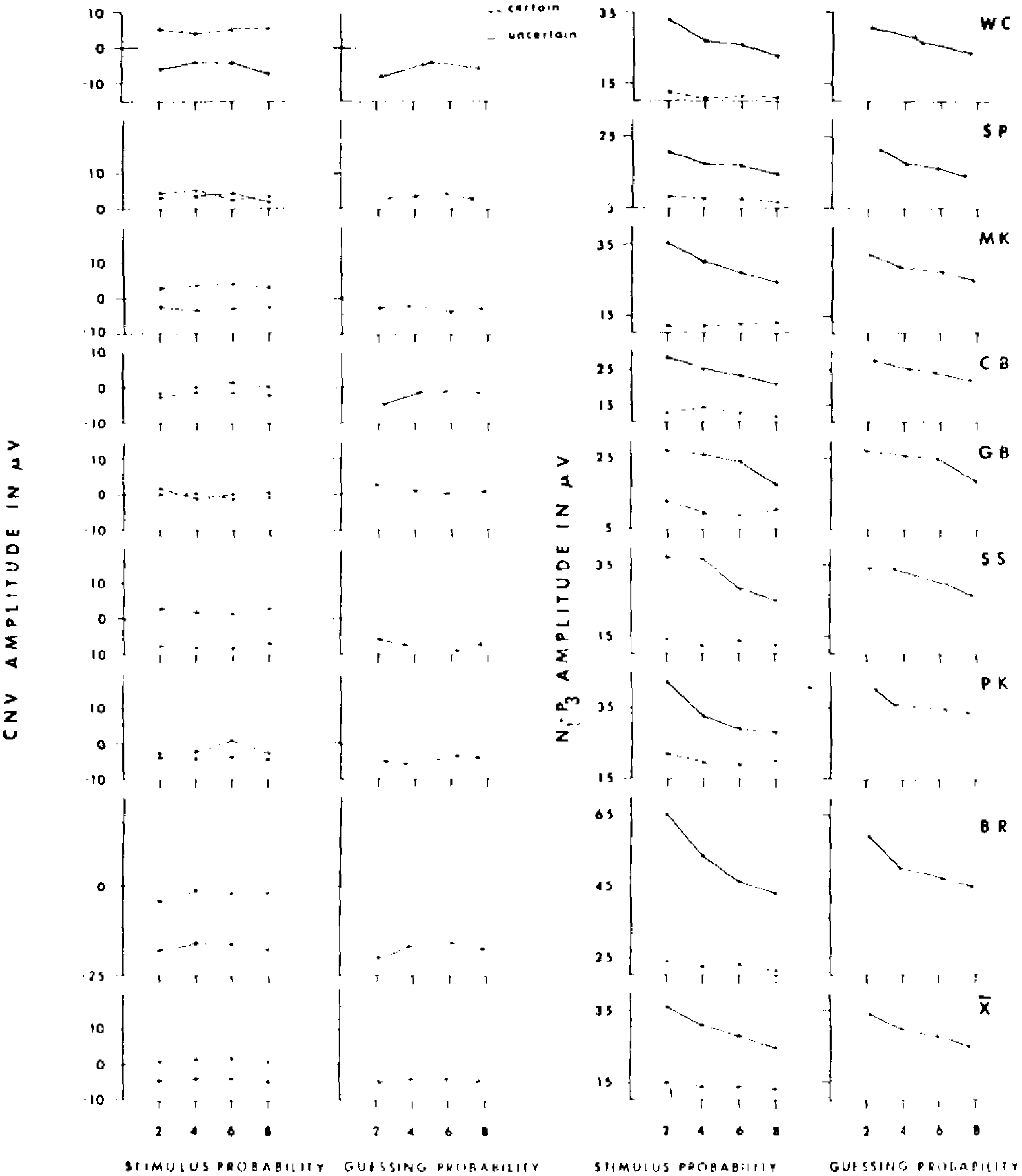

P1-N1
N1-P2
P2-N2
N2-P3
P3-N3
WC
SP
MK
CB
GB
SS
PK
BR
X̄
25
15
40
20
0
.2
4
.6
8
2
4
6
8
EP AMPLITUDE IN µV
GUESSING PROBABILITY

Figure 8. CNV and N_1-P_3 amplitudes plotted as a function of stimulus probability in both certain and uncertain conditions, and as a function of guessing probability in the uncertain condition. CNV data are presented on the left half, and N_1-P_3 data on the right half of the figure.

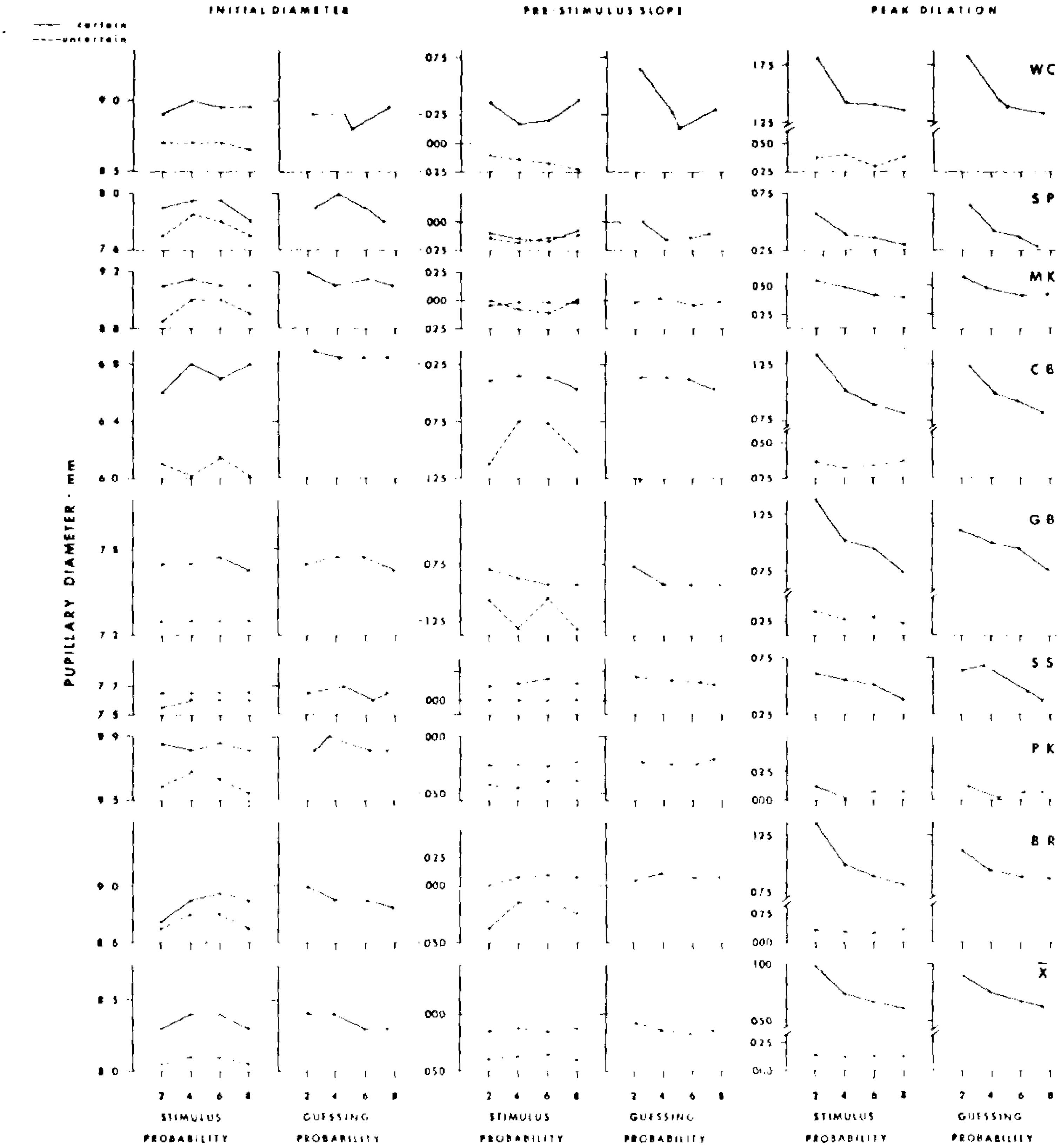

certain
uncertain
WC
SP
MK
CB
GB
SS
PK
BR
X̄
CNV AMPLITUDE IN µV
N1-P3 AMPLITUDE IN µV
10
0
-10
-25
35
25
15
5
65
45
2
4
6
8
STIMULUS PROBABILITY
GUESSING PROBABILITY

trend was noted: CNVs were generally more negative in the uncertain than in the certain condition and appeared to be mediating the large N_1-P_3 differences between the certain and uncertain conditions. That is S BR, who showed the greatest difference in CNV amplitude between certain and uncertain conditions also showed the greatest N_1-P_3 difference. CB, who produced a very small CNV difference at all probability points, also showed one of the smallest N_1-P_3 differences. However, two Ss, SP and GB, who showed no difference in CNV between certain and uncertain conditions, did show consistently greater N_1-P_3 amplitude in the uncertain condition, and this appeared to rule out CNV as the necessary mediator of the N_1-P_3 certain-uncertain disparity. In the same vein, the differences in N_1-P_3 as a function of stimulus or guessing probability did not appear to be related to CNV differences across the different probability points, since these CNV differences were very small, whereas N_1-P_3 differences were relatively large.

Pupillary findings. Figure 9 shows the effects of stimulus and guessing probability on pre-stimulus pupillary slope, peak dilation and initial diameter. Peak dilation is of much larger amplitude in the uncertain than in the certain condition ($p < .01$). In fact, only four Ss produced peak dilations in the certain condition which could be detected, and no general trend (e.g., larger peak dilations for rarer certain events) was evidenced ($p > .05$). The mean slope for the regression of peak dilation amplitude on stimulus probability was -22.15 ($p < .001$), and for guessing probability was -20.36 ($p < .001$).

With respect to initial diameter, two trends appeared: 1) initial diameters in the certain condition were smaller than initial diameters in the uncertain condition at all probability points ($p < .05$); and 2) there

Figure 9. Pupillary data plotted as a function of stimulus probability in certain and uncertain conditions, and guessing probability in the uncertain condition.


INITIAL DIAMETER
PRE-STIMULUS SLOPE
PEAK DILATION
—— certain
---- uncertain
PUPILLARY DIAMETER - mm
WC
SP
MK
CB
GB
SS
PK
BR
X̄
2
4
6
8
STIMULUS PROBABILITY
GUESSING PROBABILITY
STIMULUS PROBABILITY
GUESSING PROBABILITY
STIMULUS PROBABILITY
GUESSING PROBABILITY

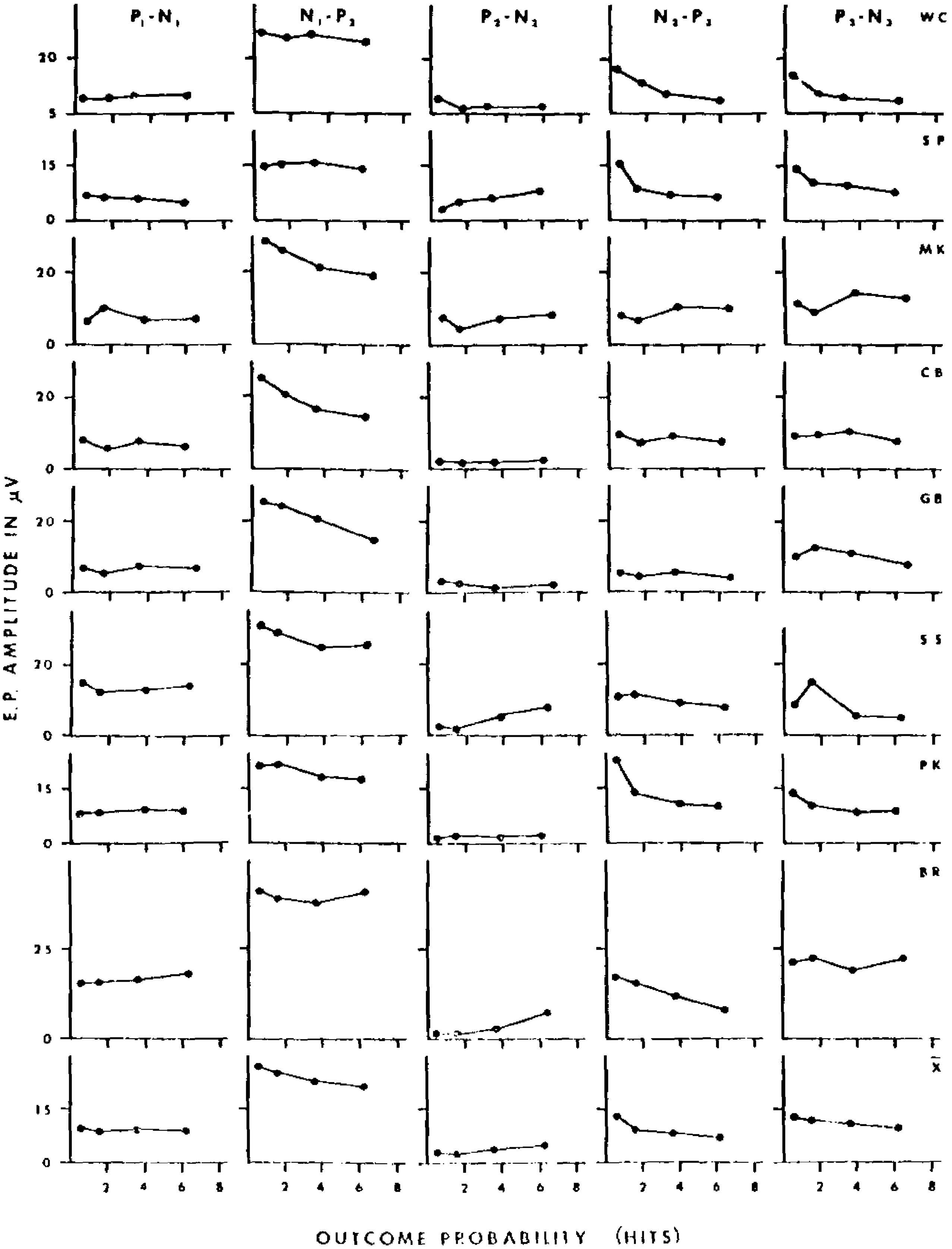
did not appear to be any relationsip between initial diameter and peak dilation amplitude, as would be expected if the Law of Initial Value (e.g., Sternbach, 1966) applied. Correlations computed across Ss at each of the four stimulus and guessing probabilities between initial diameter and peak dilation produced moderate negative values hovering about -0.3, which fell short of significance.

Pre-stimulus pupillary slope was measured from the peak of the dilation following the key press to a point at stimulus onset. Since some Ss showed continued dilation following the press dilation and some showed constriction, it was necessary to assign a value that would differentiate these opposite movements. A positive sign was applied to the data if, following the peak of the press dilation, S continued to dilate; a negative sign was applied if S's pupil constricted. Since the majority of Ss showed constriction at this point, the average curve for the eight Ss fell in the negative quadrant. The certain condition produced pre-stimulus pupil functions which tended toward greater constriction following the press dilation at each stimulus probability point ($p<.05$). This can be seen in the individual data of 6 Ss (SP and MK were exceptions). Pre-stimulus pupil appears to vary as a function of guessing probability in only three Ss. The three averaged plots for pre-stimulus slope as a function of stimulus probability in both certain and uncertain conditions, and guessing probability in the uncertain condition were subjected to slpe analysis and, as had occurred with CNV data, no slope value was significant.

Evoked Potential Components and Peak Dilation as a Function of Outcome Probability

Figure 10 presents the five evoked potential components as a

Figure 10. Five averaged peak to peak evoked potential components plotted as a function of joint or outcome probability when _S_ was right (hits).


P_1-N_1
N_1-P_2
P_2-N_2
N_2-P_3
P_3-N_3
WC
SP
MK
CB
GB
SS
PK
BR
$\bar{X}$
20
5
15
0
20
0
20
0
20
0
20
0
15
0
25
0
15
0
2
4
6
8
E.P. AMPLITUDE IN μV
OUTCOME PROBABILITY (HITS)

function of outcome probability for hits (S was right). Three components showed a negative relationship to outcome probability when S was right: N_1-P_2, N_2-P_3 and P_3-N_3 ($p < .05$). In 4 Ss, P_2-N_2 demonstrated the opposite trend, amplitude increased as outcome probability increased, but this **relationship** did not achieve statistical significance.

Figure 10 demonstrates an additional finding which is of particular interest: not every S showed an amplitude decrease in N_1-P_2 or in N_2-P_3, although the averaged slopes were significantly different from zero. Mere eyeballing of this figure shows that MK, CB, and GB produced N_1-P_2 functions which appear to decrease as a function of outcome probability, but their N_2-P_3 functions do not. The remaining five Ss appear to produce the opposite trend: N_2-P_3 functions which decrease, and N_1-P_2 functions which do not. SS appears to be an exception, producing decreasing functions for both N_1-P_2 and N_2-P_3. As a means of objectifying this observation, each S's slope terms for both N_1-P_2 and N_2-P_3 were reexamined. If one slope was larger than the other, that S was identified as belonging to the group whose component showed the larger negative slope. Employing this criterion, four Ss were placed in the N_1-P_2 group (MK, CB, GB, SS), and the remaining four Ss comprised the N_2-P_3 group. Each group's average slopes for both N_1-P_2 and N_2-P_3 were tested for significant departure from zero, with the following result: The N_2-P_3 group produced a mean slope of -19.12 ($p < .01$) for N_2-P_3, and a nonsignificant N_1-P_2 slope of -2.93 ($p > .05$). The N_1-P_2 group produced a significant mean N_1-P_2 slope of -15.52 ($p < .01$), and a non-significant N_2-P_3 slope of -1.18 ($p > .05$). This same distinction, however, did not hold for wrong outcomes, where the large variability tended to mask any effect that appeared to be present. Therefore, it appears, at least when

S is right, that the effect of probability is selective, affecting either N_1-P_2 or N_2-P_3, but not both.

Figure 11 presents the same five components as a function of outcome probability when S is wrong (misses). As can be seen, the data are much more variable than when hits are considered. All component average slope values were in the same direction as for right outcomes, but were not significant, with the exception of P_3-N_3, which produced a significant positive slope value ($p<.05$).

In figure 12, both peak dilation and N_1-P_3 amplitudes are presented as a function of both hit and miss outcome probability. There is a striking correspondence between N_1-P_3 and peak dilation when S is right, but a dissociation of the two responses in most Ss when S is wrong. For hits, the mean N_1-P_3 slope was -22.43 ($p<.001$); and the mean peak dilation slope was -29.23 ($p<.01$), indicating that amplitude decreased monotonically as a function of hit outcome probability with all Ss producing very similar slope magnitudes for both peak dilation and N_1-P_3. The data for misses were more variable. The mean slope for N_1-P_3 was -25.50, but due to the large inter-subject variability in slope magnitude and direction (SP, GB, and SS produced positive slopes) this trend was not significant ($p>.05$). The mean pupillary slope was -81.06 ($p<.01$), with all Ss yielding negative slopes.

Analyses of variance for peak dilation and N_1-P_3. It has been shown that both N_1-P_3 and peak dilation decreased monotonically as a function of stimulus probability, guessing probability, and their interaction, outcome probability. However, for outcome probability the slope was significant for N_1-P_3 only for hits. The slope analyses did not answer the question whether being correct or incorrect *per se* had any effect on

Figure 11. Five averaged peak to peak evoked potential components plotted as a function of joint or outcome probability when S̲ was wrong (misses)

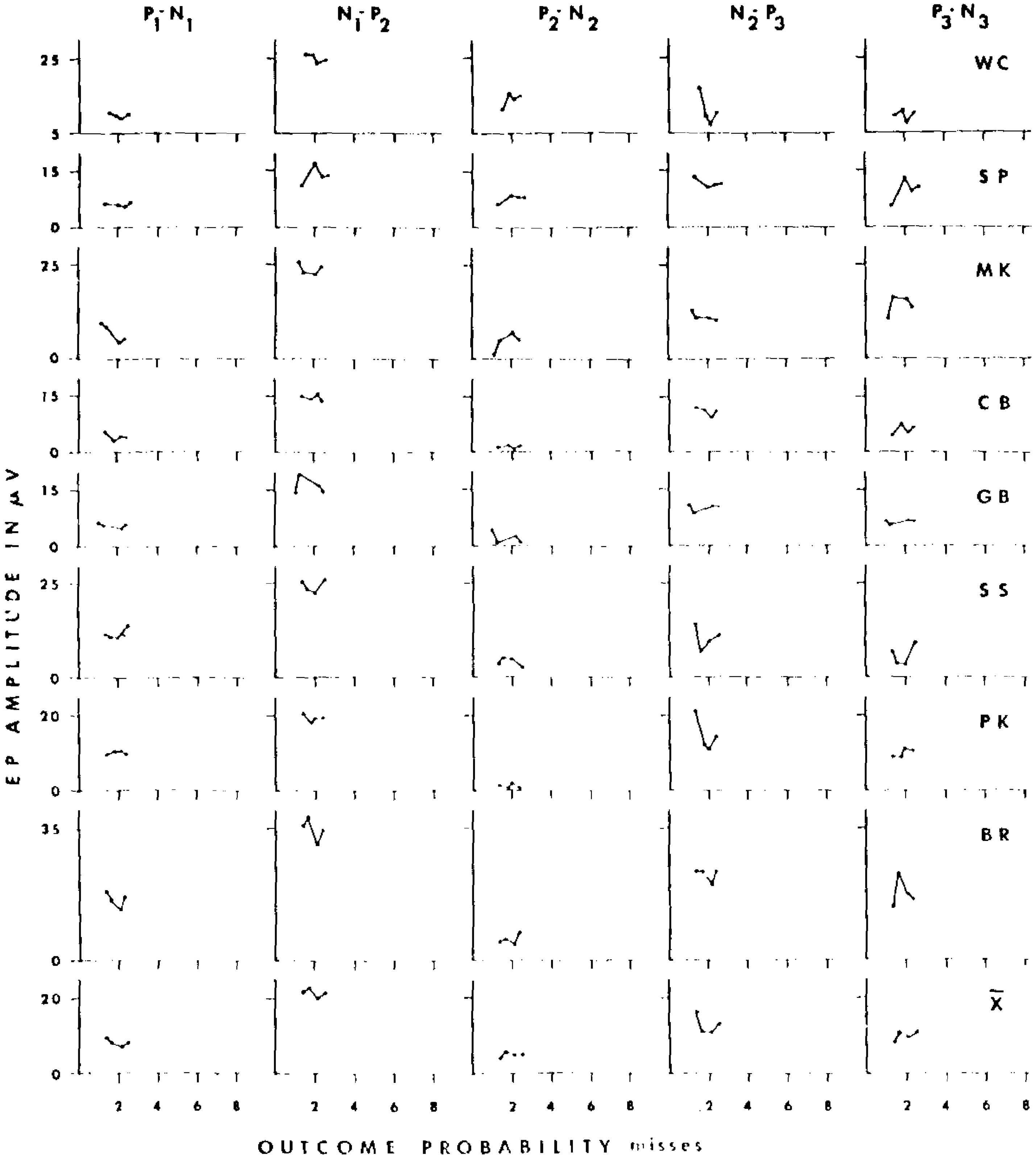
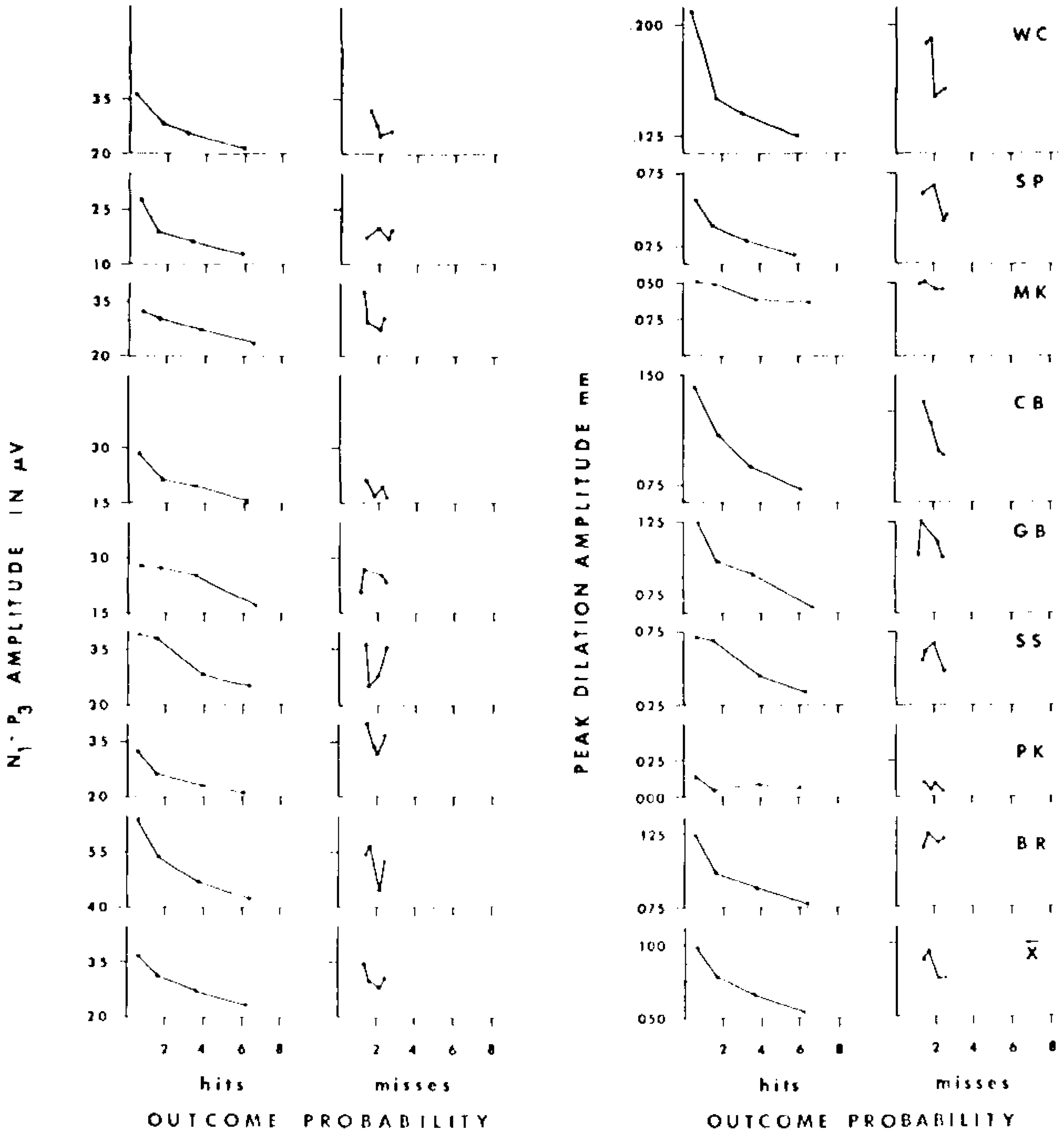

P_1-N_1
N_1-P_2
P_2-N_2
N_2-P_3
P_3-N_3
WC
SP
MK
CB
GB
SS
PK
BR
$\bar{X}$
25
5
15
0
25
0
15
0
15
0
25
0
20
0
35
0
20
0
2
4
6
8
EP AMPLITUDE IN µV
OUTCOME PROBABILITY misses

Figure 12 N_1-P_3 and peak dilation amplitudes plotted as a function of outcome probability when S was right (hits), and when S was wrong (misses). N_1-P_3 data appear on the left, peak dilation data on the right.


$N_1 - P_3$ AMPLITUDE IN µV
35
20
25
10
35
20
30
15
30
15
35
20
35
20
55
40
35
20
2 4 6 8
hits
2 4 6 8
misses
OUTCOME PROBABILITY
PEAK DILATION AMPLITUDE mm
.200
.125
.075
.025
.050
.075
.150
.075
.125
.075
.075
.025
.025
.000
.125
.075
.100
.050
W C
S P
M K
C B
G B
S S
P K
B R
$\bar{X}$
2 4 6 8
hits
2 4 6 8
misses
OUTCOME PROBABILITY

amplitude of response (see Sutton et al., 1965). Therefore, an analysis of variance was designed to check on this issue as well as to confirm the assumption that the two stimuli need not be analyzed separately. In addition, this analysis provided a check on the analysis of the data in terms of outcome probability. The way in which the analysis of variance was designed is presented in Figure 13a and 13b. The data presented there were averaged across the 8 Ss. Since no other means of obtaining variance was available, the odd and even averaged amplitudes served that purpose. Notice that, in order to examine the effect of correctness on the data, each of the cells of a 2x2 probability table was rearranged so that each row sum was the sum of evoked potential or peak dilation amplitude when S was either correct or incorrect, while the column sums remained the same.

Each of the probability programs (i.e., 20/80, 40/60 etc.) was treated as the level of a factor which was called "frequency". In addition, by collapsing across these frequencies, it was possible to examine the effect of stimulus (single versus double) and the effect of being correct or incorrect. Because of the way in which this analysis was designed, "frequency" was essentially a "dummy" variable, since, of interest was the effect of a single stimulus and its associated probability of occurrance, and not the effect of a total probability program (i.e., 20/80, 40/60 etc.). Therefore, the results of this main effect will not be discussed.

The S main effect was, of course, highly significant for both N_1-P_3 and peak dilation ($p<.01$). All interactions involving the S variable were not evaluated for significance, since in this type of analysis, the S effects are assumed to be real, due to the large variability between Ss. These S interaction variances were used in testing other main and interaction effects. The frequency by stimulus interaction was significant in

Figure 13a and b. Four-celled tables for the four probability programs for N_1-P_3 (13a) and peak dilation (13b) data. Row values represent mean amplitudes when S was either correct or incorrect. Column values represent mean amplitudes corresponding to a given stimulus with its associated probability of occurrence. Cell values are mean amplitudes resulting from the interaction of stimulus and guessing probabilities.

STIMULUS

GUESS	20%S	80%D	
Correct	37.218	24.094	30.656
Incorrect	35.398	28.476	31.937
	36.308	26.285	

GUESS	40%S	60%D	
Correct	32.648	27.750	30.199
Incorrect	32.296	28.406	30.352
	22.473	28.078	

GUESS	60%S	40%D	
Correct	27.914	32.718	30.316
Incorrect	28.078	31.242	29.660
	27.996	31.980	

GUESS	80%S	20%D	
Correct	23.273	39.633	31.453
Incorrect	28.008	36.978	32.492
	25.641	38.305	

STIMULUS

GUESS

	20%S	80%D	
Correct	.102	.052	.077
Incorrect	.089	.084	.087
	.095	.068	

	40%S	60%D	
Correct	.076	.066	.071
Incorrect	.070	.077	.073
	.073	.072	

GUESS

	60%S	40%D	
Correct	.067	.070	.068
Incorrect	.071	.073	.072
	.069	.071	

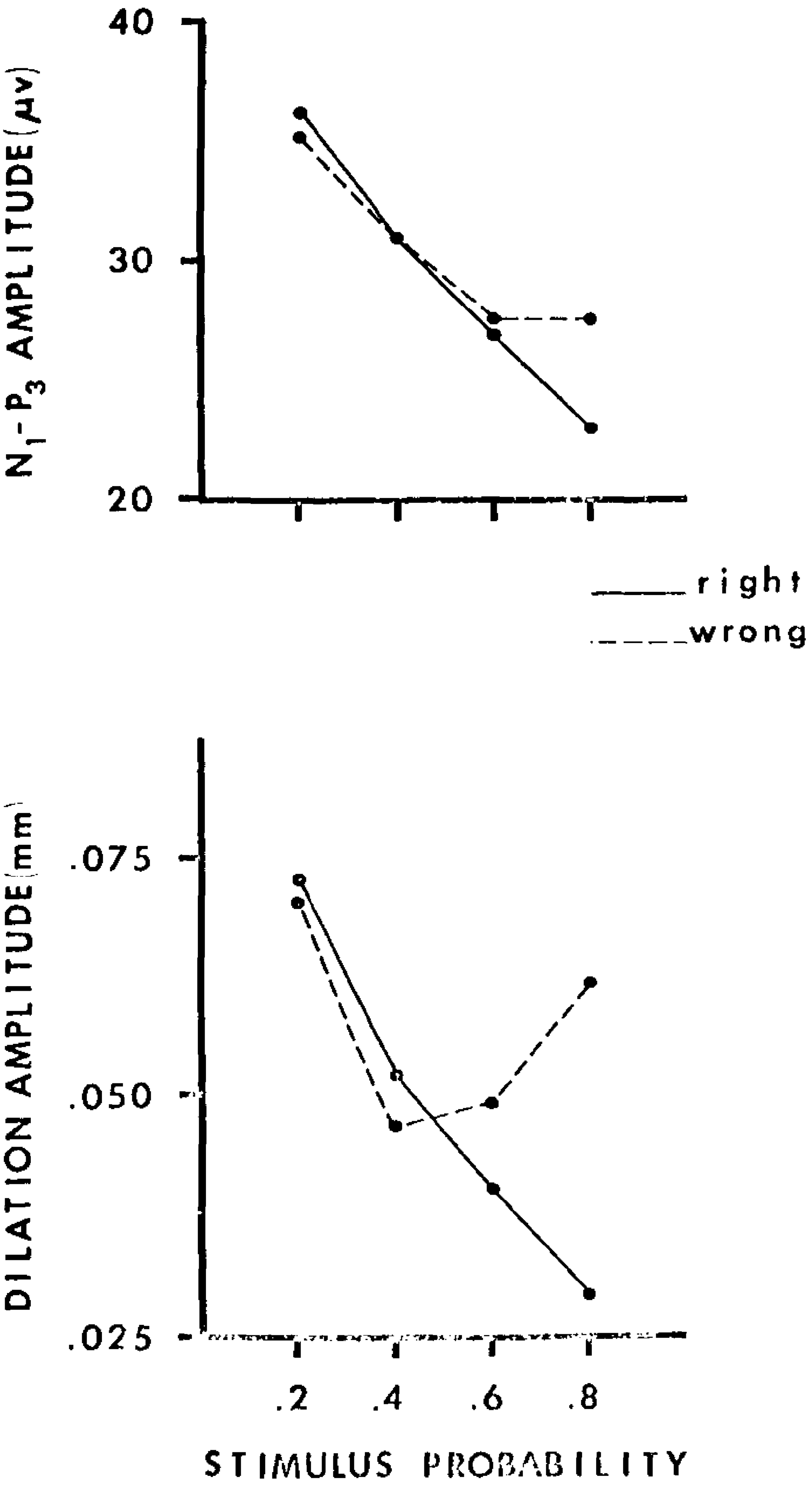
	80%S	20%D	
Correct	.053	.086	.069
Incorrect	.078	.093	.086
	.066	.089	

both N_1-P_3 and peak dilation data ($p < .01$), and indicated that both stimulus probability functions produced approximately the same mean amplitudes at each stimulus probability point.

Neither the outcome of the guess, nor the type of stimulus was significant for either the N_1-P_3 or pupillary data. The triple interaction of frequency by guess by stimulus was significant ($p < .05$): the relationship between amplitude of N_1-P_3 and stimulus probability was affected by the outcome of the guess only at the extreme frequencies (20/80 and 80/20), but not at the intermediate frequencies (40/60 and 60/40). At the extreme frequencies, wrong outcomes were associated with larger N_1-P_3 amplitudes at the 80 percent probability points, but not at the 20 percent probability points. No such relationship existed for the intermediate probabilities. The triple interaction for the pupillary data was similar ($p < .05$) except that, in addition, there was a weaker effect of outcome on the relationship between peak dilation amplitude and stimulus probability at one of the intermediate frequencies (40/60, but not 60/40). Here too, wrong outcome was associated with a somewhat larger amplitude for the 60 percent probability point, but not for the 40 percent probability point.

<u>Right - wrong differences as a function of stimulus probability</u>. The interaction effect discussed above can be seen clearly when one collapses across stimuli and plots N_1-P_3 and peak dilation amplitude as a function of stimulus probability separately for hits and misses (Figure 14). While the pupillary data exhibited this effect more strikingly, the N_1-P_3 data showed the same trends. Both responses diverged at the 80 and 20 percent stimulus probability, but in the case of N_1-P_3 there was little divergence at the 40 or 60 percent points. The largest difference for both occurred at the 80 percent probability point.

Figure 14. Mean N_1-P_3 and peak dilation amplitudes for right and wrong outcomes, plotted as a function of stimulus probability.


40
30
20
N_1-P_3 AMPLITUDE (μv)
right
wrong
.075
.050
.025
DILATION AMPLITUDE (mm)
.2
.4
.6
.8
STIMULUS PROBABILITY

The analyses of variance did not provide data on the significance of differences between right and wrong outcome amplitudes at each stimulus probability point. Therefore, t-tests for correlated means were employed. At the 80 percent point, being incorrect led to a larger mean N_1-P_3 amplitude than being correct ($p<.01$). Being incorrect led to larger mean peak dilation amplitudes at both 60 and 80 percent points than being correct ($p<.05$, and $p<.01$ respectively). From these results, it appears that the rarer the event, the larger the amplitude of response. That is, for example, being incorrect on the 80 percent stimulus is a much rarer event than being correct on the 80 percent stimulus. Although not all the right-wrong differences were significant, the general shape of the curves for both N_1-P_3 and peak dilation (with the exception of the 40 percent point for N_1-P_3)shows that amplitude is larger the rarer the outcome.

Odd Minus Even Variability Estimates for N_1-P_3 and Peak Dilation

Table 2 presents these estimates as a function of outcome probability for peak dilation, and Table 3 presents the estimates for N_1-P_3. In both pupillary and evoked potential data there is a general trend for variability to decrease with increasing outcome probability for both right and wrong outcomes. This is probably due to the fact that there are more trials in the average as outcome probability increases, and with increasing N, the odd minus even error will naturally decrease.

Since the data could also be viewed as a function of stimulus probability and S's guessing probability, odd minus even variability estimates were computed for these data points by weighting the odd-minus even estimates by their cell Ns. These estimates appear in Table 4 for peak dilation and in Table 5 for N_1-P_3. For both pupillary dilation and N_1-P_3 amount of variability is similar across both stimulus and guessing

TABLE 2

Odd Minus Even Variability Estimates for Peak Dilation for Eight Subjects as a Function of Outcome Probability[1]

Peak Dilation (mm)

Subject	Right				Wrong			
	1	2	3	4	1	2	3	4
WC	.009	.019	.005	.004	.013	.005	.001	.011
SP	.006	.006	.008	.011	.008	.013	.006	.008
BR	.029	.008	.013	.001	.008	.006	.008	.005
MK	.006	.004	.010	.005	.015	.008	.006	.009
CB	.015	.015	.014	.004	.019	.020	.013	.008
GB	.016	.018	.008	.004	.035	.008	.015	.013
SS	.019	.014	.001	.004	.003	.008	.010	.008
PK	.003	.004	.009	.005	.009	.006	.001	.008
$\bar{X}$	.013	.011	.009	.006	.009	.006	.001	.008

---

[1] Numerical headings represent magnitudes of outcome probabilities, from smallest (1) to largest (4).

TABLE 3

Odd Minus Even Variability Estimates for N_1-P_3 for Eight Subjects as a Function of Outcome Probability

Subjects	N1-P3 (uv)							
	Right				Wrong			
	1	2	3	4	1	2	3	4
WC	5.625	0.750	1.310	0.560	3.750	2.250	1.500	1.500
SP	10.000	2 630	2.630	1.500	1.690	2.250	0.940	0.750
BR	3.560	0.940	2.440	1.680	9.560	1.880	1.500	4.500
MK	6.440	5.100	2.100	1.830	3.000	3.400	0.560	1.690
CB	4.870	3.940	1.310	0.750	2.810	0.940	0.940	1.310
GB	4.690	2.100	1.310	0.560	2.810	1.200	2.100	1.120
SS	1.690	0.560	0.560	0.750	1.310	5.250	2.250	0.750
PK	2.630	1.880	2.630	1.500	1.880	0.560	1.500	2.630
$\bar{X}$	4.930	2.240	1.780	1.140	3.350	2.210	1.410	1.780

TABLE 4

Odd Minus Even Variability Estimates for Peak Dilation for Eight Subjects as a Function of Guessing and Stimulus Probability

Subject	Stimulus Probability				Guessing Probability[1]			
	.20	.40	.60	.80	.20	.40	.60	.80
WC	.011	.015	.003	.005	.005	.008	.008	.006
SP	.007	.003	.007	.012	.012	.006	.005	.011
BR	.009	.006	.010	.003	.016	.007	.009	.009
MK	.012	.007	.009	.006	.007	.005	.009	.007
CB	.017	.014	.011	.007	.018	.011	.013	.006
GB	.010	.016	.009	.008	.027	.014	.010	.004
SS	.007	.010	.004	.004	.010	.012	.003	.003
PK	.007	.006	.006	.005	.005	.002	.008	.006
$\bar{X}$	.010	.009	.007	.006	.013	.008	.009	.006

[1] Numerical headings refer to the probability of the stimulus event that was guessed.

TABLE 5

Odd Minus Even Variability Estimates for N_1-P_3 for Eight Subjects as a Function of Guessing and Stimulus Probability

Subject	Stimulus Probability				Guessing Probability			
	.20	.40	.60	.80	.20	.40	.60	.80
WC	4.100	1.150	1.560	0.900	2.550	1.410	1.400	1.230
SP	4.340	1.600	1.800	4.400	4.150	1.440	1.900	4.430
BR	4.650	3.130	2.100	2.500	5.170	1.240	3.270	2.280
MK	4.350	3.140	1.600	2.060	4.610	2.500	1.920	2.010
CB	3.500	1.850	1.300	0.810	1.950	2.450	1.140	1.130
GB	2.450	1.900	1.300	0.910	3.610	1.600	1.490	0.660
SS	1.420	0.640	1.150	1.640	4.250	1.540	0.620	0.540
PK	2.160	2.320	1.860	1.500	1.800	1.170	2 600	1.570
$\bar{X}$	3.370	2.000	1.600	1.840	3.510	1.670	1.800	1.730

probabilities. Again, variability decreases with an increase in either stimulus or guessing probability.

Odd minus even variability estimates were also obtained for baseline shifts (CNV), and these appear in Table 6 as a function of stimulus and guessing probability. Variability again decreases with increases in probability, but this trend is not as marked for CNV as it was for the other response measures.

Latency Analyses for Evoked Potential Components and Peak Dilation

Latencies for right versus wrong responses were tested using the t-test for correlated means. The peak amplitude of the P_3 component occurred earlier for right than for wrong responses only at the 20 percent stimulus probability ($p<.01$). No other difference for any evoked potential component or peak dilation reached the conventional level of statistical significance.

By collapsing across right and wrong, certain versus uncertain latency differences could be tested for significance. N_2 peaked significantly later ($p<.01$) in the certain condition than in the uncertain condition. The only other difference that was significant was for the peak of P_2, which occurred later in the certain condition than in the uncertain condition at the 60 percent probability point ($p<.05$).

In the certain condition, only four Ss had produced detectable peak dilations, and thus only their data could be used to test the differerence between mean peak dilation latency in the certain and uncertain conditions. None of these differences reached significance. In the uncertain condition mean peak dilation decreased in latency as a function of increasing stimulus probability. This trend, as measured by slope analysis, was highly significant (mean slope = -175.00, $p<.01$). No evoked

TABLE 6

Odd Minus Even Variability Estimates for CNV Amplitude for Eight Subjects as a Function of Guessing and Stimulus Probability

Subject	Stimulus Probability				Guessing Probability			
	.20	.40	.60	.80	.20	.40	.60	.80
WC	2.700	1.900	1.310	1.330	3.200	0.840	2.141	1.140
SP	2.920	4.200	3.600	2.720	4.000	0.580	2.120	0.600
BR	1.400	1.900	0.730	1.950	2.920	1.500	1.000	1.540
MK	4.300	1.710	0.910	0.520	1.130	2.000	0.750	1.310
CB	1.200	0.900	1.660	1.100	1.600	0.990	1.600	1.000
GB	0.250	2.000	1.250	2.230	3.640	1.900	1.300	1.420
SS	2.500	3.400	3.400	1.100	2.640	1.700	4.300	1.060
PK	3.340	2.400	2.060	0.400	1.520	2.400	2.120	0.800
$\bar{X}$	2.320	2.300	1.860	1.420	2.580	1.500	1.650	1.110

potential component evidenced a similar trend in either certain or uncertain conditions, nor did peak dilation in the certain condition ($p > .05$).

One further latency analysis was carried out. In a previous section, the effect of outcome probability upon the evoked potential was shown to be localized in the N_1-P_2 component for four Ss, and in the N_2-P_3 components for the remaining four. If the evoked potential is the central event leading to peak dilation, then it might be expected that those Ss exhibiting N_1-P_2 effects would produce earlier peak dilation latencies, than those Ss exhibiting N_2-P_3 effects. In order to investigate this, mean peak dilation latencies for right and wrong outcomes for the Ss showing N_1-P_2 effects, and for the Ss showing N_2-P_3 effects, were compared and shown to differ in the expected direction, but not significantly.

Fifty Percent Probability

On Day 1, six Ss were run on a 50/50 probability program of 450 trials duration, separated into sessions of 150 trials each (100 uncertain and 50 certain trials). WC and PK were also run on a 50/50 program, but because of blinking, their data were not usable for the following analyses.

Since Ss varied in the probabilities with which they guessed either of the two 50 percent stimulus events, it was possible to compute outcome probabilities for the 50/50 data. In order to determine if outcome probability affected amplitude of response, a proportional measure of amplitude was used. Each S's data for the 2 msec. inter-click-interval stimulus when the guess was correct, was divided by a weighted amplitude obtained for the 4 cells of the probability table. When N_1-P_3 and peak dilation amplitude were plotted as a function of outcome for each S, no trend in the data points was evidenced.

Even though this procedure yielded negative results, an attempt was made to use the 50/50 weighted average amplitudes as a correction for the N_1-P_3 and peak dilation amplitudes obtained for the main experiment. Each S's outcome amplitudes were divided by his 50/50 weighted amplitude. If inter-S differences were due primarily to level differences amongst Ss, then this correction would tend to bring the individual curves closer together. For N_1-P_3 this correction procedure did result in the individual curves being brought slightly closer together. This effect was greater for misses than it was for hits. However, when the pupillary outcome amplitudes were subjected to this procedure, the resulting curves were not so effected. Since the entire 50/50 program was run on a single day, a variety of variables could not be controlled by counterbalancing, as was the case for the remaining four programs. This may have accounted for the unsuccessful control procedure. Furthermore, when an attempt was made to plot the 50/50 data with the outcome probability functions, the 50/50 data were always of greater amplitude, suggesting that habituation (from days 2 through 5) accounted partially for this result.

One other important point with respect to the 50/50 data was whether or not a systematic difference had developed between right and wrong responses. Since this probability condition contained maximum uncertainty, this finding would serve as a baseline for those probabilities in which S could form expectancies as to which stimulus would occur. These results appear in Table 7. The data for each S are averaged across the two stimuli. Except for one S, BR, none of the differences is large in either direction, and the mean differences were not significant for either measure.

TABLE 7

Right and Wrong N_1-P_3 and Peak Dilation Amplitudes for Six Subjects for the Fifty-Fifty Condition

Subject	N_1-P_3		Peak Dilation	
	Right	Wrong	Right	Wrong
SP	11.91	13.63	.007	.016
BR	52.21	38.94	.073	.055
MK	25.82	23.85	.032	.037
CB	20.41	20.82	.067	.070
GB	18.08	17.78	.037	.030
SS	25.44	22.72	.027	.024
$\bar{X}$	25.64	22.72	.040	.038

Sequential Analysis of a Single Probability

While both evoked potential and peak dilation showed similar relationships to the probability measures, the analyses employed did not cast light on whether one of these responses is dependent on the other. Thus, it might be suspected that peak dilation, which occurs about a half-second after the evoked potential components of interest, might be a result of the evoked potential changes. In order to shed some light on this question, the 80 percent probability for hits only was chosen for further investigation, since it allowed the breakdown of the data into sequential averages over the entire four days of running. For this analysis, the data from five Ss were employed. Only those Ss who showed consistent CNV and pupillary dilation were used. This criterion eliminated the data for GB, PK and SP.

Since deciding on the number of trials to use in a sequential average is arbitrary, it was decided to use the smallest N per interaction cell, which turned out in all cases to be one of the 20 percent right cells. Such a choice also permitted this analysis to reflect on the question of whether or not the number of data samples per average was affecting amplitude of response. This could be done by verifying that the amplitude for the 20% right cell was always larger than any of the 80% sequential averages, which was composed of the same number of trials. By this method, it was confirmed that the number of trials in the average did not influence the results. In all cases, the sequential 80 percent hit average amplitudes were smaller than the 20 percent hit average amplitudes.

Intercorrelations of the sequential averages for the following were determined for each S: N_1-P_3, CNV, peak dilation, and initial diameter. These appear in Table 8. Within the matrix of thirty correlations, no

TABLE 8

Intercorrelations of N_1-P_3, CNV, Initial Diameter, and Peak Dilation Computed for Each Subject Across Days of Running

	N_1-P_3/PD*	N_1-P_3/ID*	N_1-P_3/CNV	ID/PD	ID/CNV	PD/CNV
Subject WC	.719	-.679	.093	-.518	-.276	.325
Subject BR	.232	.116	-.004	.177	.116	.484
Subject MK	.008	.589	.410	.120	.370	.251
Subject CB	-.132	.631	.123	-.836	-.631	.473
Subject SS	-.732	.295	-.833	-.440	-.587	.558

*PD = peak dilation

*ID = initial diameter

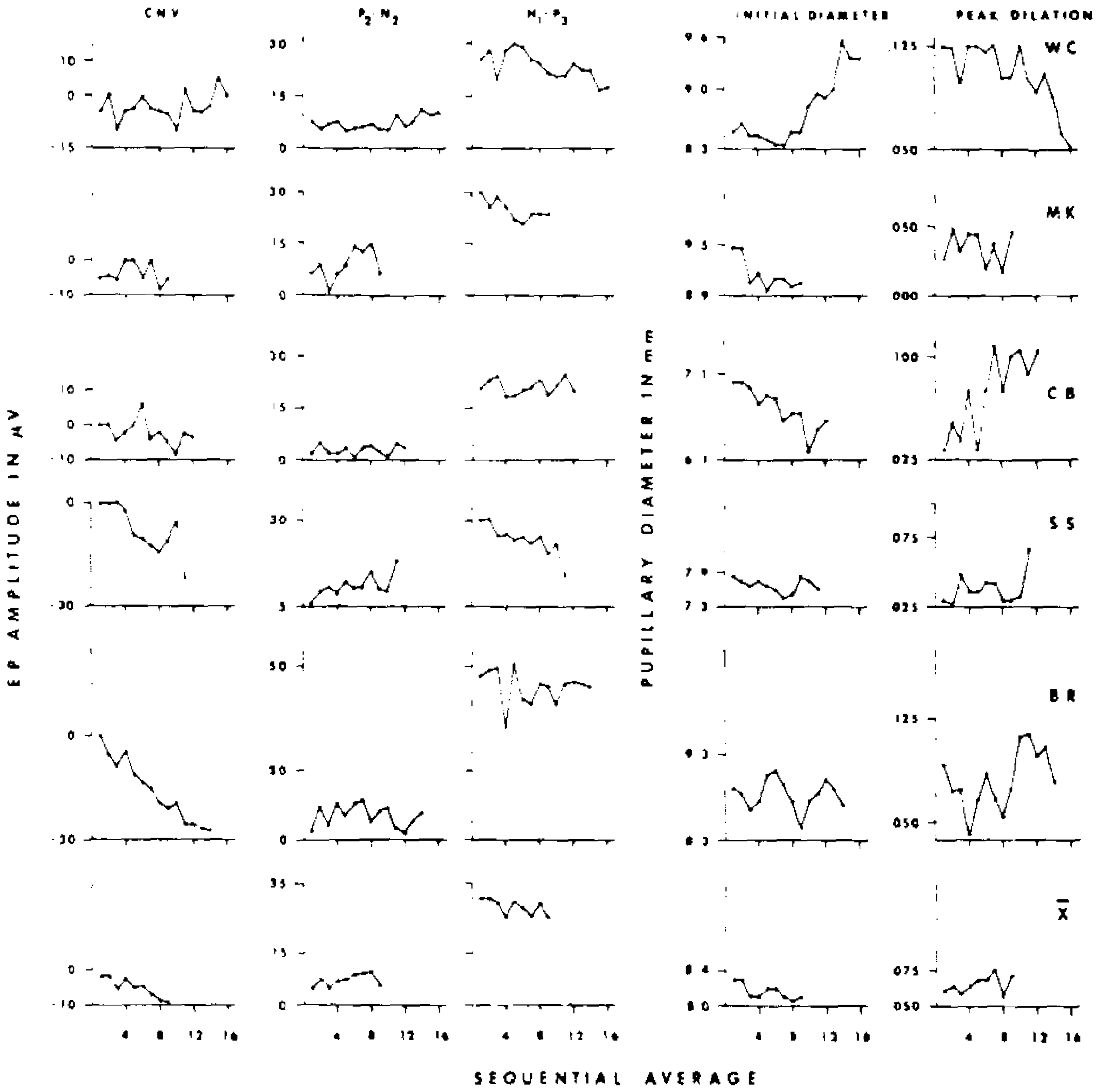
clear trends emerged. The correlation of CNV with dilation amplitude produced the most consistent result-peak dilation was greater when there was more negative shift. Another fairly consistent result was the finding of three out of five negative relationships between initial diameter and subsequent peak dilation (i.e., smaller peak dilations when initial diameter was larger). This appeared to follow the Law of Initial Value. There were no consistent relationship between N_1-P_3 amplitude and any other variable.

These correlations gave no indication of what was occurring over time for each of the above variables. Therefore, these measures were plotted individually as a function of time, and are presented in Figure 15.

Friedman two-way analyses of variance were used to test significance. Each S had a different number of trials in the sequential average, and the total number of averages was also different for each S. Therefore, the first nine sequences were used, since nine was the number of sequential averages each S had in common.

N_1-P_3 and initial diameter tended to show a decrease in four of the five Ss, but this trend was not significant in the averaged data ($p > .05$). The P_2-N_2 component of the evoked ptoential demonstrated increasing amplitude over days in most Ss, and this was significant in the averaged data ($p < .02$). Peak dilation did not evidence any clear trend ($p > .05$), except for one S, WC, for whom peak dilation increased over days. Data for CNV were variable across Ss, and produced no consistent trend ($p > .05$).

Figure 15. CNV, P_2-N_2 and N_1-P_3 amplitudes in microvolts, and initial diameter and peak dilation amplitude in millimeters, plotted as a function of successive averages of N trials each over the four days of running. The experimental contingency analyzed was the correct prediction of the 80% event.


CNV
P2-N2
N1-P3
INITIAL DIAMETER
PEAK DILATION
WC
MK
CB
SS
BR
X̄
EP AMPLITUDE IN μV
PUPILLARY DIAMETER IN mm
SEQUENTIAL AVERAGE
4
8
12
16

CHAPTER IV

DISCUSSION

The evoked potential results confirmed Tueting (1968) in finding that the P_3 component (N_2-P_3; N_1-P_3) increased systematically as a function of the rareness of the event in both certain and uncertain conditions. The clearest effect was found for outcome probability, but only for trials associated with correct guesses. The trials associated with wrong guesses were generally characterized by greater variability within and across Ss. The major new finding was that the averaged peak pupillary dilation also followed all of the above relationships, except in the certain condition, where dilation was unrelated to stimulus probability. In addition, the increase of pupillary diameter with rareness of the event held for trials associated with wrong guesses. The uncertain condition produced larger amplitudes than the certain condition at all probabilities for N_2-P_3, P_3-N_3, and N_1-P_3 of the evoked potential, and for averaged peak pupillary dilation.

The N_1-P_2 component decreased in amplitude with an increase in outcome probability (when S was right). Inspection of the data for individual Ss showed that these average effects were somewhat misleading. Four Ss showed the major effects of probability in N_1-P_2 and little in N_2-P_3, while the other four Ss showed the major effect in N_2-P_3, and little in N_1-P_2. It was such differences among Ss which made the results most consistent for the N_1-P_3 measure, which spans both components.

The two measures of activity obtained prior to the occurence of the stimulus, CNV and pre-stimulus pupillary amplitude, were both larger in the uncertain than in the certain condition. They did not vary as a function of guessing probability, nor was either measure related to either N_1-P_3 amplitude or peak pupillary dilation amplitude.

No evidence of habituation over the course of the four-day running was found for any evoked potential component, except for an increase in P_2-N_2 amplitude over the course of the experiment. The 50/50 condition produced no differences between hits and misses, nor was there any systematic influence of small variations in outcome probability.

Uncertainty Versus Certainty

Components N_1-P_2, N_2-P_3, and N_1-P_3 were significantly larger in the uncertain condition than in the certain condition, while components P_1-N_1 and P_2-N_2 showed the reverse amplitude difference. Peak pupillary dilation was larger in the uncertain than in the certain condition. CNVs tended to be more negative in the uncertain condition, with positive shifts associated with the certain condition. Pre-stimulus pupillary slope appeared to parallel CNV activity, in that certainty was associated with constriction and uncertainty with dilation. These differences were not clear-cut in all <u>S</u>s, and although it seemed as if CNV were correlated with both the peak dilation and N_1-P_3 differences between certain and uncertain conditions, two <u>S</u>s who demonstrated marked N_1-P_3 and peak dilation differences, showed no certain-uncertain CNV differences.

The findings for the certain and uncertain conditions appear to reflect a difference in physiological state arising from the difference in task. <u>S</u> involvement was greater in the uncertain condition. Most <u>S</u>s reported in informal, post-experimental interviews, that they were "bored" during the certain condition, and much more alert and interested during the uncertain condition. It has been shown that the P_2-N_2 component is larger in the certain than in the uncertain condition. Peak N_2 has been shown to increase with decreasing vigilance (Wilkinson, Morlock and Williams, 1966) as well as to increase over the various stages of sleep (Weitzman and Kremin, 1965; Williams, Tepas, and Morlock, 1962).

The finding of greater CNV negativity in the uncertain condition than in the certain condition is in general agreement with those researchers who obtained larger amplitude CNVs in more arousing situations (Connor and Lang, 1969; Low _et al._, 1967; Tecce and Scheff, 1969), and in uncertain situations where _S_ had to make a prediction (McAdam _et al._, 1967; Weinberg, Walter and Crow, 1970). CNV has also been shown to decline in amplitude over the course of a vigilance experiment, and this decline was correlated with a decrease in signals detected (Wilkinson and Haines, 1970). Arduini (1958) obtained negative shifting at cortex upon reticular formation stimulation, and Caspers (1963) found negative shifting to occur with increases in arousal. In the certain condition, positive shifts were seen. Positive shifts have been obtained by Caspers (1963) when his _Ss_ were falling asleep, and by Connor and Lang (1969) in drowsy _Ss_.

The pupillary response was characterized by the presence of a phasic component (dilation) in the uncertain condition, compared with little or no dilation in the certain condition. Since the certain condition was associated with complete knowledge of stimulus events, no change in the phasic component should be expected. Even though initial diameter (the tonic component) was smaller in the certain case, this smallness was not accompanied by a change in peak dilation (i.e., if the Law of Initial Value were operative). Instead, larger peak dilation were associated with larger initial diameters. Presumably the larger initial diameter was associated with increased sympathetic activity and inhibition of parasympathetic activity via the oculomotor nucleus.

Effects of Stimulus and Guessing Probability

The finding of amplitude decrease as a function of probability for a number of components of the evoked potential and for the peak dilation component of the pupillary response is reminiscent of findings for other systems. Lovibond (1969) employing GSR, found greater response decrement occurring to stimuli with the greatest probability of occurrence. Higgins (1971), using heart rate as a response measure, found significantly more deceleration associated with increases in stimulus uncertainty, and Pratt (1970) obtained greater pupillary dilation to stimulus characteristics that were unexpected. Evoked potential studies have shown smaller amplitude evoked potentials when stimuli were most predictable (e.g., Brazier, 1967; Fox, 1964).

The finding of increased amplitude of the N_2-P_3 and N_1-P_3 components in the certain condition with a decrease in probability would, however, be difficult to reconcile with this discussion, since all events in this condition were 100 percent certain. Tueting _et al_. (1971) obtained the same relationship between 0-P_3 amplitude and probability for the certain condition, and made an attempt to explain it partially in terms of refractoriness. She used inter-stimulus-intervals of 5 to 7 sec., somewhat less than optimal for recovery of the auditory evoked vertex potential according to Davis _et al_. (1966). In the present study inter-stimulus-intervals of more than 10 sec. were used to insure that findings would not be confounded by recovery time, and the inverse relationship between P_3 amplitude and probability in the certain condition was still obtained.

Thus, this finding is probably not due to inadequate recovery time, but perhpas, to "relief from boredom", or "novelty" generated by a rare event, even when that event is completely known (Tueting *et al.*, 1971). Further, *Ss* reported that the certain condition was boring, and may have played their own games, such as guessing when a particular event would occur(see MacKay, 1969; and Sutton, 1969 for a discussion of this point).

Amplitude of Response as a Function of Outcome

Amplitude of N_1-P_2, N_2-P_3, P_3-N_3 and N_1-P_3 decreased monotonically and significantly as a function of outcome probability when *S* was right, but not when *S* was wrong. The steepest slope was found for N_1-P_3. The effects of outcome probability were *S*-dependent, affecting either N_1-P_2 or N_2-P_3 but never both equally (when *S* was right). This accounted for the large N_1-P_3 decrease, since this overall measure spans both the N_1-P_2 and N_2-P_3 components. For peak dilation, amplitude decreased monotonically for both hit and miss outcome probability, although the function for misses was more irregular than that for hits.

Although N_1-P_3 did not produce a statistically significant inverse slope when *S* was wrong, this value approached significance ($p < .10$), so that differences between peak dilation and N_1-P_3 for wrong outcomes were probably more apparent than real, and were most likely due to the tremendous variability associated with wrong outcomes both within and between *Ss*. One possible reason for this greater variability is the fact that since *S* knew the a priori probabilities, he would be right more often than wrong. This led to an artificial constriction of probabilities when *S* was wrong (e.g., the averaged wrong outcome probabilities varied from .138 to .245, a range of only .107, and this range is considerably larger than the ranges produced by some Ss), compared to an average probability range of .060 to .624 (range of .564) when S was right. Assuming that the relationship between amplitude and outcome probability was linear (as it appears to be from the individual plots of right outcomes), this restricted range of probability values for wrong outcomes may not have allowed enough variation in either response system for the function relating amplitudes and outcome probability to take on any consistent shape.

The question being dealt with here is the same as that asked in a number of studies of the "threshold problem" (Sutton, 1969): is the evoked potential sensitive to subtle changes in a psychological variable or is S himself aware of such changes. Sutton (1969) concluded that "..the human organism, even under highly controlled conditions, cannot be made to follow a strict isomorphism between stimulus and psychological events" (p.239). In other words, can an outcome probability of .100 be perceived as different (either in behavioral or electrophysiological terms) from one of .120?

Right-Wrong Differences as a Function of Stimulus Probability

The results of the t-tests between hit and miss evoked potential and peak dilation amplitudes for stimulus probability provided support for a possible psychological mechanism accounting for the diminution of response over probability. When hits were compared with misses at the same objective stimulus probability, miss amplitudes produced different functions than did hits, and this effect was more striking for the pupil. Missed amplitudes at the 60 and 80 percent stimulus probability points for peak dilation, and at the 80 percent point for N_1-P_3, were significantly larger than hit amplitudes. These results suggest an explanation in terms of surprisal (Attneave, 1959) of an event. In the present case, since the probability for both right and wrong functions was the same at each point, surprisal as Attneave (1959) explains would have to be defined in psychological terms -- not as a simple function of the objective probability of an event, but dependent upon that particular event's probability relative to the probabilities of other events. Thus, while being correct on an 80 percent event is not surprising, being wrong on that same probability event is, since the occurrence of this contingency is relatively rare. Although not all differences were significant, the general trend for rare outcomes to yield larger-amplitude responses seemed to hold for both the pupil and the evoked potential. Tueting _et al_. (1971) employed the same analysis for their data, and the data from the present experiment tend to confirm that analysis.

The fact that the 50/50 data yielded non-significant right-wrong differences coupled with the absence of an outcome probability effect, points out the importance of _S_'s expectancy as it affects amplitude of response. Most _Ss_ indicated that the 40/60 and 60/40 manipulations were very much like the 50/50 configuration, in that there was no way of accurately predicting events (i.e., developing an expectancy). It appears, therefore, that _Ss_ must have some basis for the differential prediction of events, before the relationship between outcome probability and amplitude of response appears. It would be interesting to employ probability programs in which _S_ is not informed of the a priori probabilities, in order to determine when in the learning process amplitude of response would be affected.

CNV and Pre-Stimulus Pupillary Slope

Neither CNV, nor pre-stimulus pupillary slope varied significantly as a function of guessing probability. Pre-stimulus pupillary slope has not been investigated before, so that data directly comparable to this experiment do not exist. However, Levine and Hakerem (1969) have obtained a large difference between certain and uncertain conditions in a pupillary component similar to the present slope component.

The results of probability manipulation on CNV amplitude do not support the findings of Wilkinson and Haines (1970) who obtained smaller CNV amplitudes to signal stimuli with a low probability of occurrence in a vigilance task, as compared with CNV amplitudes to signal stimuli with a high probability of occurrence. In a number of studies, the effects of probability dilution on CNV amplitude was studied by randomly omitting a predetermined percentage of S2s. The effect on CNV amplitude was then assessed by averaging all stimulus events, regardless of whether or not S2 had occurred. The general finding was that CNV amplitude was reduced as the probability of S2 occurrence was lowered. For the present study to be comparable to the "probability dilution" studies of Low _et al_. (1966), Hillyard and Galambos (1967), and Walter _et al_.(1964), the CNV amplitude of an _entire_ probability program (i.e., 20/80) must be considered. These amplitudes were determined, resulting in four overall CNV amplitude values for each _S_ (one for each probability program). According to the analysis of Grey Walter (Walter _et al_., 1964), CNV should have been smaller for the programs with the greatest overall uncertainty (i.e., 40/60 and 60/40). T-tests were run to test the differences between the 20/80 and 40/60 mean CNV amplitudes, and between the 80/20 and 60/40 mean CNV amplitudes. Neither t-value was significant. These results support those of Hillyard and Galambos (1967), who found no effect of dilution on CNV amplitude, and contradict those of Low _et al_.(1966), and Walter _et al_. (1964). However, the experimental paradigms used in those studies differed from the present study, and in that respect the data are not directly comparable. The employment of the S1-S2 - R paradigm (the Grey Walter paradigm) in a guessing situation when dilution is in effect has not beeninvestigated.

CNV and the notion of predictability of events. Even though probability manipulation created expectancies about future stimulus events, the number of times an event was repeated or alternated was not controlled. For example, manipulating the percent occurrence of a single click following a single click (repetition), or a single following a double (alternation), gives S a much more restricted way of making his predictions. Weinberg *et al*. (1970) found CNV to occur only on those trials when Ss expected an event to occur, and not on trials when no expectation was indicated. Naatanen (1970) obtained CNV only when the delivery of relevant stimuli could be accurately predicted. For the present experiment, it is difficult to say whether CNV occurred to all predicted events, or selectively to events that S predicted with certainty (i.e., that S definitely expected). However, when S guessed the 80 percent event he was guessing with more certainty than when he guessed the 20 percent event, and CNV amplitudes for these two predictions did not differ significantly. Further, since CNVs were recorded in all four cells of Ss' 2x2 probability tables, it appears that CNV occurred with all predictions. Nevertheless, the problem of covert expectation cannot be ruled out as a possible confounding factor.

To the extent that any average contains a preponderance of trials in which S was fairly certain about his predictions, then we might expect CNV to be large; to the extent that the average contains a preponderance of trials on which S was not sure of his predictions, we might expect CNV to be of lowered amplitude. Thus, we might be averaging physiological events of vastly different psychological meaning. One way to examine this problem is to have S employ a criterion in predicting, and indicate his degree of certainty about his prediction prior to each trial. Then, averaging would be done by criterion of prediction.

The most compelling argument against the notion that high predictability is associated with large CNVs is provided by the comparison of the certain and uncertain conditions of this experiment. Here, the uncertain condition yielded significantly larger CNVs -- exactly the opposite of the probability dilution literature. While the use of guessing in the present experiment does not allow direct comparison of results with the Grey Walter paradigm, it does argue strongly against the predictability interpretation of these data.

Relation of the CNV to evoked potentials and pupillary dilation. Both pupillary dilation and the evoked potential have been shown to increase in amplitude under conditions which make a response task relevant (e.g., Hakerem and Sutton, 1966; Sheatz and Chapman, 1969; Simpson, 1969; Simpson and Hale, 1969), and when selective attention is required (e.g., Donchin and Cohen, 1967; Donchin and Smith, 1970; Smith, Donchin, Cohen and Starr, 1970). In both cases, S is required to make a response, either motor or mental, to a particular stimulus of a total stimulus configuration. The mechanism by which evoked potential enhancement occurred (in studies in which relevant and irrelevant stimuli alternated) has been explained away by Karlin (1970) and Naatanen (1967, 1970) on the basis of alternation of attention produced by accuracy of prediction of when the relevant stimulus would occur, and is based on Naatanen's (1967, 1970) failure to find evoked potential enhancement or CNV to relevant or irrelevant stimuli when the stimuli were randomly presented.

In this study, stimuli were randomly presented and evoked potential enhancement (N_1-P_3) did occur from certain to uncertain conditions (while CNV became more negative), thus supporting the conclusion that the difference between these two conditions was due to differences in arousal or activation. However, evoked potential enhancement occurred under conditions where CNV remained at the same amplitude (as in the uncertain guess and stimulus probability functions), and even in those Ss who produced no CNV activity at all, thus contradicting the arguments proposed by both Karlin (1970) and Naatanen (1967, 1970) that "preparatory cortical activation" (as evidenced by CNV) is responsible for evoked potential enhancement. The pupillary data lead to the same conclusion. Peak dilation enhancement occurred when the cortical potential shifted in a negative direction as well as in those Ss who produced no CNV. In further support of the present findings, Eason et al. (1969) and Tueting (1968) did find evoked potential enhancement to relevant stimuli when preparatory activation was precluded by randomly presenting the stimuli.

From the present results, it appears as if CNV is the cortical representation of attentive state, but does not reflect changes along a graded psychological continuum (i.e., expectancy). Something other than the very general state of S is accounting for changes in the two response systems as a function of probability.

Orienting as an Explanatory Model

Sokolov (1960) has talked of orienting responses to stimuli that carry information (i.e., uncertain events), and so has Brazier (1967), who states: "...novelty, the unexpected, should convey the most information, whereas repetition of a completely predictable experience would convey none at all" (p . 340). When S makes a prediction as in the present study, it is based on past experience, on information stored in the nervous system. If the event which is presented was expected, the "neuronal model" (no matter what its physiological basis) is matched; if unexpected, an orienting response takes place. This type of analysis can be applied to the Weinberg et al. (1970) study, in which an "emitted potential" (i.e., phantom wave), with positive peak at P_3 latency, occurred only when an event was predicted and did not occur. Similar findings have been reported by Sutton et al. (1967), by Klinke, Fruhstorfer, and Finkerzeller (1968), as well as by Levine and Hakerem (1969). In the latter study, a "phantom dilation" was present when Ss predicted a triple click would occur, but received a double click.

These findings suggest, as have the findings of other investigators (e.g., Haider, Groll, and Studynka, 1968; Lynn, 1966; Mackworth, 1968; Pribram, 1967; Sokolov, 1960) that a basic function of the CNS is the comparison of incoming information with information already stored in memory. This comparison is then extrapolated with respect to future stimulus events. Mackworth (1968) has pointed out that expectancy of an event can profoundly alter the response to that event. In the present study, Ss have information about the probability associated with an event, and are predicting future events. As the outcome probability findings demonstrated, the more unexpected the outcome of the prediction, the larger the amplitude of response.

Habituation

The fact that the N_1-P_2 component has been localized in primary auditory cortex (Vaughan and Ritter, 1970), in conjunction with the fact that N_1-P_2 reflects the physical parameters of the stimulus (e.g., Davis and Zerlin, 1966; Rapin, Schimmel, Tourk, Krasnegor, and Pollak, 1966), might lead one to predict that habituation of the N_1-P_2 component should have occurred in the present experiment. However, there was no decline in N_1-P_2 amplitude as a function of stimulus probability in the certain condition, and this fact militates against an interpretation in terms of habituation. The P_3 data are also difficult to interpret in terms of habituation due to P_3's long latency and the fact that it is correlated with nonsensory factors.

Whether or not habituation of sensory evoked potentials occurs is open to question (see Thompson and Spencer, 1966). Nevertheless, many investigators have reported habituation of the N_1-P_2 component of the auditory evoked potential (recorded from C_z) upon repreated presentations of the same stimulus (Fruhstorfer, Soveri, and Jarvihleto, 1970; Roth and Kopell, 1969; Weber, 1970). This problem is complicated by the fact that an increase in repetition rate generally results in reduced response amplitude, which has been interpreted in two ways (Tueting, personal communication): 1) a decrease in recovery time; 2) an increase in habituation. For example, Fruhstorfer et al. (1970) describe the increased habituation of averaged evoked potentials to stimuli presented at a rate of one per sec., as compared with stimuli presented at a rate of one per three sec., when, in fact, what has been varied is recovery time.

The confusion between recovery or refractoriness and habituation has been discussed by Ritter et al. (1968). They found a decrement in N_1-P_2 amplitude from the first to the last stimulus in a series, when a repetition rate of one stimulus per two sec. was used. When the repetition rate was changed to one stimulus every ten sec., no such reduction in amplitude was obtained. Further, they demonstrated that the reduction in amplitude with a fast repetition rate was not habituation of response, since an unexpected pitch change (interpolated within the stimulus series) did not lead to an increase in N_1-P_2 amplitude (dishabituation), but instead produced a change in the waveform of the evoked potential. Thus, the N_1-P_2 amplitude reduction was due solely to the fact that a two sec. inter-stimulus-interval was not sufficient to allow full recovery of the N_1-P_2 component. Perhaps one should not attempt to interpret reduction in amplitude as due to habituation, unless optimal recovery time is allowed to elapse between stimulus presentations. Due to the work of Davis *et al.* (1966), we know that optimal recovery time for the vertex auditory potential is about ten sec.

Additional information from the analysis of the 80 percent probability when *S* was right would also preclude habituation as a major factor operating in the present experiment. No evoked potential component showed a significant decrement of response amplitude over the four days of running. P_2-N_2 did show an increase, but this probably reflects changes in arousal associated with task familiarity (Wilkinson *et al.*,1966).

Pupillary data would also be hard to reconcile with a pure sensory habituation model. In unpublished studies, we have shown that pupillary dilation to clicks is markedly resistant to habituation over several hundred trials. This data is in agreement with that of Clynes (1962), who also found no peak dilation habituation over a large number of trials. Sokolov (1963b), however, has found peak dilation decrement, which occurred upon repeated presentations of dark pulses to the light-adapted eye, a situation very different from the present experiment. Lowenstein and Loewenfeld (1952) also obtained habituation of peak dilation in cats, but this was to pistol shots, stimuli much more intense than those used in the present study.

Further evidence detrimental to an interpretation in terms of sensory habituation is the fact that four Ss showed no dilation to any of the stimuli in the certain condition, while the remaining four Ss produced dilations which were extremely small and remained constant in amplitude across stimulus probabilities. In the uncertain condition, only one S (WC) showed a decrease in peak dilation over time when the 80 percent condition was examined, while four Ss showed no changes in peak dilation.

The pupillary data (in not exhibiting habituation of response) are in disagreement with studies by Dureman and Sholander (1962) and Lehr and Bergum (1966) who found significant pupillary habituation in the phasic component over the course of an experiment. However, in these studies, data were recorded under diffuse light conditions. Secondly, the stimuli, at least overtly, were not psychologically meaningful, and were simply presented serially, without change in conditions, for the entire experiment. Further research in this area of pupillary responsivity is definitely necessary to determine the parameters contributing to response decrement.

N_1-P_2 Effects Versus N_2-P_3 Effects

One finding difficult to reconcile with this discussion is the fact that either N_1-P_2 or N_2-P_3 carried the effect of outcome probability. If N_1-P_2 represents the primary response of the auditory cortex, and reflects the physical parameters of the stimulus, why should this component, which is probably proceeding via classical afferent pathways to cortex, be affected in some individuals, and not P_3, which has the opportunity to be elaborated upon in association cortex? This is extremely difficult to explain in light of the evidence that it is the late components of evoked response which are affected by the effective information carried by the stimulus (e.g., Brazier, 1967; Sutton and colleagues, 1965, 1967). Nevertheless, it is the combination of these two components (N_1-P_2 and N_2-P_3) that yields the N_1-P_3 measure which showed the greatest effect. It is quite possible that Tueting's (1968) Ss exhibited N_1-P_2 effects, in the absence of N_2-P_3 effects, since the 0-P_3 measure, which she employed, includes part of the N_1-P_2 wave. This would mean that the entire evoked potential is affected by the experimental manipulations, with modulation occurring probably at a number of levels in the CNS, the net effect being the pull of the evoked potential toward greater positivity, whether by N_1-P_2 enhancement, or N_2-P_3 enhancement.

It is interesting to note that both twins belonged to the N_1-P_2 component group. Although not pursued further in the present investigation this fact warrants additional study. Perhaps the differentiation of these 2 groups of Ss on the basis of evoked potential component decrease can be related to differences in guessing strategy, or perhaps, as the twin data suggest the component that is affected is part of one's biological individuality.

Neurophysiological Implications

There are two types of pupillary dilation, each due to a different physiological mechanism: 1) a passive reflex dilation of long latency due to inhibition of the efferent outflow of the oculomotor nucleus (Edinger-Westphal) by higher brain centers, and 2) an active dilation via the hypothalamus, through the brainstem to the pupillodilator fibers in the cervical cord to the superior cervical ganglion, and thence to the dilator muscle (Loewenfeld, 1958). A fully-integrated dilation is comprised of both types, and begins 600-800 msec. following stimulus onset (Loewenfeld, 1958), the same onset latency found in the present experiment.

The location of the pupillary dilation reflex center in the hypothalamus (Loewenfeld, 1958), allows a number of neural systems to converge upon and modulate pupillary activity. For example, the thalamus receives fibers from the hippocampus (and therefore from the limbic system) and the reticular formation (Truex and Carpenter, 1965). The intimate relationship of the limbic lobe with the hypothalamus has been demonstrated often (Truex and Carpenter, 1965). The intralaminar nuclei of the thalamus (which are implicated in the diffuse thalamic activating system, Lindsley, 1960; Jasper, 1960) receive ascending inputs from the reticular formation and project diffusely to cortex, as well as pass fibers to the hypothalamus (Jasper, 1960).

Pupillary dilation has been observed upon cortical stimulation (Loewenfeld, 1958; Siebens and Woolsey, 1946; Ward and Reed, 1946), upon stimulation of the reticular formation (Naquet, Fischer-Williams, and Fernandez-Guardiola, 1960) and diencephalic structures (Hodes and Magoun, 1942; Loewenfeld, 1958), such as the posterior hypothalamus. Stimulation of the amygdaloid complex has also produced dilation (Koikegami, 1953).

The existence of two "arousal" systems, the Ascending Reticular Activating System (ARAS), and the Diffuse Thalamic Activating System (DTAS) was demonstrated by Lindsley (1960). Stimulation of ARAS with high-frequency electric shocks produced EEG arousal and behavioral arousal of enduring persistence, whereas similar high-frequency stimulation of DTAS produced the same effects, without the long-lasting duration. Lindsley concluded that the existence of these two systems might reflect different modulation of attentional states, the ARAS producing long-lasting states of alertness, and the DTAS modulating the general state on a short-term basis. Lynn (1966), cites evidence that stimulation of the DTAS elicits the localized orienting response of Sokolov (1963b), while stimulation of ARAS produces autonomic and EEG components of the generalized orienting response. Sharpless and Jasper's (1956) model of habituation of the arousal reaction also involves two mechanisms, a tonic (generalized) reaction which is long-lasting, but habituates quickly, and a phasic reaction (localized) which habituates very slowly. They too implicated the ARAS as mediating the former and the DTAS as mediating the latter. Sokolov's theory of the orienting response also postulates two reaction types, but does not employ two neural mechanisms.

The findings of similar averaged evoked potential waveforms to somatosensory, visual and auditory stimuli at a C_z electrode, led several investigators to conclude that the "vertex potential" was modality non-specific (e.g., Davis, 1968; Goff, 1966, 1967). Goff, working primarily with the somatosensory evoked potential to shock stimuli, concluded from a variety of experimental evidence that the vertex potential was probably mediated via two neural systems, one reflected in early components (prior to 80 msec.) and mediated via the lemniscal system, and the second extra-lemniscally mediated and involving the reticular formation. This latter system was supposed to mediate the large N_1-P_2 wave of the vertex evoked potential. Recent evidence from Goff's laboratory (Williamson, Goff, and Allison, 1970) has proven this not to be the case.

While it is generally agreed that components earlier than N_1-P_2 of the auditory evoked potential are mediated classically (e.g., Celesia, Broughton, Rasmussen, and Branch, 1968; Ruhm, Walker, and Flanigin, 1967), recent studies by Vaughan and Ritter (1970) have demonstrated that the large N_1-P_2 wave of this potential is also mediated by the classical ascending sensory system. On the other hand, the late positive component or P_3, which has been implicated in orienting (Ritter et al., 1968) has been shown to arise in parietal association cortex (Vaughan and Ritter, 1970). Furthermore, during sleep, the auditory evoked potential to clicks assumes a completely different waveform shape, with loss of the P_2 component, and gain of a large-amplitude positive component in the latency vicinity of P_3 (Skinner and Antinova, 1969). This fact probably reflects the different neural genesis of the P_3 wave.

Apical dendrites in association cortex are known to receive projections from the non-specific DTAS, and these are mainly axodendritic with physiological effects in the superficial cortical layers (Truex and Carpenter, 1965). Vaughan (1969) has stated: "To the degree that axodendritic endings represent highly redundant inputs, the electrotonic propogation of their effects could provide an important modulation of cellular excitability" (p. 54). Would it not then be possible that P_3 is generated by the activity of the DTAS whose axons could modulate the activity of apical dendrites in association cortex?

The finding of no CNV differences across probabilities suggest that CNV reflects a more generalized response, indicative of the overall level of arousal. P_3 and pupillary dilation, which were independent of CNV amplitude, would then be linked to phasic attentional or arousal processes mediated by the DTAS. These components would reflect transient changes in arousal, probably a consequence of selective attention and the making of a task relevant response.

Pribram (1967) has stated that arousal can vary along a continuum, related to the degree of uncertainty of the organism, and that the amount of arousal is directly related to the orienting response, in that it is shown to be "dependent upon the configuration of the expectancies challenged by the novel input. 'Amount' is thus viewed as amount of match and mismatch between configurations, not on amount of excitation or energy available to the neurobehavioral system" (p. 833). Lindsley (1969) has also implicated the orienting response in situations of prediction and expectancy. Such a mechanism as that proposed above would account for response decrement as uncertainty decreases.

CHAPTER V

SUMMARY

Averaged pupillary movements, averaged baseline shifts and the averaged evoked potential from a vertex scalp lead were recorded simultaneously and studied as a function of degree of stimulus uncertainty. Degree of stimulus uncertainty was manipulated by varying the probability of occurrence of two double-click stimuli, which differed in the length of their inter-click-interval. Probability programs were constructed so that each stimulus, in separate sessions counterbalanced across days of running, was associated with 20, 40, 60, and 80 percent probabilities of occurrence, with the other stimulus associated with the converse probability of occurrence. In this way, each stimulus served as a replication. A 50/50 probability condition was run on the first day for each S. Probability programs were presented in both certain (S was informed of the identity of the next stimulus) and uncertain (S had to guess the identity of the next stimulus) conditions.

Uncertain - Certain Differences

There were clear and statistically significant differences between the certain and uncertain conditions in the slow (CNV and pre-stimulus pupillary slope) and fast (evoked potential and peak dilation) processes of both response systems. These differences were tested at each stimulus probability point. CNV was more negative in the uncertain condition, with positive shifting associated with the certain condition. Pre-stimulus pupillary amplitude paralleled CNV activity, in that this pupillary component was characterized by a significant trend toward dilation in the uncertain condition, and a trend toward constriction in the certain condition. Initial diameter was consistently larger in the uncertain condition.

Peak dilation was markedly larger in the uncertain condition than in the certain condition. Results for the averaged evoked potential were dependent upon the component studied. P_1-N_1 was larger in the certain condition at all probability points, with the exception of the 20% point, where no difference was found. N_1-P_2 was larger in the uncertain condition at the 20% and 40% points, with no difference at the 60% and 80% points. P_2-N_2 was consistently larger in amplitude in the certain condition, while N_2-P_3 was consistently larger in the uncertain condition. N_1-P_3 was consistently larger in the uncertain condition. These results led to the conclusion that these differences in slow and fast processes were caused by a change in physiological state from certain to uncertain conditions, with the latter reflecting increased arousal.

Pre-Stimulus Events - CNV and Pre-Stimulus Pupillary Slope

While CNV appeared to be correlated with the large N_1-P_3 differences between certain and uncertain conditions, these differences occurred even in those *S*s who showed no CNV differences between certain and uncertain conditions. Further evidence in support of independence between CNV and evoked potential amplitude was obtained from the probability functions in which N_1-P_3 amplitude varied systematically as a function of stimulus and guessing probability, while CNV did not. In a similar fashion, there was no relationship between pre-stimulus pupillary amplitude and peak dilation amplitude, nor was there a relationship between CNV amplitude and peak dilation amplitude.

Although not directly comparable, these results were analyzed in terms of Walter's (Walter et al., 1964) "probability dilution" conditions by computing CNV amplitudes for an entire probability program. The results of this analysis indicated that in this experiment CNV amplitude was not affected by probability manipulations.

Stimulus and Guessing Probability Effects

Both pre-stimulus response measures (CNV and pre-stimulus pupillary slope) did not vary as a function of stimulus or guessing probability in the uncertain condition, or of stimulus probability in the certain condition. Peak dilation amplitude was a significant inverse function of both stimulus and guessing probability in the uncertain condition, with largest amplitudes associated with the lowest stimulus and guessing probabilities. N_1-P_2, N_2-P_3 and N_1-P_3 produced significant inverse monotonic functions for stimulus probability in the uncertain condition. N_2-P_3 and N_1-P_3 produced inverse monotonic functions in the certain condition as well, which, though significant, were markedly less steep than in the uncertain condition. N_2-P_3 and N_1-P_3 produced inverse monotonic functions; P_3-N_3 amplitude also decreased significantly as a function of guessing probability.

Outcome Probability Effects

The data were also considered, in light of the Tueting et al. (1971) results, in terms of outcome probability, or the interaction between stimulus probability and S's guessing probability. In addition, analyses of variance of both peak dilation and N_1-P_3 amplitudes indicated that an analysis in terms of outcome was justified.

The data for hits were much more consistent both within and between

Ss than were the data associated with misses. Peak dilation amplitude varied inversely and monotonically as a function of outcome probability both when S was right and when he was wrong. N_1-P_3 produced a significant inverse monotonic function only when S was right. Components N_1-P_2, N_2-P_3 and P_3-N_3 demonstrated negative monotonic relationships with outcome probability only when S was right. P_2-N_2 showed the opposite trend when S was right, but this effect failed to reach statistical significance. When S was wrong trends were grossly similar but, with the exception of P_3-N_3 which produced a significant positive slope, no other trend was significant. No trend for outcome probability in the 50/50 data was discernible.

Right - Wrong Differences as a Function of Stimulus Probability

Analysis in terms of right and wrong differences as a function of stimulus probability revealed significant differences for peak dilation at the 60 and 80 percent points, with wrong outcomes associated with larger amplitudes. For N_1-P_3, only the difference at the 80 percent point was significant, and again larger amplitude was found for the wrong event. No right-wrong differences were found for the 50/50 data.

Differential Effect of Outcome Probability on N_1-P_2 and N_2-P_3

An additional finding of importance was demonstrated when individual S data were studied for right outcomes. Four Ss showed the effect of outcome probability on the N_1-P_2 component, but little effect on the N_2-P_3 component, while the reverse trend held for the remaining four Ss. This fact accounted for the clear-cut trends in N_1-P_3 for all Ss, since this overall measure spans both the N_1-P_2 and N_2-P_3 components.

Latency Findings

Latency analyses of all evoked potential components and peak dilation yielded no consistent trends. N_2 component amplitude peaked significantly later in the certain condition at all probability points than in the uncertain condition. Peak of P_2 occurred later in the certain condition than in the uncertain condition only at the 60% probability point. In the uncertain condition, but not in the certain condition, peak dilation latency produced a significant monotonic inverse trend as a function of stimulus probability. This did not occur for any evoked potential component in either condition.

Right versus wrong latency differences occurred only for the P_3 component, and this was restricted to the 20% probability point, with hits yielding earlier peaking than misses.

An additional latency analysis was accomplished: it had been postulated that if the evoked potential were the central event leading to peak dilation, than those Ss exhibiting probability effects in N_1-P_2 might show earlier peak dilation latencies than those showing N_2-P_3 effects. Although mean peak dilation latency differences between these two groups of Ss were in the expected direction, they fell short of statistical significance.

Additional Findings

No trend for the habituation of any evoked potential component over days was evidenced, as seen by the analysis of the 80 percent probability. P_2-N_2 did show a significant amplitude increase over days, and this was interpreted as indicative of lowered arousal associated with task familiarity. Peak dilation showed no consistent trend over days, nor did CNV. No consistent relationships amongst four measures of activity, N_1-P_3, initial diameter, peak dilation and CNV, were found.

The effect of the number of data samples per average curve was also investigated, and was shown to be negligible for these data.

Explanatory Mechanisms for These Data

The results of this experiment were considered in terms of possible explanatory mechanisms, such as Sokolov's (1963b) orienting reflex, and the relevance of habituation was discussed. The relevance of these data to the analysis of Tueting *et al*. (1971) in terms of surprisal was also considered. In addition, possible neurophysiological mechanisms were discussed.

LITERATURE REVIEW

I. Introduction

This chapter will attempt to review and relate a number of studies dealing with three distinct response processes: pupillary dilation, averaged evoked potentials (mainly the late components), and the contingent negative variation (CNV). All three of these responses have been studied independently and have been shown to react similarly to manipulation of a variety of psychological variables. For example, manipulations designed to increase the subject's arousal, lead to increased response amplitude for all three processes.

The physiological mechanisms of pupillary dilation will be discussed first, followed by a review of the relevant pupillary psychological literature. This will include a discussion of pupillary habituation, dilation as indicative of orienting, and a brief review of experiments relating to the Law of Initial Value, since this could be a confounding effect in pupillary experiments. In addition, some methodological problems involved in pupillary research will be discussed.

The next major topic covered will be the relationship between autonomic and central measures of activity, with special reference to the variable of stimulus uncertainty, since this is the major focus of the present experiment. The mechanisms involved in CNV genesis will be discussed, as well as the relationships between CNV amplitude and psychological variables that have been manipulated in pupillary and evoked potential experiments. Since both P_3 and CNV were recorded in the present study, the final section will deal with the relationship between CNV amplitude and P_3 amplitude.

II. Pupillary Dilation

The fact that the pupil dilates when an organism is in an excited or emotional state has been known for over 200 years (Loewenfeld, 1966). In 1765, Fontana (cited by Loewenfeld, 1958) observed that the pupils, which are contracted during sleep, dilated upon awakening, the dilation occuring even in the presence of bright light. He also observed that when a cat's eye was exposed to light and the animal was hurt or frightened at the same time, the pupils dilated and remained mydriatic until the animal calmed down. The mechanisms responsible for pupillary dilation have been hotly debated as long as the fact that the pupil dilates has been chronicled, and are still contested (Loewenfeld, 1958).

A. Physiological Mechanisms

Lowenstein and Loewenfeld (1961, 1962) attribute pupillary dilation to four basic mechanisms, two of them neural and two of them humoral. The first neural element is sympathetic. Hypothalamic discharges, elicited reflexly or due to electrical stimulation, travel via the brain stem to the cervicothoracic spinal cord. The preganglionic fibers leave the cord via the ventral roots of the first and second thoracic segments, and eventually synapse with the cells of the superior cervical ganglion, and from there pass to the dilator muscle of the pupil. Rapid and extensive dilation depends upon the integrity of the sympathetic nervous system, as shown by a variety of proofs (Lowenstein and Loewenfeld, 1950, 1961, 1962).

The second neural element is the result of what Lowenstein and Loewenfeld call "supranuclear inhibition". According to these authors, the Edinger-Westphal portion of the oculomotor nucleus (parasympathetic impulses) is subject to inhibitory influences from supranuclear structures, such as the cortex, thalamus, and hypothalamus. Psychosensory stimuli cause impulses from higher brain centers to converge upon the motor nucleus, thus preventing it from sending impulses to the pupillary sphincter, the end result being dilation. This, for example, would account for the dilation of the pupil in bright light. Therefore, pupillary dilation is due to the contraction of the sympathetic dilator and a relaxation of the pupillary sphincter, mediated by an inhibit on of the third nerve nucleus.

That two humoral mechanisms exist, is clearly evident following sympathetic denervation (Lowenstein and Loewenfeld, 1961). This operation produces a supersensitivity to adrenergics in the dilator muscle. The fact that the pupil dilates following sympathectomy has been called "paradoxical pupillary reaction" by Lowenstein and Loewenfeld. This "remnant" dilation is caused by adrenergic substances released into the blood reflexly, or in response to a hypothalamic stimulus (Lowenstein and Loewenfeld, 1961). This dilation is considerably longer in latency (2 to 3 seconds) than the fully-integrated response to a psychosensory stimulus (latency of 600-800 msec.). With more intense or prolonged stimulation, adrenal epinephrine reaches the iris approximately 9 to 15 seconds following the stimulus.

The analyses of pupillary dilation in terms of dual innervation have, in general, been supported by a host of other investigators (Bailey and Guth, 1959, Guth and Bailey, 1960a, 1960b; Siebens and Woolsey, 1946; Ward and Reed, 1946; Weinstein and Bender, 1941). However, that this dual innervation explanation of the mechanism of dilation may not be so simple has been demonstrated by Schaeppi and Koella (1964a, 1964b). They have shown, using in vitro preparations, that both the dilator and the sphincter muscles have cholinergic as well as adrenergic receptors. While their results must be qualified because of their use of in vitro preparations, these findings complicate considerably the simplistic dual innervation scheme that has had such long tenure.

B. Psychological Experiments and the Pupil

Many excellent reviews of the pupillary literature have recently appeared (Daves, 1969; Goldwater, in press), and the reader is referred to these for extensive surveys of the literature. For purposes of the present review, only prototypical experiments, classified by type of psychological variable involved, will be presented.

Although Lowenstein and Loewenfeld in their many papers have dealt with psychological phenomena, their approach, in terms of analysis of data, leaves much to be desired (Goldwater, in press). Recent interest for the psychologist in pupillary motility has been kindled by Hess and his colleagues (e.g., Hess, 1965; Hess and Polt, 1964). Pupillary motility has even been the subject of an article in a large-circulation, man's magazine (Maxwell, 1969). Using Hess's technique, a number of investigators have studied pupillary motility as a function of a wide spectrum of psychological variables. Some of these experiments will be reviewed in the following sections.

1. Information processing tasks. Kahneman and Beatty (1966) presented their Ss with 1) strings of digits (3-7 per string)presented for immediate recall; 2) a string of four high-frequency monosyllabic nouns presented for immediate recall; and 3) a string of four digits presented for transformation (each S was asked to add one to each digit).

The S's pupil was photographed at the rate of one frame per second, in light. Five frames of baseline were taken and then digits were presented in time with the advance of the camera. The S waited for two clicks of the camera before responding. The results indicated that the pupil dilated with every digit heard (loading phase), and constricted during recall. The size of the dilation was directly related to the number of digits processed. Dilation was also greatest for the transformation task (i.e., the more difficult task), as opposed to the recall of words or digits.

In a second study, Beatty and Kahneman (1966) assessed the effect of short - versus long - term memory on pupillary diameter. The stimuli for long-term memory were telephone numbers and their associated names, with which S was thoroughly familiar. The short-term stimuli were unfamiliar phone numbers which S had to repeat. To test for long-term memory, E verbally presented a name which S had supplied, and S had to report the associated number. In both conditions, pupillary diameter increased during the intake of information, and constricted during the report. Peak dilation was greater for the long term task than for the short-term task.

In an effort to determine if heart rate and skin resistance were sensitive to problem-solving tasks, Kahneman, Tursky, Shapiro, and Crider (1969) studied these two measures as well as the pupil during a digit transformation task. Three levels of task difficulty were employed, by asking Ss to add 0, 1, or 3 to the digits presented by the E. All three systems produced extremely similar results, with a sympathetic-like increase in activity occurring for all three during the input and processing of the information. Although difficulty level affected maximal response in all three systems, the most clear-cut differences were those obtained for the pupil.

Pupillary activity appears, on the basis of the above studies, to be sensitive to tasks designed to monitor "mental activity". All of these investigations show that dilation is the pupillary response to be expected whenever information input and processing take place, with constriction occurring during the report phase of the task. However, the Kahneman _et al_. (1969) study demonstrated that this increase in sympathetic activity is not unique to the pupil, but occurs in other systems as well. Thus, dilation which occurs upon information processing on the part of the organism may simply be one aspect of an overall response pattern which is indicative of arousal, caused by the fact that _S_ is engaging in mental activity.

2. _Task difficulty_. A second area in which numerous studies of pupillary activity have been accomplished is task difficulty. Initial findings with this variable were published by Hess and Polt (1964), who reported that the size of the pupil during multiplication problems increased with the difficulty level of the problem.

Payne, Parry and Harasymiu (1968) used percentage of pupillary dilation as a measure of item difficulty. Difficulty was defined as the number of digits involved in a multiplication problem. Control slides, similar to those used by Hess (one of the number 1 to 4 displayed in each corner and the number 5 in the center of the slide) were employed to measure average pupillary diameter prior to test slide onset. The test stimulus was a slide with the multiplication problem (e.g., 1x5) displayed in the center. Percentage of pupillary dilation was obtained by taking the difference between the average diameter during the test slide and the average of the control slides preceding and following the test slide, dividing this result by the average of the two control slides, and multiplying by 100. It was found that, based on the Ss rating of item difficulty, percentage dilation increased as difficulty increased.

However, the results of this study have to be considered in light of some factors which were not well-controlled. First, percentage dilation is a measure which is influenced by initial diameter of the pupil during the control slide. If there is any systematic increase or decrease in initial diameter, then percentage of dilation is a poor response measure. Although obtaining basal pupil readings before and after the test slide is a control for changes in pupillary baseline occuring from control to test slide presentation, it cannot be assumed that pupil diameter remains fairly constant over the entire course of an experiment. Secondly, no attempt was made to match control and test slides for overall brightness. Since easier problems contain fewer digits, the slide displaying an easy problem will probably appear brighter than one which is more difficult (e.g., 7574x7). Therefore, one would expect more dilation during the more difficult task due to the confounding of slide intensity and difficulty.

Bradshaw (1967), as well as Elshtain and Schaeffer (1968) have reported larger dilations with more difficult tasks. However, Bradshaw (1967) employed a key press during his procedure, and this alone has been shown to cause dilation (Simpson and Paivio, 1966).

These investigations have demonstrated an association between task difficulty and pupillary dilation, with more difficult tasks associated with greater dilation. However, not all of these studies have been methodologically sound. Aside from problems that arise with the use of visual stimuli (these will be discussed in a later section), the use of percentage dilation as in the Payne _et al_. (1968) study is subject to criticism. One way to overcome problems arising from changing baselines (which are reflected in the precentage measure) is to randomize the appearance of control and test slides, so that changes in baseline from control to test slide presentation are minimized.

3. _Arousal_. In a normal alert man or animal, the pupils are large in darkness (Lowenstein and Loewenfeld, 1964). They contract to light and redilate after the stimulus. Even after many minutes in darkness, the pupils show very little oscillatory behavior (Lowenstein, Feinberg, and Loewenfeld, 1963). When the _S_ becomes tired, the pupils begin to oscillate.

> In ever deepening waves of sudden, spontaneous arousal and gradual slipping into a doze, the pupils dilate rapidly, then recontract gradually in an unsteady, wavering decline. The more the _S_ is tired, and the less he tries to suppress his sleepiness, the shorter the time of initial mydriasis, and the deeper and more frequent the following pupillary oscillations (Lowenstein and Loewenfeld, 1964, p. 142-143).

In their 1963 paper, Lowenstein _et al_. present proof of the central nervous origin of pupillary waves: a) dilation and contriction coincide with cyclic activity in other systems. Since many effector systems are affected, their simultaneous action cannot be brought into play by separate peripheral mechanisms; b) the spontaneous waves of contraction and dilation in normal man are equal on both sides; c) when a decrease in arousal occurs, and the _S_ falls asleep, psychosensory stimuli will cause _S_ to awaken, and upon awakening show all the physiological effects, including dilation. However, upon destruction or blocking of cortical and/or diencephalic connections, stimulation of sensory nerves fails to produce these effects; d) centrally-acting depressants or stimulant drugs (e.g., nembutol or benzedrine) may decrease or increase pupillary movements. However, peripherally-acting drugs decrease the extent, but do not alter the rhythm of the spontaneous movements.

Yoss, Moyer, and Hollenhorst (1970) have shown that pupillary wave amplitude and duration in darkness are different for the various stages of alertness. They identified seven pupillographic stages corresponding to different levels of alertness. In general, mean initial diameter decreased from Stage A through Stage H, while the number and amplitude of pupillary oscillations increased from Stages A to H (in Stages G and H, S̲ was asleep). Upon awakening from sleep, S̲'s pupil, which was 35 percent the size of his alert diameter, dilated, and in approximately thirty seconds reached 85 percent of his alert diameter.

Very little research, other than the work by Lowenstein and his colleagues, has been done in which pupillary correlates of states of arousal have been identified. This becomes an important area of pupillary research, especially since changes induced by psychosensory stimuli are relatively small, and might be "wiped out" (especially when recording pupillary diameter with low sampling rates - see "Methodology" section) by superimposed diameter fluctuations due to changes in arousal. It thus becomes necessary for the investigator to determine if averaged dilation responses are, for example, in some way different (in amplitude as well as shape or waveform) during states of lowered arousal than they are during states of heightened arousal. The substantial contribution made by Yoss *et al.* (1970) should be replicated, using an averaging technique, with simultaneous EEG recording, in order to determine if the classical means of determining states of arousal correlate well with pupillary stages.

4. Sensory stimuli. As Loewenfeld states (1958): "It was recognized at an early period of physiological research that stimulation of any sensory nerve in the body will elicit pupillary dilation. The reaction is so sensitive and reliable that it was often used as an indicator for sensation in physiological experiments" (p.277). Stimuli used by Loewenfeld (1958) in eliciting pupillary dilation were a sudden sound (pistol shot), sudden blowing into the animal's face, or pain (pin prick, tail squeezing).

Nunnelly, Knott, Duchnowski, and Parker (1967) investigated the pupillary response to a variety of sensory and psychological stimuli. Only the pupillary response to auditory stimuli will be discussed here. Their Ss were presented with an ascending and descending series of constant 200 cps tones of ten dB increments from 64.2 to 94.2 dB. Only the 94.2 dB tone produced a significantly larger pupil size than the other tones.

Clynes (1962) also reported data dealing with the auditory pupil reflex. He used an average response computer to retrieve pupillary responses. His Ss were presented with 500 cps tones at 40 dB above threshold, in blocks of 50 trials. The dilation response was extremely short in latency (.15 seconds), and large in amplitude (.5 millimeter). Investigations in this laboratory have found dilations to click stimuli well above threshold with latencies from 600-800 msec., and amplitudes as large as .2 mm. Our recordings were made in darkness, while Clynes recorded under "moderate light conditions". This probably accounts for the differences in pupillary dynamics.

Nunnally et al. (1967) present data for an experiment in which the threat of a gunshot was anticipated. Presumably this was an "arousing" stimulus. The gun was never actually fired, but pupillary diameter during the trial on which the gunshot was anticipated was considerably larger than on any other trial.

Research dealing with the effects of cognitive variables on pupillary activity abounds in the psychophysiological literature. However, basic questions are still unanswered, especially about the dilation response. The parameters of stimulation, such as intensity, frequency, and inter-stimulus-interval, have not been systematically investigated. Some work has been done on the "habituation" of this response, but this research has only scratched the surface. This aspect of the dilation response will be reviewed in the next section.

5. Pupillary habituation and the orienting response. Contrary to Sokolov's orienting response (OR) theory, Clynes (1962) reported no habituation or diminution of the dilation response over several hundred trials. However, since stimuli were presented in blocks of 50, there may have been a decrement of response within a block, that could not be seen when the averaged response was obtained for 50 trials. In unpublished data from this laboratory (Friedman, unpublished), it was found that the dilation response to one-half second, 500 cps tones, presented at approximately 60 dB above threshold, did show a decrement within a block of twenty trials, but also showed recovery within that same block of trials. Therefore, any decrement across blocks would be partially counteracted by recovery occurring within a block.

Sokolov (1963a, 1963b) lists pupillary dilation as one component of the orienting response. The orienting response can be elicited by the stimulus characteristics of novelty, intensity, conditioned stimuli, and surprise (Lynn, 1966). Sokolov (1963b) reports that pupillary dilation is an omnipresent sign of the orienting response, and that it habituates rapidly with repeated presentations of the stimulus. Lieberman (1965) reports that the pupil "reacts with dilation not only to the pain of a sound stimulus, but also to a variety of stimuli directed at any analyser. This reaction extenguishes quickly with repeated presentations of the same stimulus...the extinguished reaction recovers quickly after a pause." (p. 188).

Lieberman (1965) used adult Ss between the ages of 20 and 45, and a variety of stimuli (sound, tactile, thermal and olfactory) in studying the pupil reflex. All stimuli were presented for 1.5 seconds, with the exception of the olfactory, which was presented for four seconds. The inter-stimulus-intervals varied from 10-30 seconds, and the number of stimuli presented did not exceed 10-12. The results showed that the pupil dilated to all stimuli, and the reaction habituated. Lieberman (1965) also reported that in some cases (20%) the pupil dilated to the presentation of a visual transparency or picture. This has also been reported by Sokolov (1963b), and was interpreted as the precedence of the orienting response over the "photoreaction" (i.e., the light reflex). Quantitatively, Lieberman (1965) found dilation amplitudes ranging from .2 to .8 millimeters, with latencies from .15 to .50 seconds. These latencies and amplitudes did not differ as a function of the stimulus category. Unfortunately, no statistical presentation of the data was given with respect to the habituation of the response, but a qualitative description will give the reader some idea of the situation: "A weak bell at ten-second intervals yields a zero reaction after 3-4 presentations...

A loud bell at ten-second intervals results in a zero reaction after 12-18 presentations." (p. 191). One particularly interesting result was the fact that presentation of from 45-65 <u>different</u> stimuli, changed continuously at 15-20 second intervals, did not result in "extinction of the reflexes". Shaknovich (1965) also reports that in the case of painful stimuli no habituation of the pupillary orienting response occurred.

Although not much research on pupillary dilation habituation has appeared in other than the Russian literature, some recent investigations have reported a decrement in the dilation response with repeated exposures of the same stimulus (e.g., Dureman and Scholander, 1962; Lehr and Bergum, 1966; Nunnally *et al.*, 1967).

Lowenstein and Loewenfeld (1952) present a curve demonstrating what they call "extinction of sympathetic reflex activity under repeated sympathetic (sound)stimuli". The stimuli used were pistol shots and the *Ss* were cats. The extent of reflex dilation diminished progressively from each stimulus to the next. By the fourth presentation, the speed as well as the amplitude of dilation were about half their initial value. Later reactions became more and more sluggish and inextensive, and soon subsided.

Lehr and Bergum (1966) present data showing what they term a fairly systematic "pupillary adaptation effect". Stimuli were control and test words (pleasant versus unpleasant) presented both visually and auditorily. Each test word was preceded by the control word "rock". Each data point in the curve they present was based on the sum of twelve measurements made at consistent intervals during the ten-second stimulus presentation period. For both test sessions of ten trials each, pupillary adaptation was consistent and fairly large. However, both auditory and visual stimulus responses were averaged in computing the curves. Until more is known about the nature of the habituation of this response, averaging of responses resulting from different presentation modes is not valid.

Nunnally _et al_. (1967) found significant pupillary habituation using sound stimuli at a constant frequency of 2000 cps. Starting with an ascending series of tones from 64.2 dB and proceding in 10 dB steps up to 94.2 dB, these investigators observed a significant drop in pupil size from the first tone to the next _higher_ tone, but no difference between the second and third tone reactions. In the descending series of tones, none of the differences among the three tone levels below 94.2 dB was significant, but all were significantly smaller than the 94.2 dB tone.

In an exploratory study of what they termed the "psychosensory reflex", Dureman and Sholander (1962) found significant pupillary dilation decrement riding on a significant increase in initial pupillary diameter. Their _S_s were 35 students whose pupillary diameters were adjusted to a mean of 4.5 mm. with the use of a diffusely-illuminated screen placed at a distance of 72 centimeters from _S_. The _S_s were exposed to 30 white noise stimuli presented with durations of .1 second, and at a constant intensity of 105 dB above threshold. Inter-trial-intervals were randomly varied between 20 and 40 seconds. Dureman and Sholander (1962) used two aspects of the psychosensory reflex to describe their data: a) "tonicity", or the relatively persistent or slowly changing tonus balance; and b) "the acute or phasic reactivity" caused by the stimulus. Measurement of the tonic process was in terms of pre-stimulus area (mm^2) and areal change; measurement of the phasic process was in terms of maximal area of post-stimulus dilation over trials.

This area of research with the pupillary dilation response has produced the most inconsistent findings. Russian work is not easily interpretable due to the method of results presentation, with their lack of statistical analyses and quantitative treatment of the data. In general, comparisons among the different studies (whether Russian or not) are difficult to make, since stimuli, stimulus durations, inter-stimulus-intervals, inter-trial-intervals, and background stimulus conditions vary considerably from study to study. More work, in which systematic manipulation of the parameters of stimulation is done, is clearly needed.

6. The law of initial value and the pupillary response. One result of the Dureman and Sholander study (1962) is relevant to this section. They pointed out the fact that within the first three trials a decline in areal change was accompanied by a decline in post-stimulus area, and a rise in pre-stimulus area. This was interpreted by Dureman and Sholander (1962) as indicating that an increase in the initial phase of the tonic pupillary component induces a resistance towards further dilation, this causing a decline in both measures of phasic reactivity.

This result, obtained by Dureman and Sholander (1962) is directly related to a problem commonly encountered in psychophysiological research, that is subsumed under the heading of the Law of Initial Value (Sternbach, 1966). Simply stated, this law is, "As the function of an organ rises, the size of the response to a given stimulus diminishes" (Block and Bridger, 1962, p. 1229). In terms of the pupillary response, this means that the larger the initial diameter, the smaller the subsequent dilation. The question is: does the law of initial value operate in the pupillary system? Little research, bearing directly on this problem as it affects the pupil, has been done.

Loewenfeld and Newsome (1969) manipulated pupillary diameter in one eye with autonomic drugs, using the untreated eye as a control. They showed that the pupil operates in a linear range, within which dilations to periods of darkness moved freely. Beyond this range, the dilations decreased in velocity and extent, and this decrease occurred at a particular pupillary diameter, different from S to S. This decrease occurred regardless of stimulus intensity and pre-stimulus pupillary diameter (i.e., initial diameter). This, therefore, demonstrated that the pupil was operating under a mechanical limiting factor, and not the Law of Initial Value.

Recent experimentation in this laboratory (unpublished) has shown that the function relating pupillary dilation amplitude and initial diameter is somewhat more complicated than the linearity of the Law of Initial Value would imply. In a number of exploratory experiments, we have manipulated pupillary diameter with the use of an eye patch containing a light bulb and a diffusion plate. The intensity of the light was adjusted by using a decade resistance box. Six resistances, all yielding different initial diameters, were employed. The results, replicated with two Ss, showed that the function relating initial diameter and dilation amplitude was curvilinear, with maximal dilation occurring at some middle value of initial diameter (approximately 5 mm.), and extremes of initial diameter associated with smaller dilations.

Although the above experiments were designed in an attempt to determine if the pupil obeys the Law of Initial Value, the conditions of those experiments were not the same as those of the present study. In the present experiment, the pupil was measured in complete darkness. The following experiment had been undertaken prior to the above investigations, and its data were reanalyzed in order to see if the pupil obeyed the Law of Initial Value in darkness. The stimulus was a 500 cps tone of 500 msec. duration, presented repeatedly without change in 15 blocks of 20 trials each. Amplitude of peak dilation was plotted as a function of mean initial diameter over the 15 blocks of trials. This function produced no systematic relationship between initial diameter and peak dilation. Further, initial diameter variability was quite small, approximately one millimeter in range.

In summary, very little research dealing with the question of the relationship between pre-stimulus diameter and post-stimulus dilation amplitude has been accomplished. The studies that have been done do report some relationship between these two measures. However, those experiments were performed under diffuse light conditions, thereby increasing the constrictor tonus of the pupil. In an unpublished study in darkness, no relationship was found.

7. Emotional states. The use of pupillary motilitity as a response measure in a task involving emotional phenomena is not a recent innovation. Berrien and Huntington (1943) tried to use the dilation response as a measure of deception. They rigged an experimental situation such that the experimental group were required to lie to all questions asked them by E, while the control group was "innocent". According to these authors, one of the Es was able to correctly identify 13 out of 16 "criminals" (the experimental group) by simply looking at the pupillary records. However, since the device used to measure pupillary motility was extremely crude, and the responses were not averaged, one can see by looking at the records presented in the paper, that the dilations reported were well within the range of spontaneous oscillation in light.

Following up the long-known fact that the pupil dilates during emotional states, Hess and Polt (1960) investigated pupillary changes to pictorial stimuli in four men and two women. These investigators scored pupillary responses in terms of the percentage increase in pupil size to a test slide over a preceding control slide. On the average, women gave larger dilation responses to pictures of a baby, mother and baby, and male nude, while men showed greater dilation responses to pictures of a female nude.

In another experiment, Hess, Seltzer and Shlien (1965) reported that four out of five homosexuals dilated to a larger extent to pictures of male nudes than to those of female nudes, while five out of five heterosexual males showed greater dilations to pictures of female nudes.

Hess reported that the repeated presentation of extremely unpleasant pictures (e.g., concentration camp scenes) while initially causing dilation, later evoked pupillary constriction. On the basis of these data, Hess (1965) concluded that the pupil is a bi-directional indicator of affect, dilating to "pleasant" stimuli, and constricting to "unpleasant" stimuli. These data run counter to most of what is known about reflex dilation of the pupil. Most emotional stimuli, regardless of their affective quality, tend to evoke dilation. Loewenfeld (1966) has stated:

> The assumption that pleasant emotions dilate the pupil whereas unpleasant ones contract it is not merely unsupported, but is contrary to fact. It has been known for many decades that the suddenness and intensity of an emotion, and the state of consciousness at the moment of stimulation (drowsy or excited, confortable or uncomfortable, etc.) determine the extensiveness of the reaction, but not the content of the emotion, and, furthermore, that all psychological and sensory stimuli, with the exception of light, dilate the pupil and none of them contract it. (p. 294).

Bergum and Lehr (1966a) reported finding dilation to both pleasant and unpleasant stimuli (pictorial), with unpleasant slides producing slightly, but significantly smaller, pupil sizes. However, they use technicolor stimuli, and Bouma (1962) has shown that pupil size varies as a function of wavelength with luminance held constant. In a second study, Bergum and Lehr (1966b) failed to replicate the significant difference in pupil size obtained between pleasant and unpleasant stimuli when they used black and white slides.

Woodmansee (1969) attempted to replicate Hess's constriction findings. In an extremely well-controlled study, Woodmansee (1969) classified 22 female undergraduates as either strongly anti-Negro or equalitarian, based upon their scores on the Multi-Factor Racial Attitude Inventory. Five test slides, four consisting of Negroes portrayed in various situations, the fifth of a filthy toilet and surroundings, were matched to five neutral-content control slides for overall brightness. The results showed that only on the first of eight trials did the two groups differ significantly, and even then, the anti-Negro group's responses were essentially neither dilation nor constriction. In fact, in all eight presentations, their responses were either positive (i.e., dilation) or essentially zero.

Hutt and Anderson (1965) studied the relationship between pupil size and recognition threshold. A Hess pupillometer was used, in which neutral- and emotionally-charged words were presented for a ten-second period. Each emotional word was paired with a neutral word matched to it on the basis of Thorndike-Lorge frequency, with the recognition threshold of the neutral word and pupil size while viewing the neutral word serving as baseline measures. The authors reported a correlation of -0.189 between pupil size and recognition threshold. This is the direction of the relationship to be expected if the pupil is the mechanism underlying perceptual defense. However, the magnitude of the obtained correlation does not allow these investigators to state that "these data lend unequivocal support to the hypothesis tested". Given a large enough df (here it was 239), most any correlation will be significant.

In summary, investigations of pupillary motility, sparked by Hess and colleagues, have shown that the pupil reacts to manipulations of a number of psychological variables. However, many of these studies have pointed out the necessity of strict control in pupillary experiments, owing to the influence of many extraneous variables on pupillary diameter. These problems are especially marked in experiments performed under diffuse light conditions. These problems will be reviewed in the next section.

8. Methodological problems in pupillary research. In view of the many complicating factors one encounters when using pictorial stimuli in pupillometric research, basic methodological problems inherent in this type of experimentation will be briefly reviewed here.

In Hess's (and it must be assumed in all other researches that report using Hess's pupillometer), control and test slides are matched for overall brightness in order to control the effects of the pupillary light reflex. As well as the matching of test and control slides, brightness contrasts within a slide were minimized in order to reduce the effect of looking from a relatively dark area to a relatively light area within the slide. However, Woodmansee (1966) reported that, using photographic stimuli prepared by Hess's illuminance standards, the S's pupil constricted from one to five percent when he shifted his gaze from a relatively dark to a relatively light area of a test stimulus.

In view of the fact that the pupil exhibits a marked degree of "noise" and "unrest" (Lowenstein _et al._, 1963; Stark, 1959; Woodmansee, 1966), these changes due to light intensity effects within a slide are not insignificant. In darkness, the pupils of young, healthy, alert _S_s are large and relatively quiet (Lowenstein _et al._, 1963). The pupils, however, are never at rest, and when observed for a period of time show two types of oscillation (Lowenstein _et al._, 1963): a) slow waves of dilation and contraction, lasting from about four to forty seconds, and measuring up to ± .5 mm.; b) superimposed, fast and very inextensive oscillations of from .5 to 1-second duration, and about .1 to .3 mm. in amplitude. In diffuse light, pupillary "unrest" is even more pronounced (Lowenstein and Loewenfed, 1962; Woodmansee, 1966). The pupils can be expected to change at least 1 percent from second to second, and often as much as 10-20 percent over a period of several seconds. With increasing area and intensity of light, the rate of oscillations will increase, becoming maximal at about 2 per second. This means that the signal one looks for in the form of a dilation is often smaller than the _noise_ in which it is embedded, making reliable measurement difficult. Furthermore, most of the _E_s using Hess's technique, photograph the pupil at a rate of 2 frames per second, a sampling rate which corresponds to the expected frequency of oscillation of the pupil in light.

A second important factor in pupillary experiments is the distance of the stimulus from the _S_. With light stimulation constant, there is a constriction of the pupil which accompanies the convergence of the eyes and accommodation of the lens when viewing a near object. In general, this effect becomes more pronounced with increasing age (Woodmansee, 1966). Kahneman and Beatty (1966) reported an enhancement of ten percent of pupil size when their Ss fixated a stimulus at six feet rather than at six inches.

Thirdly, extraneous stimuli tend to dilate the pupil. Any stimulus to which S is not adapted will cause the pupil to dilate (Woodmansee, 1969). In many of the experiments so far reviewed, the pictorial stimuli were presented to S by means of a filmstrip projector. In most standard projectors, the filmstrip advancement is accompanied by a loud clicking noise clearly audible to S. This clicking would probably cause the pupil to dilate, at least for the first few presentations, and would therefore contaminate the data.

A related problem is the effect of movement on the pupillary response. This was shown to be a factor by Simpson and Paivio (1966), in an experiment in which a key press enhanced the pupillary dilation response by about ten percent of the value without a key press.

A very recent report (Chapman, Chapman, and Brelje, 1969) describes an experiment in which the attitude of the E influenced pupillary diameter to sexually-provocative pictures. In this study, two graduate student Es, known to differ in their manner of interaction with Ss, each tested half of the Ss in the experiment. All Ss were male. One E was business-like and formal, while the other had a "breezy" approach to interaction with Ss. Both Es used the same instructions, with the exception that the breezy E said in a suggestive tone, "I think you will find some of these pictures interesting". (p. 398). Five experimental slides were pictures of women, nude or semi-nude, from Playboy or Esquire. Another five experimental slides were pictures of attractive men. There were also twelve control slides prepared using Hess's technique. The device used to measure the pupil was a Hess pupillometer, modified to control the clicking noise produced by the advancement device on the projector. Bothe E's Ss dilated to both the male and female slides. However, fourteen of E_1's (business-like) twenty-two Ss showed larger pupil size while viewing female slides than while viewing male slides. Twenty of E_2's ("breezy") twenty-five Ss showed larger pupil size while viewing female slides than while viewing male slides. This difference in number dilating to female slides was significant for E_2 but not for E_1. The authors concluded that their results were consistent with the hypothesis that "differing modes of interacting with S produce differing pupillary responses" (p. 399). Of interest, is the fact that 44 of 47 male Ss dilated to male slides as well as female slides. This is in contradiction to Hess's (1965) findings.

In summary, a great deal of control in pupillometric research is necessary if one uses pictorial stimuli, and if one records under diffuse light conditions. Recording in darkness eliminates some of these problems (Hakerem, 1967), especially when coupled with the use of an electronic pupillograph which allows very fast sampling rates (60 times per second). However, in darkness the pupil is maximally dilated, and we have seen Ss whose pupils did not react under these conditions. If one wants to insure maximal dilation responses, then some illumination (resulting in smaller initial diameter) appears necessary. This, of course, then leads to the problems associated with recording under light conditions. One solution is to employ only those Ss whose dark-adapted pupils exhibit dilation to psychosensory stimuli, but this would introduce sampling biases. An alternative, which appears feasible, is to record under light conditions, using faster sampling rates, in order to insure that what is recorded is not simply pupillary oscillations in light. We have done this using the Lowenstein-Loewenfeld electronic pupillograph (see section on Law of Initial Value), and preliminary testing has yielded promising results.

III. Relationship Between Autonomic and Central Measures of Activity

In a number of papers, pupillary motility and the electrical state of cortex have been compared and found to be highly related. These studies fall in to two categories, those using gross EEG and pupillary measures (frequency characteristics of the EEG, and size of the pupil to the naked eye), and those studies employing averaging techniques for both the pupil and the EEG. In addition, other autonomic systems have been studied as a function of similar variables and these papers will also be reviewed, since these results appear to indicate a communality of response with pupillary reactivity.

A. Gross EEG and Pupillary Relationships

Naquet, Regis, Fisher-Williams and Fernandez-Guardiola (1960) studied pupillary and EEG responses to nociceptive stimulation (tail pinch) and reticular formation stimulation. Upon either form of stimulation, cortical EEG became desynchronized. At the same time, the pupil dilated, remaining mydriatic throughout the period of synchronization. When cortical activity slowed, the pupil became progressively smaller, remaining myotic throughout the period of synchronization.

Berlucchi, Moruzzi, Sabi and Strata (1964) investigated pupillary activity during the sleep-wakefulness cycle in blinded cats. While the animal was awake, the EEG was desynchronous and the pupil widely dilated.

When S assumed a sleeping posture, a progressive reduction in diameter was noticed, usually beginning prior to the appearance of slow rhythms in the EEG. Upon EEG slowing, and during spindling, the pupils became progressively constricted. During this period, it was possible to evoke an arousal reaction with auditory stimuli. This was accompanied by a "striking pupillary dilation".

Villablanca (1966) obtained similar results. He employed two preparations of the chronic decerebrate cat: 1) a low preparation (post-collicular); and 2) a high preparation (pre-collicular). In the "high" mesencephalic S, changes in the electrocorticogram were correlated with changes in pupillary diameter (i.e., arousal = mydriasis; sleep = myosis). In the "low" mesencephalic preparation, pupillary activity and electrocorticogram were dissociated. This "low" preparation is accomplished by transection caudal to the third nerve nucleus, thus interrupting its ascending reticular formation influences. Therefore, this study supports those of Lowenstein and Loewenfeld in demonstrating the necessity of an intact third nerve for a fully-integrated pupillary dilation. Villablanca (1966) concluded that mydriasis in the decerebrate cat is related to wakefulness, and is probably due to influences of the rostral medulla and mesencephalic reticular formation inhibiting the constrictor tonus of the Edinger-Westphal nuclei.

The studies reviewed above, demonstrate a marked correspondence between spontaneous EEG and pupillary motility. This correspondence is evidence in averaged evoked activity in both systems, as will be seen in the next sections.

B. Relationships Between Averaged Evoked Potentials and Averaged Pupillary Responses

Independent studies of averaged evoked potentials and averaged pupillary responses have shown both of these responses to be highly related. Specifically, in the studies to be reviewed, effects of psychological variables on the late positive component (P_3) of the evoked potential have been shown to be similar to the effects of these variables on the pupillary dilation response. These studies will be discussed separately, according to the type of variable manipulated.

1. Vigilance and discrimination. Hakerem and Sutton (1966) investigated the effects of vigilance on the diameter of the pupil by comparing sessions in which S was instructed to report whether a threshold-level light was seen, to sessions in which S was not required to report the light as seen. Averaged pupillary curves differed in amplitude, depending upon whether or not S was required to report. In the "report" condition, the dilation continued beyond the occurrence of the light; in the "no report" condition, the dilation levelled off. Presumably, the differences between these curves reflected differences in the degree of vigilance required for the two tasks.

In a second experiment, averaging of the pupillary response was based upon whether the S had "seen" or "not seen" the light. In this case, contraction to the light appeared only on those trials on which the light was reported as seen. In a similar experiment, with light intensity at a threshold level (reported as seen fifty percent of the time), Hakerem and Sutton (1966) asked their Ss to press a key on half the trials only when the light was seen, in the other half to press only when the light was not seen. In a second session of the same experiment, Ss were required to press whether or not the light was seen. Blank trials, in which the stimulus energy was one-tenth that of the threshold stimulus, were interspereresed at random throughout the first session. The averaged curves for the "seen" trials showed a definite dilation. The averaged curves for the "not seen" trials, and trials in which no disciminations (seen versus not seen) was required produced averaged dilations not substantially different from "blank trial" averages, in which the stimulus was probably never seen. Hakerem and Sutton (1966) concluded that this dilation occurred only when two conditions were met: 1) the threshold stimulus was seen by S; and 2) the detection of the stimulus had significance (i.e., a discrimination was required, and only then did dilation occur).

Using the averaged evoked potential recorded from scalp, Ritter and Vaughan (1969) obtained extremely similar results to those of Hakerem and Sutton (1966), with an analysis of a late positive component occurring at 450-550 msec. after the stimulus. Ritter and Vaughan (1966) used both auditory and visual discrimination tasks, with active electrodes placed at vertex and mid-occiput. Only the results of the auditory task will be presented here. In the auditory condition, the signal and non-signal stimuli were tone bursts separated by a 5 dB interval (the non-signal was louder than the signal). S was instructed to press a key whenever he detected the signal. The averaged evoked response for detected signals contained a prominent late positive component, with peaks from 450-550 msec., while averaged evoked responses to non-detected signals and non-signals had similar waveforms, but contained no late positive component.

These studies have shown that both pupillary dilation and the late positive component of the evoked potential occur only when S detects the signal, and is required to make a decision based on that detection. Similar results have been obtained by Hirsch (1970) for the P_3 component of the evoked potential, and by Simpson (1969) for the pupil. Paul (unpublished data), and Hillyard *et al*. (in press) have shown that P_3 is large in amplitude in a signal detection experiment when the signal is detected, but that P_3 is absent when responses to correct rejections, non-detected signals, and falsely-reported non-signals are averaged. Thus, taken together, these investigations demonstrate a close correspondence between Ss' perceptual reports and both P_3 and dilation response amplitudes.

2. *Pupillary correlates of stimulus uncertainty*. Similarity of response between pupil and evoked potential has been demonstrated with the variable of stimulus uncertainty. In this, and the next section, these studies will be reviewed. In addition, recent reports have shown that heart rate and GSR are also affected similarly by this variable. These studies will also be discussed.

Assuming that introducing stimulus uncertainty into an experimental situation involves emotionality, attention and mental activity for S, Levine (1969) and Levine and Hakerem (1969) studied the pupillary dilation response as a function of stimulus uncertainty. Stimuli were auditory clicks delivered at 60 dB above threshold. There were three types of click stimuli: 1) a single click never followed by another click; 2) a double click with an inter-click-interval of 50 msec.; and 3) a triple click, consisting of the double click as described in 2 , followed one second later by a third click. There were three conditions in the experiment: 1) *Told condition*, in which the *E* told *S* what the next click-type would be; 2) *Guess condition*, in which *S* was required to guess the identity of the upcoming click-type. In this condition, the single click resolved all uncertainty. However, if *S* was presented with a double click, he would have to wait one second in order to resolve his uncertainty. At that time, the third click would or would not occur; and 3) *Guess/Told condition*, in which *S* was required to guess what the next stimulus would be, but immediately after his guess, and prior to stimulus presentation, he was told both, whether he was right or wrong, and exactly what that trial's stimulus would be.

The results of the Levine and Hakerem (1969) study showed that, in all cases, dilations averaged across stimuli within the same individual *S*, were larger in the Guess condition than in either of the other two conditions. Both the Told and the Guess/Told conditions yielded similar averaged dilation responses. When the responses were averaged with respect to stimuli within a condition, the effect of stimulus uncertainty was clearly seen. For the Told and the Guess/Told conditions responses to the three click-types were identical, a small initial dilation to the single click and the rapid double click, with no detectable response to the third click. In the uncertain or guessing situation, the response depended upon the stimulus and the amount of information it conveyed. Dilations to the three stimuli were identical up to the point in time at which the amount of information conveyed was similar. Thus, all three averaged responses showed an initial dilation, but only the curves for the double and triple clicks showed a continued dilation, lasting until the point in time when uncertainty was resolved (i.e., when the third click did or did not occur). Thus, in the case of the double click, a "phantom" dilation was produced whenever S̲ had to wait for confirmation that the double click was, in fact, a double click.

Bradshaw (1968) studied pupillary and reaction-time changes associated with stimulus uncertainty. He employed three conditions: 1) No warning signal was given, and the signal to which S̲ had to respond was randomly either visual or auditory; 2) A warning signal was given, but the foreperiods preceding the response signal were randomly long (5 and 1/2 seconds) or short (2 and 3/4 seconds); 3) A warning signal was given, and the foreperiod was always short. As one would expect from the large body of reaction time literature (e.g., Hyman, 1953), the longest reaction times were obtained in condition one, the next longest in condition two, and the shortest for condition three. Continuous pupillary records were obtained at 2.7 intervals per second. The mean highest point in the pupillary curve while S̲ w̲a̲s̲ ̲r̲e̲s̲p̲o̲n̲d̲i̲n̲g̲, was consistently and significantly lower for the no-warning condition. The last ten pupillary records showed the opposite result: a significantly higher mean amplitude for the no-warning condition than for the other two conditions.

The points in time for which Bradshaw (1968) does report data are subject to criticism, since he recorded pupil size while S̲ was making a motor response, and this has been shown to enhance pupil size (Simpson, and Paivio, 1966). Since S̲ has no idea which interval will occur, the logical point in time for which pupillary data should be reported are during or at the end of the two intervals. Bradshaw (1968) commented that, "In three S̲s there was a small peak in pupillary dilation followed by a drop, in the variable-long condition, at that point in time when a response signal would have occurred had that interval been variable short" (p. 70). This comment by Bradshaw (1968) is exactly what was found for the pupillary dilation response by Levine and Hakerem (1969).

Pratt (1970) found a significant linear increase in peak pupillary dilation as stimulus "unpredictability" (Pratt also calls this "cognitive uncertainty") increased.

The above investigations extend the conclusion drawn earlier (Section IIA), that pupillary dilation is a physiological correlate of information processing in man. This was convincingly demonstrated by Levine and Hakerem (1969), whose results showed the existence of a "phantom dilation" at the point in time when a stimulus was expected, but did not occur. These data suggest, as have the data of other investigators (e.g., Sokolov, 1963a, 1963b), that a basic function of the CNS is the comparison of incoming information with information already stored in memory. This is not simply a qualitative finding. Pratt (1970) was able to demonstrate the existence of a linear relationship between dilation amplitude and uncertainty. These results have also been obtained with the P_3 component of the averaged evoked potential, and suggest that the evoked potential might be mediating the "peripheral" dilation response. The next section discusses findings for this component of the evoked potential.

2. Evoked potential correlates of stimulus uncertainty. Of considerable interest has been the finding of a late positive component (250-350 msec.) of the scalp evoked potential, which seems to be a correlate of the cognitive evaluation of the stimulus complex. This has been termed the P_3 component by Sutton and his colleagues (Sutton *et al.*, 1965, 1967). Except for latency, this late positive component appears to be independent of the sensory modality of the stimulus which delivers the

information (Sutton _et al._, 1967).

Sutton _et al._ (1965) investigated the effects of stimulus uncertainty on the P_3 component of the auditory evoked potential recorded from vertex electrodes. In one experiment, a cueing stimulus indicated to _S_ that a sound would always occur, or a light would always occur following a random interval of 3 to 5 seconds. In this situation, _S_ was certain of the nature of the stimulus that followed the cue. A second cueing stimulus indicated to _S_ that _either_ a sound or a light would occur. There were differences between the waveforms elicited by certain and uncertain stimuli in all of the components measured. However, the most marked difference occurred for P_3, this component being larger in the uncertain than in the certain condition. In a second experiment of the same paper, degree of uncertainty was varied by changing the probability with which a sound or a light followed a cueing stimulus. One cue was followed 33 percent of the time by a light and 66 percent of the time by a sound. A different cueing stimulus was followed by the inverse ratio. In all cases, P_3 was present, since _S_ was always uncertain. However, P_3 was greater in amplitude for the lower probability stimulus.

In a later study, Sutton _et al._ (1967) were able to demonstrate that the latency of the P_3 component corresponded to the point in time when _S_'s uncertainty was resolved. _S_ was either told in advance (certain) or had to guess (uncertain) what the next stimulus would be. The stimulus was a single click, which could or could not have been followed 180 msec. later by a second click. In the certain condition, P_3 was either absent or of minimal amplitude. In the uncertain condition, the occurrence of P_3 corresponded to that point in time when _S_'s uncertainty was resolved (i.e., 300 msec. following the second click). When the conditions were changed, and the second click occurred 580 msec. following the first, P_3 was delayed until 300 msec. following the second click.

A final study of the same paper (Sutton et al., 1967) convincingly demonstrated that P_3 latency was related to time of S's uncertainty resolution. S was presented with two click stimuli, separated by either a short (180 msec.), medium (580 msec.), or long (980 msec.) interval. Prior to each trial S was required to guess the length of the upcoming inter-click-interval. This resulted in a matrix of 9 contingencies (3 guesses by 3 intervals). P_3 was largest in amplitude, in all cases, when the presence of the second click delivered all the information (e.g., when S had guessed "long", but received "short"). Where the absence of the second click (e.g., guess "short", but receive "long" delivered the information, P_3 was relatively flattened. This was attributed to the precise time-locking of P_3 when the stimulus was present, as opposed to time jitter associated with information delivery via the absence of the second click.

Ritter, Vaughan, and Costa (1968) studied whether the P_2 component of the auditory evoked potential was subject to habituation. These investigators attempted to demonstrate habituation by presenting S with the same auditory stimulus for 30 trials. Using an averaging technique which allowed them to look at changes within a block of 30 trials, they found P_2 amplitude decrement when using inter-stimulus-intervals of 2 seconds. However, when they switched to an inter-stimulus-interval of 10 seconds, no decrease in P_2 amplitude occurred across stimuli. In order to determine if the amplitude decrement found using 2-second inter-stimulus-intervals was true habituation, a pitch change was introduced within the stimulus series to elicit dishabituation. Instead of finding an enhancement of P_2 amplitude with pitch change (which would be indicative of true habituation), they found a change in waveform, which consisted of a large positive component (P_3) peaking at about 350 msec. Further experiments led these investigators to conclude that P_3 reflected a shift of attention associated with the orienting response to unpredictable changes in pitch. However, in these experiments S was also uncertain as to when the pitch changes would occur, and therefore orienting may not wholly account for the results.

Tueting (1968) measured P_3 amplitude ($0-P_3$) as a function of degree of uncertainty. She varied the frequency of occurrence of high- and low-pitched tones, while S was required to guess (uncertain) or was told (certain) what the next stimulus would be. Four probabilities of occurrence were used: 20, 40, 60 and 80 percent. P_3 amplitude varied inversely and monotonically as a function of the probability of the stimulus. Also employed was an outcome probability measure (the interaction of S's guessing rate and the stimulus rate). When P_3 amplitude was plotted as a function of outcome probability, this same monotonic and inverse relationship was present.

Fox (1964) has shown that light-deprived Phesus monkeys show different rates of termination of sequences of light depending upon the nature of the light sequence. He used three such sequences: 1) regular sequences - repetitive flashes of 0.5 seconds duration, with an inter-flash-interval of 2 seconds; 2) random sequence - 0.5 seconds-duration flashes with randomly varying intervals, having a mean of 2 seconds and a range of 0-4 seconds; 3) derived self-sequence - consisted of $\underline{S}$'s own pattern as he had generated it on a previous test day by bar-pressing for light reinforcement. The monkeys were placed in a completely-darkened chamber and exposed to each stimulus sequence. A bar press terminated light for 30 seconds. Therefore, the higher the number of presses, the less preferred was the sequence. Termination rates were highest for the regular sequence, next for the random sequence and least for the derived sequence. With these results, Fox (1964) reasoned that these three sequences of sensory change should be differentially represented in the CNS. He then implanted his $\underline{S}$s with recording electrodes, and again exposed them to the three sequences. The main finding was that evoked potential amplitude recorded from a variety of structures habituated dramatically for the self-sequence and the regular sequence. No habituation was apparent for the random sequence, thus leading Fox (1964) to attribute these results to the amount of uncertainty in the random sequence.

Clearly, information processing is reflected in the evoked potential, especially the late components. This is both a qualitative (P_3 present in uncertain condition, but not in the certain condition), and a quantitative finding (P_3 amplitude decreased as event frequency increased). These quantitative relationships appear to hold for other physiological measures, such as heart rate and GSR.

3. Heart rate and GSR correlates of stimulus uncertainty. Heart rate changes as a function of stimulus uncertainty have also been investigated. A very recent report by Higgins (1971) has shown changes in heart-rate deceleration as well as acceleration as a function of degree of uncertainty. Higgins' experiment was designed to manipulate $\underline{S}$'s expectancy

as to whether a signal or a non-signal would occur. The stimulus configuration was a horizontal array of five lights. Every 27 seconds, one of the five lights would come on at full intensity and then dim. The order of light-occurrence was random over 100 trials. As the light went off, a tone occurred - either the T_s (signal) at 1343 Hz, or the T_{ns} (non-signal)at 1265 Hz. The probability of the T_s following each of the five lights was manipulated so that it was most likely to follow the left-most light (L_1), and least likely to follow the right-most light (L_5), with a graded probability of occurrence between these extremes (from a probability of 1.0 - 0.0). The T_{ns} took on the reverse probabilities of the T_s at each of the five lights.

S was informed, as in the present experiment, of the exact probabilities at each light. Two groups were formed, group VIG simply delayed their button press to the T_s, while group RT had to respond to the T_s as quickly as possible. No response was to be given to the T_{ns} in either group. Reaction time in group RT was a decreasing function of the T_s's light-generated expectancies (i.e., RT to L_1, in which S was 100 percent certain that the T_s would occur, was faster than at L_4, where the probability was .2 that the T_s would occur). The heart rate curves for both groups were triphasic waveforms, consisting of an initial acceleration, followed by a deceleration lasting until tone onset, and followed by a final acceleratory phase. Only the first two heart rate components were subjected to analysis, and both were significantly related to the stimulus uncertainty engendered by the lights, with faster acceleration and deceleration occurring prior to the T_s which followed the light having maximal uncertainty. Although the final, post-stimulus acceleratory phase was not measured, it appears from the curves presented in figures 4 and 5 of Higgins' (1971) paper that this acceleration was also affected by uncertainty.

Lovibond (1969) has presented results for multiple stimulus sequences. Employing the orienting response as a theoretical model, Lovibond (1969) predicted that an inverse function would best describe the relationship between GSR habituation and stimulus uncertainty. Stimuli were presented in pairs in a classical-conditioning paradigm, with S_2 occurring at S_1 offset. The probability that S_2 would follow S_1 was varied for seven groups of Ss, representing 0, 10, 20, 50, 80, 90, and 100 percent reinforcement. The results were in accord with Lovibond's prediction, the 100 and 90 percent groups habituating more rapidly than the 80 or 20 percent groups, which habituated faster than the 50 percent group. Lovibond (1969) concluded that his results were "consistent with Sokolov's neuronal model of the orienting response, and offered further support for the view that human information processing involves a form of probability analysis similar to that postulated by information theory" (p. 438).

In summary, results of studies employing stimulus uncertainty as the main independent variable have shown remarkably consistent and similar effects in a variety of physiological system. This would appear to indicate that some common neurophysiological mechanism mediates these responses.

IV. The Contingent Negative Variation

Considerable research interest has been invested lately in the study of a slow, negative DC shift that seems to be the correlate of "expectancy", attention, intention, and conation. This negative shift has been correlated with such a wide variety of psychological states, that the literature describing it does not lead to any general conclusions regarding its significance or genesis. Grey Walter et al. (1964) were the first to describe this negative shift as developing between two stimuli, S_1 and S_2, when a contingency between S_1 and S_2 had been established by requiring S to make a motor response as quickly as possible to S_2. Therefore, Walter et al. (1964) called it the "contingent negative variation " (CNV). It has also been called an "expectancy" or "E-wave" (Walter, 1966), since it supposedly reflects the attitude of S to the anticipated pairing of S_1 and S_2.

Hillyard and Galambos (1967), Low, Borda, Frost and Kellaway (1966), and Walter et al. (1964) have indicated that a motor response is not necessary for CNV occurrence. However, some investigators report a somewhat larger CNV when a motor response (a key press) is instructed to S_2 (e.g., Low et al., 1966). Some response, either mental (e.g., estimation of time occurrence of S_2), or motor (e.g., key press) is required for maintenance of CNV.

Generally, the field of the CNV over the scalp is maximum anteriorally and medially, although it can be recorded over the entire head (Low et al., 1966; Walter et al., 1964). It is usually of maximal amplitude at the vertex electrode (Cohen, Offner and Blatt, 1965; Cohen and Walter, 1966; Low et al., 1966). It has also been reported that CNV is independent of the modality of the stimuli used, and is not affected by the intensity of the stimulus (Low et al., 1966; Walter et al., 1964).

That these shifts are indeed cerebral activity has been demonstrated by Walter (1965b), and Walter and Crow (1964) who recorded them from cortex in patients with chronic implanted electrodes. A CNV has been recorded from the cortex of Rhesus monkeys, when S_1 and S_2 were associated in an escape conditioning paradigm (Low, Borda and Kellaway (1966). Low _et al_. (1966) and Walter (1965a) have demonstrated that the CNV is not due to eye movements, and Low, Borda, Frost and Kellaway (1966) have produced CNV in an enucleated _S_.

A. _Physiological Mechanisms_

Activity that is wide-spread and synchronized over cortex is attenuated only about one-half from scalp leads (Cooper, Winter, Crow, and Walter, 1964). The CNV is just such activity, and has been seen in depth recording from the human brain (Walter and Crow, 1964). These responses to _single_ stimuli show marked habituation with monotonous repetition, but are re-established upon stimulus change, and/or conditional, association between the repeated stimulus and another one.

Slow potential changes in the brain have been studied in a number of situations involving pronounced changes in level of arousal. Arduini (1958) obtained a slow negative DC shift in cat cortex in response to electrical stimulation of a sensory nerve, as well as to natural stimuli, such as startling noises. He hypothesized that these enduring changes were mediated by the reticular formation. Stimulation of midbrain reticular formation, whether superimposed on a background of synchronized or desynchronized EEG activity, led to negative potential changes similar to those occurring during sensory stimulation. These responses were obtained over the entire cortex, but with highest amplitudes in frontal areas. Both the sensory and reticular effects were blocked by nembutol, which did not affect the primary response of the specific projection areas. Arduini attributed these potential changes to post-synaptic activity of cortical neurons underlying the recording electrode.

Caspers (1963) has shown a remarkably consistent relationship between the sleep-wakefulness spectrum and steady-potential shifts in unrestrained, freely-moving rats. In the awake animal, these DC steady-potential shifts exhibited considerable fluctuation, which were strictly synchronized with behavioral activity changes. These potential changes were negative and occurred especially in connection with events which Caspers classified as "orienting movements". At the transition from wakefulness to sleep, the steady potential of the cortex shifted to the positive side, relative to the mean waking level. Full arousal, evoked by a peripheral stimulus, was always associated with a complete return of the DC component to the negative waking level. During the transition from sleep to wakefulness, the steady potential of the cortex shifted to the negative side. These shifts were recorded from all areas of the cortex.

The cortex consists of vertically-oriented neurons, sending dendritic processes to the surface. Therefore, either negative or positive changes might develop when the subsurface dendrites and deeper neuron somata become unequally polarized. Surface negativity may be caused by depolarization of apical dendrites, or could be cause by hyperpolarization of deeper neuron cell bodies (O'Leary and Goldring, 1964). Evidence supporting this interpretation has been provided by Fromm and Bond (1964). They observed that positive shifts in cortical potential were associated with faster firing of single cortical neurons than during negative shifts, in which case rates of firing were much slower or non-existent. They assumed they were recording from pyramidal neurons. Therefore, inhibitory neural mechanisms appear to play a role in the genesis of negative shifts.

B. Psychological Correlates

CNV amplitude has been studied as a function of a wide spectrum of psychological variables, the most common of which have been motivation and attention-arousal. As stated previously, CNV has been implicated as the cerebral correlate of "expectancy", so that some investigators have studied CNV during expectancy situations, particularly "probability dilution". In view of the fact that both CNV and P_3 have been recorded in the same experiment and have been found to covary, these studies will also be reviewed.

1. Attention. About the only conclusion one can make regarding the CNV and its relationship to psychological variables is that when a task is given to S which requires an assumed attentional state, CNV is present, and is usually of greater amplitude when S must "pay attention" than when he relaxes his attention.

Rebert, McAdam, Knott and Irwin (1967) varied the difficulty of detecting S_2 by manipulating its intensity. S_2 was a tone which, if preceded by a light flash on S's left was faint, but detectable with difficulty (S_2 was adjusted for each S). If preceded by a light flash on S's right, the tone was of moderate intensity (the same for all Ss), and easily detectable. CNVs were significantly larger preceding the moderate tone. These authors interpreted this result as showing that the difficulty level of the discrimination increased S's motivation, and therefore led to greater CNV amplitude. However, these results are entirely consistent with those studies demonstrating increased amplitudes of evoked potentials under vigilance conditions (e.g., Ritter and Vaughan, 1969), as well as those studies showing increased CNV amplitude during vigilance conditions, correlated with percent detections (e.g., Wilkinson and Haines, 1970). Requiring S to detect a faint tone would tend to increase his vigilance and/or arousal, and, unless he is paid, not his level of motivation.

McAdam (1969) studied cortical excitability during CNV genesis by interposing a shock to the median nerve during CNV production. The experimental group was required to respond to S_2, thus producing a CNV, while Ss in the control group were given the same stimuli, but did not respond to S_2 (producing minimal CNVs with amplitudes between zero and five microvolts). Each group received three types of trials: 1) tone alone, in which tone onset served as S_1, tone offset as S_2; 2) median nerve shock alone; and 3) median nerve shock delivered one second after tone onset (i.e., during CNV genesis). Analysis of peak to peak amplitudes within the two groups between the shock alone, and the shock plus tone conditions, showed no differences between CNV and non-CNV groups. However, analysis of changes in peak latencies showed significantly shorter latencies in the later components of the somatosensory evoked potential during the tone plus shock than during the shock alone, and these changes were unique to the CNV group. The author interpreted his results as supporting the hypothesis advanced by Walter et al. (1964) that the CNV represents the "electric sign of cortical priming", and therefore increased excitability of the CNS. In support of McAdam's (1969) findings, Hillyard (1969), and Tecce and Scheff (1969) have reported shorter reaction times to S_2 associated with larger-amplitude CNVs.

Wilkinson and Haines (1970) studied CNV amplitude changes as a function of vigilance decrements (percent detections). S_1 was a warning click, followed 1.92 seconds later by an "inspection click", which, if softer than usual, was the signal. S had to report a signal by pressing a key as fast as possible. CNV as well as percent signal detections declined over quarters of an experimental run. Thus, CNV was correlated with a decline in vigilance. It is interesting to note that one of their Ss showed no CNV activity at all, but did show positive shifting, apparently unrelated to the task.

McCallum and Walter (1968), in a series of experiments, were able to demonstrate CNV amplitude reduction during "distraction" conditions. These conditions varied from interspersing a tone between S_1 and S_2, to talking by E during CNV production. With instructions to concentrate on obtaining fast reaction times to S_2, CNV increased in amplitude.

In an experiment designed to determine the relationship between CNV and "attentiveness-alertness", Low, Coats, Rettig, and McSherry (1967) manipulated the intesnity of S_2 around a threshold value. Ss were given a series of flash-click pairs in runs of 24 trials, from clearly audible to inaudible, and vice versa. The data reported were averaged over the two runs at each intensity. These investigators reported that, after their Ss had been performing for some time, or during periods when the clicks were inaudible, the graphically-recorded EEG showed signs of decreasing alertness. This was also reflected in the number of incorrect responses to clicks known to be audible or inaudible. Low *et al.* (1967) demonstrated that CNV variability tended to decrease, and CNV amplitude increase as click intensity neared threshold. These data support those of Rebert *et al.* (1967).

Connor and Lang (1969) investigated the relationship between CNV and heart rate in a reaction-time experiment. Following Lacey's (1967) postulation that the degree of heart-rate slowing reflects an attentionfacilitating effect of cardiovascular feedback on cortical activity (as evidenced by a negative correlation between degree of heart-rate slowing and reaction time), they attempted to determine if CNV was the cortical consequence of heart-rate slowing. In Experiment I of their report, two non-signal conditions, in which S simply listened to a series of tones, were compared to a simple reaction-time task, in which S had to respond to S_2 by pressing a microswitch, and to a disjunctive reaction-time task in which S responded to S_2 only if it was the same as S_1. Experiment II was essentially the same, without the use of a disjunctive task, and with the addition of the recording of vertical and horizontal EOG. The results of both experiments were similar. There was heart-rate acceleration following S_1, and in the reaction-time tasks, there was continued deceleration to S_2, while in non-signal conditions there was a return to baseline. CNV showed significantly more negativity in the signal conditions, with trends toward positivity in the non-signal conditions. The correlation between cortical negativity and downward EOG was 0.62. Within-S analyses demonstrated significantly more heart-reate slowing for fast reaction times than for slow reaction times. The same was true of CNV: more negativity for fast than for slow reaction times. Connor and Lang (1969) also had their Ss rate their level of alertness. There was no association between heart rate, or EOG and ratings, but CNV tended toward greater positivity in Ss who rated themselves as drowsy.

In summary, most studies directed specifically at this problem have shown that CNV does reflect the attentional state of S.

2. Stimulus uncertainty. CNV amplitude has also been found to vary with the probability of occurrence of S_2, although there are

contradictory reports of the effect of "probability dilution" (Walter _et al._, 1964) on CNV. Walter (1965a; 1966) and Walter _et al._, (1964) report that the CNV is reduced in amplitude during probability dilution of S_2 (i.e., S_2 omitted on a certain percentage of trials). However, Hillyard and Galambos (1967) in more systematic studies, were unable to replicate this finding. Low, Borda, Frost, and Kellaway (1966) confirmed the finding of smaller CNV amplitude during probability dilution of S_2.

In additional support of Walter's (1965a; 1966) dilution findings, Wilkinson and Haines (1970), in a vigilance setting, obtained larger CNV amplitudes to signal stimuli with a high probability of occurrence than to those with a low probability of occurrence.

Cohen and Walter (1966) have shown increased CNV amplitude to pictorial stimuli which were meaningful or symbolic. CNV was larger when stimuli shown were randomly varied and all different, than when the stimuli were all the same (repeated from trial to trial), or when blank slides were presented. Cohen and Walter (1966) attributed this to the variation in stimulus pattern, and the interest value of the stimuli, but it could also be argued that _S_ was more uncertain in the situation where the slides were all different than he was when they were all the same.

In another study involving uncertainty, McAdam, Knott and Rebert (1969) asked their _S_s to predict the length of the interval interposed between S_1 and S_2 that they were to receive. There were two interval lengths, long (2400 msec.), and short (1200 msec.). CNVs and reaction times to S_2 were measured in each of the four possible contingencies: predict short-receive short; predict short-receive long; predict long-receive long; predict long-receive short. Reaction times were significantly longer when Ss received an interval other than that which they had predicted. CNVs were measured at two points, the point at which the short interval ended (1200 msec.), and the point at which the long interval ended (2400 msec. following S_1). When measured at the 1200 msec. point, CNVs were largest for the predict short-receive long contingency, than for any other contingency. This is to be expected, if CNV amplitude and uncertainty are related, since 1200 msec. is the point in time at which S is uncertain about the interval he is to receive. At that point he could either receive a short or a long interval. When measured at both "short" and "long" points for only the receive long contingencies, CNV amplitude declined between the 1200 and 2400 msec. points for the predict long-receive long trials. It also declined for the predict short-receive long contingency, but was larger at the 1200 msec. point for this contingency than for the former contingency, and was smaller in amplitude at the 2400 msec. point for the predict short-receive long trials than for the predict long-receive long trials. The authors related this finding to the correctness of S's prediction. However, this finding can be explained without invoking correctness of S's guess as an explanation. In both these contingencies (receive long) S's uncertainty is dispelled at the 1200 msec. point. If CNV amplitude is related to uncertainty, than it would be expected that the CNV would decline in amplitude from short to long points in both these contingencies, since maximal uncertainty is resolved at the short points.

In a study similar to the present experiment, Weinberg, Walter and Crow (1970) recorded CNV and evoked potentials from intracerebral electrodes located in orbito-frontal, cingulate and surface superio-frontal cortex, in patients undergoing psychosurgical procedures. Weinberg et al. (1970) required their Ss to guess whether or not they expected a stimulus to occur. Stimuli either did or did not occur on a given trial. Ss used a lever, which was pressed to the right if a stimulus was expected, and pressed to the left if no stimulus was expected. Ss received sixpence for three consecutive correct guesses, whether they were affirmative (yes stimulus) or negative (no stimulus) guesses. The occurrence or non-occurrence of the stimuli was pre-programmed, and the stimulus was either a click, a flash, or a mild electric shock. The results confirmed those of Sutton et al. (1967) in demonstrating the production of "emitted" potentials (phantom wave) when a stimulus was expected, but did not occur. They obtained P_3 in the expectancy condition (i.e., when S indicated he expected a stimulus to occur), but not when the contingency was such that S had predicted no stimulus would occur, and no stimulus did occur. Weinberg et al. (1970) also obtained CNVs preceding evoked as well as "emitted" responses under expectancy conditions, but none in which S indicated that he did not expect a stimulus

To summarize, CNV does appear to reflect the expectancy of S. This was definitively shown by Weinberg et al. (1970). However, the "probability dilution" paradigm does not employ the guessing of whether or not S_2 will occur. Probability dilution is more like an extinction process in a classical-conditioning experiment. Whether or not CNV amplitude is affected by probability manipulation in a guessing-expectancy situation is one of the foci of the present experiment.

3. Motivation. Many investigators have implicated CNV as a

physiological correlate of motivation (e.g., Irwin, Knott, McAdam and Rebert, 1966; Rebert, McAdam, Knott and Irwin, 1967). In experiment I of their report, Irwin _et al._ (1966) instructed their _S_s to a) not respond to serial pairings of a tone (S_1) and a flash (S_2); b) press the response key as quickly as possible in response to the flash when the tone was heard on _S_'s right, and not to press the key when the tone was on _S_'s left and c) not to respond to the flash regardless of where S_1 was heard. An analysis of CNV amplitudes indicated that when no response was instructed to the flash, the CNV was smaller than when a response was required. There were no differences between magnitudes of the shifts in any of the no-response conditions. One surprising result, not in line with other data (e.g., Hillyard, 1969; Lansing, Swartz and Lindsley, 1959; Walter, 1966) was the finding that the ten fastest reaction times to S_2 were not accompanied by signficiantly higher-amplitude CNVs than the ten slowest reaction times.

In Experiment II of the same paper, the two stimuli were tone followed by shock. In condition A, 30 left warning signals were followed by weak shock to the middle finger of the left hand, while 30 right warning signals were followed by strong shock. No response was required to S_2. In condition B, the same conditions prevailed except that _S_ was required to respond to S_2 by pressing a key. Both shock level and response instructions were significant variables which affected the amplitude of CNV. A larger CNV was present preceding strong shock than preceding weak shock, as was a larger CNV found for response than for no response conditions. Reaction times for strong shock were significantly shorter than for weak shock.

Requiring S to exert more pressure in making his key press (2 pounds versus 14 pounds of force) reliably increased the magnitude of the CNV (Rebert *et al.*, 1967). This was interpreted as an operation designed to increase S's motivation. Correlations between CNV amplitude and reaction times within the high- and low-effort conditions yielded coefficients of -0.38, and -0.39 respectively, both significant. Similar results for anticipated emergy output were reported by Low and McSherry (1968).

McAdam, Irwin, Rebert and Knott (1966) presented results which indicated that amplitude of the CNV could be affected by asking Ss to "think high" or "think low" amplitude. However, this effect seemed to be related to the state of vigilance S created. When "thinking low" amplitude, Ss reported relaxing their speed efforts and vigilance, while imagining that S_2 was difficult to detect when "thinking high" amplitude CNVs.

A fact that complicates the picture of the CNV as the representation of cerebral events related to cognitive functioning (e.g., motivation), is that slow, surface-negative potential shifts, maximal at vertex, are also recorded prior to voluntary movement (Deecke, Scheid, and Kornhuber, 1969; Gilden, Vaughan and Costa, 1966). CNV, however, has been shown to develop without a motor response to S_2 (Donchin, Gebrandt, and Leifer, 1970). When a motor response is required, the resultant CNV might be a combination of motor potential and "mental potential". Therefore, requiring S to exert more pressure in making his response (as in the Rebert *et al.*, 1967 study) might have nothing to do with motivation. This requirement may have simply increased the "motor" portion of the CNV. Ss in the McAdam *et al.* (1966) study were able to generate high-amplitude CNVs by pushing the key as hard and as fast as possible. Thus, the variables of force and speed should be controlled before amplitude changes in CNV are attributed to intervening cognitive variables.

4. The CNV and the late positive wave of the averaged evoked potential. A number of studies have recently been published which demonstrate a marked covariation between CNV and P_3. That is, when CNV is present, so is P_3. Since P_3 has been related to such variables as the "significance" of the stimulus to S (Sutton et al., 1967), and since S_2 in Walter's CNV paradigm is usually "task-relevant", or 'meaningful" to S, CNV ends with a positive-going process, peaking at approximately 300 msec. following S_2. This resolution corresponds to most reports of P_3 latency. Thus, as Donchin and Smith (1970) point out, CNV and P_3 may be two aspects of the same process, due to the fact that in most studies that report P_3 enhancement, a CNV might be expected to develop prior to the stimulus.

In order to test their hypothesis, Donchin and Smith (1970) replicated an earlier study of theirs (Donchin and Cohen, 1967), in which two figures alternated randomly with an average rate of once every two seconds. Ss viewed the stimuli in a tachistoscope. Superimposed on the alternating figures was a square flash of light. This was done at the rate of once every two seconds. S had two tasks: 1) In Task FC, S had to respond to the falshes by pressing a switch as fast as possible; 2) In Task RC, S had to press the switch each time the two figures alternated. As Donchin and Smith (1970) explain, when flash was relevant it served not only as a response cue, but also to indicate that another flash could be expected within a certain time period. They reasoned, therefore, that a CNV might develop between successive flashes in the FC condition, but not when flashes were irrelevant. The same would hold for the development of a CNV between successive alternating figures. In the 1967 study (Donchin and Cohen 1967), the inter-stimulus-intervals were not constant, nor was the time constant of the amplifiers long enough to allow them to record slow, baseline shifts. In the 1970 study (Donchin and Smith, 1970), band pass at the low end was 0.1 cps, figures alternated every two seconds, and 50 msec. flashes were presented every 2.25 seconds. The results conformed to prediction; when the eliciting stimulus was task-relevant, a CNV developed between the successive relevant stimuli, and culminated in a positive-going shift (P_3) 300 msec. following the stimulus.

Naatanen (1970), using a very similar design, obtained similar results. He alternated loud and soft clicks at a regular rate of one per second. S knew which stimulus would occur. There were two conditions: 1) in Condition S, loud clicks were relevant; 2) in Condition W soft clicks were relevant. A total of 50 relevant and 50 irrelevant stimuli were delivered in each series. S's task was to determine which 5 out of the 50 relevant clicks differed in intensity. S indicated this with a key press. These five "signal" stimuli were not employed in the averaging process. Naatanen used an overall measure of evoked potential amplitude, which appears to correspond to an N_1-P_3 measure of the vertex auditory evoked potential. He found increased evoked potential amplitude to task-relevant clicks as well as larger CNVs preceding the relevant click. Naatanen also measured the last 267 msec. of background EEG activity preceding the stimulus, and found a significant decrease in amplitude preceding the relevant stimulus compared to that preceding the irrelevant stimulus. From this combination of results, Naatanen concluded that evoked potential enhancement was due to "preparatory cortical activation" as evidenced by larger CNVs and decreased "raw" EEG amplitude.

While these two studies have demonstrated parallelism between CNV and P_3, this covariation may be due solely to the experimental conditions. It is, therefore, possible that the failure to delineate differentiating conditions, under which, for example, CNV is present and P_3 is not, has accounted for the association between CNV and P_3.

Small and Small (1970) examined the relationships between CNV and evoked potential using flash-click pairings with a .5 second inter-stimulus-interval. They required their Ss to either respond to S_2 by a button press, or not to respond to S_2. Whether or not a response was required produced no difference in either the visual evoked potential or the auditory evoked potential (recorded from vertex), while responding did produce larger-amplitude CNVs. It appears from their data that P_3 was included in their measurement of the auditory evoked potential, although no presentation of a typical evoked potential is given, and measurement procedure is rather vague.

In a well-controlled study, Donald and Goff (1971) were able to dissociate CNV and P_3. They had their Ss performing a difficult tone discrimination, with a two-second foreperiod. S_1 was a .1 msec. click and S_2 was a 32-msec. tone pip, which varied in 100 Hz steps from 100-1500 Hz, which S identified by pressing the appropriate key. The press was delayed to prevent confounding of motor potential with P_3. During the two-second foreperiod, averaged evoked potentials to left median nerve shock were recoreded at 500, 1000, and 1500 msec. (when shock would occur was unknown to S) after S_1. On shock irrelevant trials, S's task was simply to identify the tone by an appropriate key press, even if they were shocked. Shock-relevant trials occurred only when no shock was given. In this case, Ss were told to press a "no shock" button, rather than to identify the tone. CNV amplitudes did not differ on shock-relevant or shock-irrelevant trials, while P_3 amplitudes were significantly larger on shock-relevant trials. These investigators then divided the relevant and irrelevant trials for each S into CNV amplitudes above (High) and below (Low) that S's median CNV amplitude. Regardless of CNV amplitude, P_3 was always larger on relevant trials. Donald and Goff (1971) concluded that the correlation between P_3 and CNV could be either zero, negative, or positive, depending upon experimental conditions.

Hillyard et al. (1971) studied CNV and P_3 in a detection experiment, in which the signal occurred on 50 percent of the trials. S_1 was a warning flash, followed 500 msec. later by a signal (1000 Hz tone pip of 50 msec. duration) on 50 percent of the trials. CNV amplitude as well as P_3 amplitude were larger on trials in which the signal was correctly detected. For correct rejections, undetected signals, and falsely-reported signals P_3 was of minimal amplitude or absent completely. CNV preceding hit trials was "several times smaller" than P_3. CNV was also present on correct rejection trials, while P_3 was not.

The Hillyard et al. (1971), as well as the Weinberg et al. (1970) study discussed under a different topic, and the Donchin and Smith (1970) study demonstrated parallelism between CNV and P_3. However in the Hillyard et al. (1971) study there was a dissociation between P_3 and CNV in the case of correct rejections. CNV was present, while P_3

was not. CNV appeared, therefore, to be mediating attention directed toward the stimulus, while P_3 represented an evaluation of the stimulus.

To summarize, most studies in which concomitant recording of CNV and P_3 has been done have demonstrated that these two responses react similarly in response to the same experimental operations. However, as Donald and Goff (1971) have shown, this does not mean that they are causally related. Instead, they appear to be independent processes, affected in similar ways by the same experimental procedures.

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