GALVANIC STIMULATION AND
THE PERCEPTION OF ROTATION

by

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Chairman, Departmental Graduate Committee

"Concern for man, himself, and his
fate must always form the chief
interest of all technical endeavor...

....Never forget this in the midst of
your diagrams and equations."

-Albert Einstein

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ABSTRACT

The influence of galvanic vestibular stimulation on the perception of rotation was investigated. The study was intended to lay the groundwork for future, more detailed study of the galvanic reaction. Of particular interest are possible clinical applications in the treatment of vertigo and the diagnosis of certain vestibular disorders.

A set of experiments were designed to measure the gross effects of current intensity and point of application on a subject's perception of rotation. An approximate threshold for the intensity effect was determined. Among points of application only polarity differences could be shown to be significant. A tentative linear relation between the bias in perception threshold and the intensity of current was found. The galvanic reaction of one vestibularly abnormal subject is also discussed.

Comparisons were made between galvanic stimulation and other common means of vestibular stimulation. Current mathematical models of vestibular function were reviewed and the extension of these models to include the galvanic reaction was examined.

Possible future directions for research in this area are also discussed.

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CHAPTER 1

INTRODUCTION

Most animals, including man obtain information about their spatial orientation in several ways: visual cues, proprioceptive and tactile cues and vestibular cues. The vestibular labyrinth, the non-auditory portion of the inner ear, plays a particularly important role in providing this information. The vestibular system has been studied by a variety of researchers for many different reasons. The physiologist approaches it as he would any biological organ, the clinician as an important sensor which can and does fail, and the bioengineer as a control system element which is coupled to other systems in order to guide the animal through its environment.

1.1 Background

Clinical interest in the vestibular system has always been high. Additional impetus for vestibular research has been provided in recent years by the manned space flight program due to the special orientation difficulties experienced by man in space. Nevertheless, much about the vestibular system is not fully understood, especially in those areas concerning the diagnosis and treatment of vestibular disorders.

Of particular interest to the clinician and to the space physician are the responses of the vestibular system to rotation and disorders related to rotation or to movement. Vertigo, dizziness, and motion sickness are familiar problems related to this area of concern.

A number of stimuli have been employed to study the response of the vestibular system. The most common two have been rotation and caloric stimulation. The latter is a common clinical technique in which hot or cold water irrigation of the ear produces a response similar to that obtained during rotation.

Using the caloric test, which is discussed in more detail in Chapter 2, the physician is able to obtain a good idea of the functioning of a portion of the vestibular system one ear at a time whereas rotation stimulates both ears.

Another means of stimulation has been observed to produce disorientation effects similar to those experienced during rotation. It has been known for some time that direct current passed through the head gives rise to a swaying or rotatory sensation. The galvanic vestibular reaction, as this effect is called, has been studied with varying interest since the 1800's. The lack of enthusiasm has apparently resulted from several factors. One is that the action site of the current is not known exactly making it of somewhat questionable value in clinical testing. A second reason is that until comparatively recent, constant current stimulation equipment and precise response measurement devices were not readily available, making it difficult to perform repeatable experiments.

Though the action site is not known exactly, it is currently felt that galvanic stimuli do not act at the same points as rotational or caloric stimuli. Rather the current is thought to act closer to the central nervous system. This suggests that the galvanic stimulus might be used to distinguish between certain vestibular disorders and indeed this approach has been taken by a number of people with some apparent success. Most studies have been rather qualitative however. What seems to have been lacking in the past was an attempt to establish quantitatively the effects of current intensity and polarity on subjective sensations of rotation and on eye movements.

If quantitative measures of response were available and if the action site of the stimulus were well understood, the galvanic reaction might be of definite value as a clinical diagnostic test. Quantitative knowledge of the effects might also make galvanic stimulus useful as a treatment for such disorders as vertigo. For example, a certain current intensity might be shown to cause a sensation similar to that experienced during a specified angular stimulus or during vertigo. A patient with vertigo might then receive a galvanic stimulus of proper polarity in an attempt to cancel his dizziness sensation(In Chapter

3 will be noted that reversing polarity generally reverses the effect of a galvanic stimulus).

A number of questions must be answered before such a treatment could be used however.

1.2 Scope of Thesis

This thesis is intended to lay the groundwork for a future more detailed study of the galvanic vestibular reaction. Past work on vestibular response to rotational, caloric and galvanic stimuli is reviewed. Similarities in rotational and galvanic reactions are discussed.

A group of experiments were designed to study the gross effects of vestibular stimulation on the perception of rotation. Both voluntary subject response and eye movements were studied. The primary objective of the experiments was to determine whether galvanic stimulation can indeed bias the threshold for rotation sensation. Secondary related objectives were to determine which intensity levels and modes (electrode locations), if any, influenced the results. Also, if a threshold bias could be found, some quantitative measure of the cause-effect relationship would be sought.

1.3 Results

The experimental results indicate that it is possible to bias the threshold for rotational perception in a predictable manner. Further substantiation was also given to the belief that a certain constant bias or directional preponderance is present in so called normal subjects without the galvanic stimulus. Polarity of the stimulus was found to have a significant influence on the results bearing out past findings. For a given polarity however, no significant differences in response could be found between the various standard electrode modes (see Chapter 3 for a discussion of these modes).

A threshold for current intensity effect was found to be between 400 and 800μa. Using this information and the observed bias in perception, a probable plot of bias in perception vs current intensity was drawn. On the same basis, a first hypothesis of how to add the galvanic reaction to existing vestibular control theory models is hypothesized.

The work performed also suggested a number of future directions for the research.

1.4 Outline of the Thesis

The thesis is arranged as follows:

Chapter 2 reviews the anatomy and physiology of the vestibular stystem with emphasis on rotation sensing mechanisms. Techniques for vestibular study are discussed as are current mathematical models of vestibular response including the caloric reaction.

Chapter 3 outlines the history of research into the galvanic vestibular reaction and discusses the various types of tests which can be run in order to study the reaction in a gross sense. An attempt is made to organize what is presently considered to be the nature of the reaction.

The experimental method used to study the gross influence of galvanic stimulation on the perception of rotation is the subject of Chapter 4 and Chapter 5 discusses the results of these experiments.

Chapter 6 presents the conclusions and gives suggestions for further research.

The Appendices contain discussions and listings of the computer programs used for data analysis.

CHAPTER 2

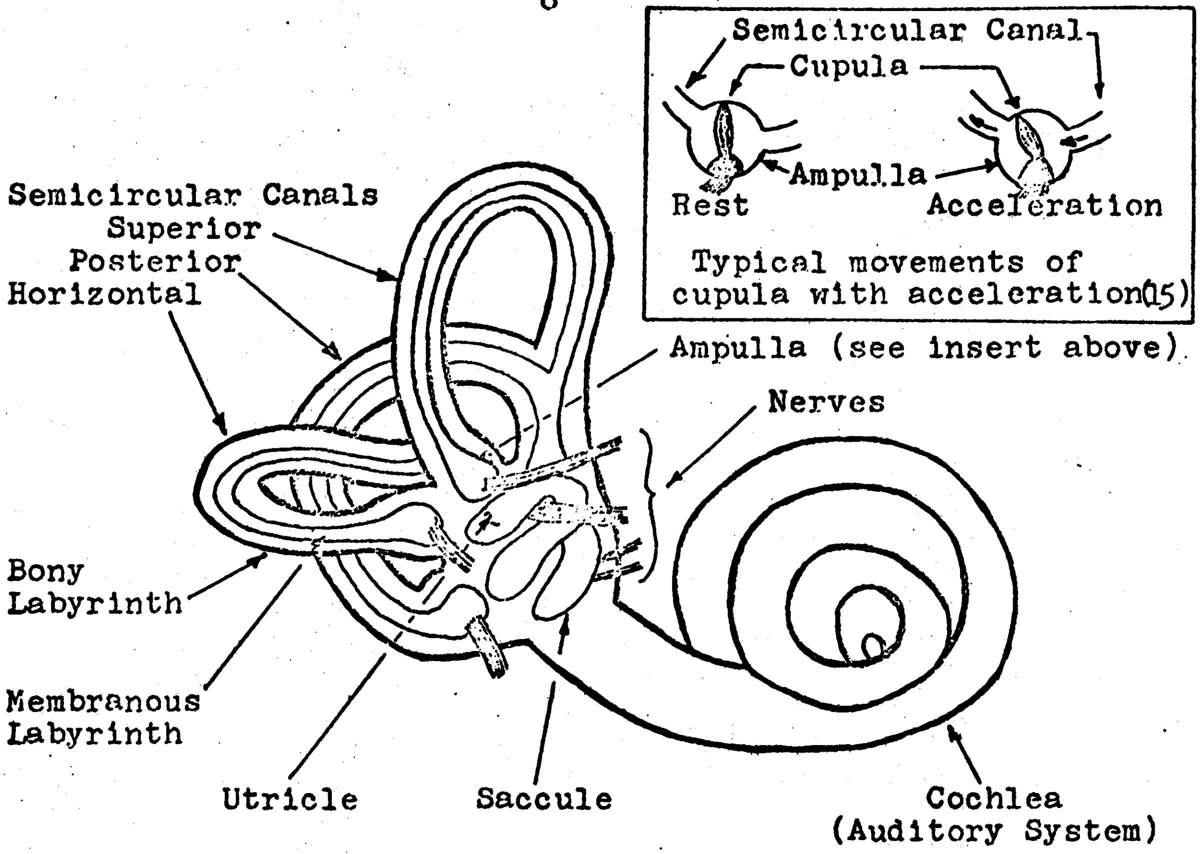
THE ANATOMY AND PHYSIOLOGY OF THE VESTIBULAR SYSTEM

The vestibular system, the non-auditory portion of the inner ear, enables an animal to sense its motion and verticality with respect to its environment. So basic is the vestibular system that in lower animals, its proper function is essential for the maintenance of life. Higher animals, including man, experience difficulty maintaining orientation if vestibular function is lost, but are partially able to compensate for the loss by using other cues such as vision.

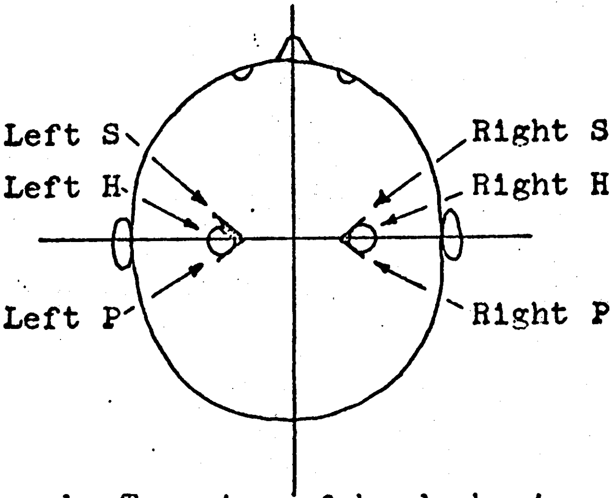
This chapter discusses the structure and function of the human vestibular system with particular emphasis on the features which enable it to sense angular accelerations. Means of studying vestibular response to rotation are discussed and current mathematical models of this response are reviewed briefly.

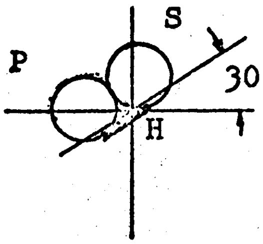
2.1 Location and Gross Structure of the Labyrinth[14,27,29]

The paired vestibular system is contained within the temporal bone of the skull in a cavity known as the bony labyrinth. Figure 2.1 shows the approximate location of both and the structure of the vestibular apparatus.



a, Vestibular labyrinth of the right ear (21)





c.View into right ear (29)

b. Top view of head showing approximate locations of semicircular canals (29)

Figure 2.1

Gross structure and location of the vestibular apparatus

A portion of the labyrinth consists of the cochlea, an organ of hearing. The vestibular system is connected to the cochlea and occupies the remainder of the cavity. Each side of the system is composed of an utricle, a saccule, and three semicircular canals.

The utricle and saccule are located between the cochlea and the semicircular canals in an area known as the vestibule. Each has a structure called the maculae which is fixed with respect to the labyrinth. In the maculae are imbedded sensory hair cells with several types of innervation. The hairs extending from these cells support a gelatinous mass containing calcium carbonate crystals known as the otolith. Surrounding the otoliths in the utricle and saccule is a fluid called endolymph which serves as a damping medium.

Motion of the otoliths with respect to their maculae stimulates the hair cells and induces a linear motion sensation. The utricle is thought to sense linear accelerations omnidirectionally. Thus it is sensitive to the acceleration due to gravity.

The function of the saccule is not clear and some researchers feel it may be more an auditory than a vestibular organ. The utricles are not of primary importance in rotational sensation.

Continuous with the utricle and saccule are the three semicircular canals whose function is to sense angular accelerations. Each resembles a flexible toroid with an enlarged portion at one end. The flexible toroid, known as the membranous canal, is enclosed in a second more rigid toroid called the bony canal.(See Figure 2.1) The membranous canal contains endolymph while the space between the inner and outer toroid contains another fluid known as perilymph.

The enlarged end of each toroid is the ampulla. The ampulla contains a gelatinous, flapper type valve called the cupula.(See insert, Figure 2.1) The cupula is attached to a raised area of the inner wall of the ampulla, the cristae. The free end of the cupula is in close contact with the ampulla wall. The latter is fixed by connective tissue to the skull and may be considered stationary with respect to the head.

When an angular acceleration is imparted to the head, the endolymph lags behind the canal due to inertia and causes a deflection of the cupulae. Hair cells within the cristae receive this deflection information and translate it into nerve impulses.

The hair cells in the cristae are direction specific, i.e. they are able to distinguish the direction of cupula deflection. These hairs are grouped in bundles known as stereocilia. At one side of each bundle is a single stiff hair, the kinocilium. Deflections of the cupula toward the kinocilium cause an increase in the discharge rate of the nerves in the sensory cells. Deflections in the opposite direction cause a decrease in this discharge rate. Ewald first described this phenomenon in the cat and it is often known by his name.[21]

The fact that there are three semicircular canals in each labyrinth suggests that angular accelerations about the three principal axes of the body are each sensed by a seperate canal. With the head held erect however, none of the canals lies exactly in one of the principal planes. Coupling between the three canals is thus to be expected though it is not of great consequence.

The corresponding canals on each side also act as pairs in most situations. This action has an especially important role in the conjugated eye movements experienced when the head is turned.

2.2 Central Nervous System Connections[15,32]

Figure 2.2 shows the principal central nervous system connections of the vestibular system. The various nerve fibers and nuclei appear on both sides of the brain stem. For clarity, the figure shows only those of the left side.

The cell bodies of the sensory neurons of the cristae and maculae are found in the vestibular ganglion. The nerves terminate in the ipsilateral(same side) vestibular nuclei and in the cerebellum. From the vestibular nuclei, fibers descend in the vestibulo-spinal tract as shown and also in the lower portion of the medial longitudinal fasciculus(not shown). The vestibulo-spinal tract plays an important role in postural reflexes and in muscle tone. Some of the descending medial longitudinal fasciculus

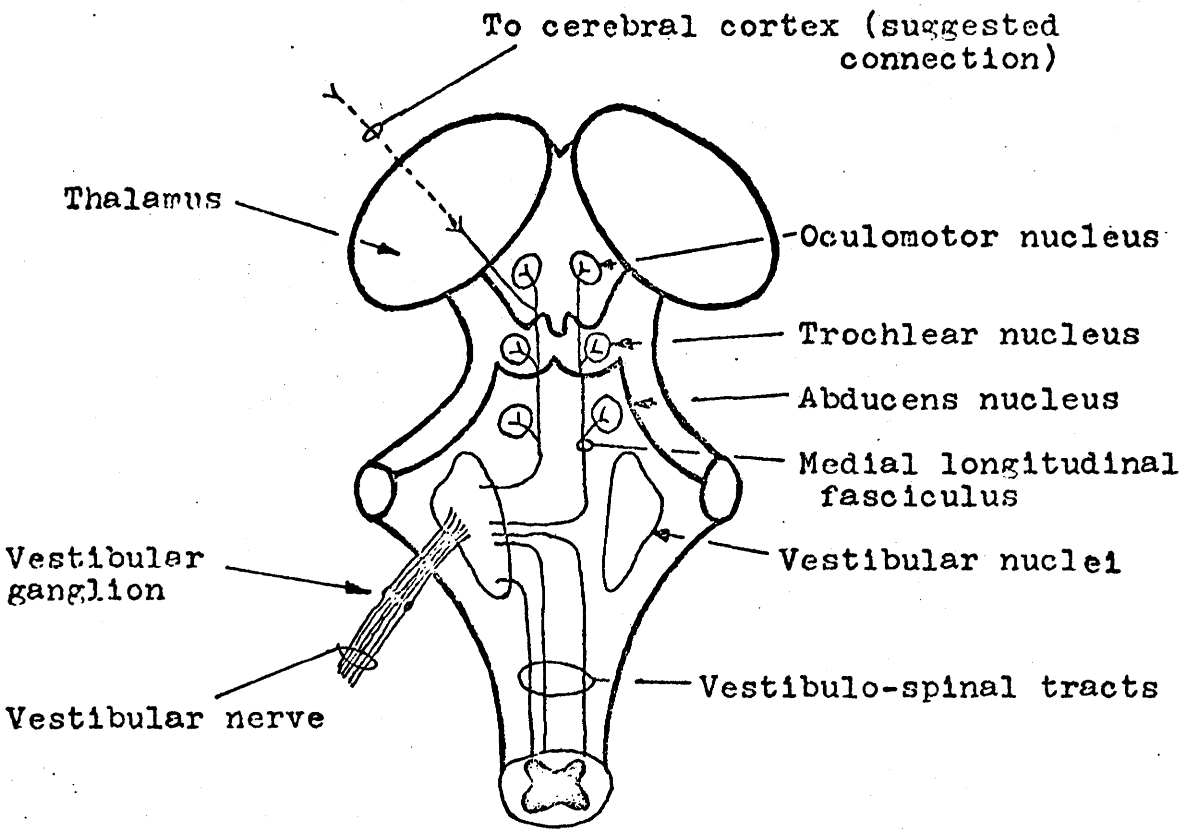


Figure 2.2

Dorsal view of the brain stem showing the principal vestibular pathways (15)

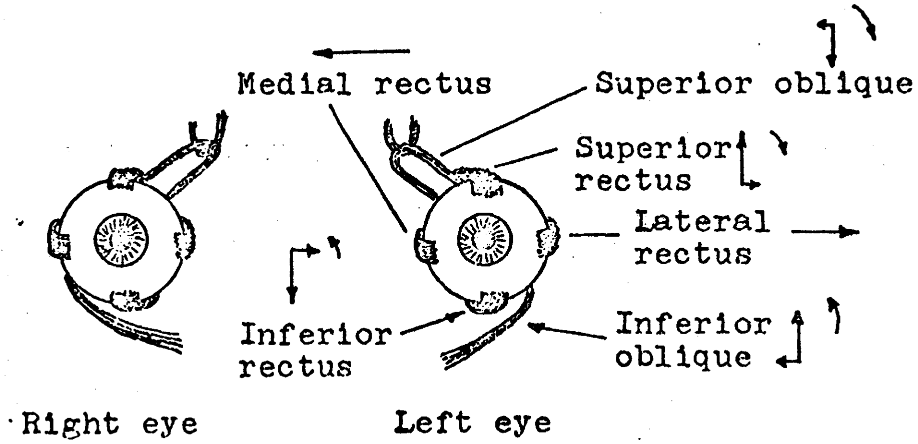


Figure 2.3

Extrinsic ocular muscles (arrows represent movements effected by each muscle) (21) fibers are thought to reach the visceral motor nuclei thereby effecting the nausea, vomiting, and other symptoms of excessive vestibular stimulation such as motion sickness.

The upper portion of the medial longitudinal fasciculus contains fibers passing from the vestibular nuclei to the abducens, trochlear, and oculomotor nuclei and to the cerebral cortex via the thalamus. The latter connection is probably responsible for conscious sensation of motion. The three nuclei to which the fibers pass are responsible for the control of eye movements.

2.3 Vestibular-Oculomotor Connections [21]

If one fixates on some object while turning one's head, compensatory eye movements (i.e. opposite to the direction of head movement) are necessary in order to keep the object in view. These movements depend on a sensation of head motion which is given to a large extent by the vestibular apparatus.

Eye movements are produced by three pairs of muscles, the lateral and medial recti, the superior and inferior recti, and the superior and inferior oblique as shown in Figure 2.3. The arrows in the figure represent the approximate eye movements effected by each muscle. All of the muscles except the lateral rectus and the superior oblique are controlled by the oculomotor nucleus (see Figure 2.2 and the discussion in the last section). The trochlear nucleus controls the superior oblique muscle while the abducens nucleus controls the lateral rectus.

It has been shown by Szentágothai,[30] Cohen, and others, and reported by Peters that electrical stimulation of a single ampullary nerve of one of the semicircular canals of the cat produces compensatory movements in both eyes similar to those observed during rotation.[21] As Figure 2.2 indicates, there are connections between each set of vestibular nuclei and both the ipsilateral and contralateral nuclei controlling eye motion. Stimulation of the horizontal canals, which is of the most interest in this thesis, causes compensatory eye movements about the yaw (vertical) axis of the head. These movements are determined primarily by the medial and lateral recti but, as with all eye motion, are modified somewhat by the states of the other extraocular muscles. Several authors have studied the various connections between the semicircular canals and these muscles. Peters has summarized the results of these studies.[21]

Szentagothai has also studied the neural connections between the utricles and the oculomotor system and has developed a theory of the possible pathways. These are also reviewed by Peters but are probably not of consequence in the present work however.[21]

Eye movements are thus a direct external indication of vestibular function and are of great interest in most vestibular research.

2.4 Techniques for Vestibular Study

A number of techniques are employed to study vestibular response. These may generally be distinguished either by the type of stimulus used or by the form of response obtained.

Several of the most popular methods are reviewed below. These and other methods are discussed in detail in the literature. The galvanic test is discussed separately in Chapter 3.

In what is sometimes called a subjective test, a subject is placed in a darkened Barany chair (a device which rotates about the yaw axis) and a random input of zero mean and known frequency content is applied to the chair's drive motor.[21] The subject indicates by pressing a button or a "joy" stick the direction and/or magnitude of his motion. A "normal" subject is able to detect most motions above some threshold, but will generally not have a zero mean response. Mirchandani recently employed this technique to study directional preponderance, a condition in which a subject is more sensitive to movements in one direction than the opposite.[20] He found that even clinically "normal" subjects displayed at least slight directional preponderance.

The subjective test can be run about the other two axes also but certain additional complicating factors relating to otolith function enter to a greater extent than about the yaw axis. Meiry, in particular, has conducted extensive experiments of this sort about the roll axis.[19]

The Barany chair or a similar device may be employed in a more objective test of vestibular response. Such a test employs eye movements as discussed above as an objective indication of vestibular state.[21] Thus if a subject is placed in a darkened chair and given a test input, either sinusoidal or random rotation or a transient such as a step or ramp, and his eye movements are monitored, a good indication can be had of vestibular "output," Mathematical models of this input-output relation can then be hypothesized. Several of these models are discussed below.

2.5 Eye Movement Monitoring [23,29,38]

Several techniques are presently in use to record eye movements.

One is the electro-oculogram or E.O.G. which is a measure of the differential corneo-retinal potential. Surface electrodes near the corners of the eyes sense these potentials which change as the eyes move. The electrodes also pick up muscle noise, however, and are subject to drift.

High speed movies of the eye have also been employed in experiments but these do not yield an analog output and are not readily useful for data analysis.

The technique used in the experiments described in this thesis measures the difference in light reflected from the iris and the sclera. An infrared source and two photoelectric cells are mounted on a standard eye glass frame. The electronics are battery operated and are mounted in a separate case. The frame is mounted with relative ease and adjustment is simple. The unit tends to irritate most subjects if left on for more than about thirty minutes, due to the drying effect of the infrared source on the eye. Also the resolution (±¼°) and the linearity (±15°) are inadequate for some experiments.

These techniques are discussed in detail in several of the references.

2.6 The Caloric Test [14,27,29]

A common clinical technique for determining vestibular condition is the caloric test. In this test, the external auditory canal is irrigated with a fluid which is slightly above or below ambient body temperature. Barany and others state that this irrigation sets up a convection current in the endolymph. This current in turn causes displacement of the cupula resulting in rotational sensation and nystagmus eye movements. The intensity of the response depends upon subject threshold, the temperature of the irrigating fluid, and certain other factors. The test is relatively simple to administer and requires the least equipment of the techniques mentioned. It is perhaps the most widely used vestibular test.

2.7 Control Models of Vestibular Response [19,21,29,39]

Considerable effort has been devoted to mathematical formulations of vestibular response, mostly for the semicircular canals. Such models are useful in describing vestibular function and in predicting labyrinth response to various input stimuli including rotation. In particular, such models have helped to explain the threshold, adaptation, and habituation phenomena associated with the canals. These phenomena are of interest in studies of rotation perception and will be discussed at the end of this section.

2.7.1 The cupula model

The basic response of the semicircular canals to motion inputs is usually deemed analogous to that of a damped torsion pendulum, an analogy first proposed by Steinhausen in 1931. Mathematically, this response is expressed, for a single semicircular canal as:

$$I\theta + B\theta + K\theta = I\alpha \qquad (2.1)$$

where

I = moment of inertia of the endolymph about the sensitive axis of the canal

B = viscous damping torque of endolymph with respect to the skull at unit angular velocity

K = stiffness, or torque per unit angular deflection of cupula with respect to the skull

θ = angular deflection of cupula with respect to the skull

α = input angular acceleration about the sensitive axis of the canal

This equation is often expressed in the Laplace domain as

$$\left(S^2 + \frac{B}{I}s + \frac{K}{I}\right)\theta = \alpha \qquad (2.2)$$

It is also generally assumed that the visions torque is much greater than the elastic torque, i.e. $\frac{B}{I} >> \frac{K}{I}$. With this assumption, equation 2.2 becomes:

$$\frac{\theta}{\alpha} = \frac{1}{(s + \frac{K}{B})\,(s + \frac{B}{I})} \tag{2.3}$$

Typical values for the time constants B/K and $\frac{I}{B}$ are

$$\frac{B}{K} = 10 \text{ seconds} \qquad \frac{I}{B} = 0.1 \text{ seconds}$$

These constants and other useful information are obtained in the following manner. First, taking the inverse Laplace transform and using the fact that $\frac{K}{B} < \frac{B}{I}$ the following time relationship is obtained for a velocity step input, γ.

$$\theta \approx \gamma \frac{I}{B} [e^{-\frac{K}{B}t} - e^{-\frac{B}{I}t}] \tag{2.4}$$

Also for a unit acceleration step input, α, one finds

$$\theta \approx \alpha \frac{I}{K} [1 - \frac{K}{B}(\frac{B}{K}e^{-Kt/B} - \frac{I}{B}e^{-Bt/I})] \tag{2.5}$$

If it is noted that the exponential $e^{-K/Bt}$ dominates equation 2.4 it may finally be written as:

$$\theta \approx \gamma \frac{I}{B} e^{-\frac{K}{B}t} \tag{2.6}$$

Taking the logarithm of this expression, one has:

$$\ln \theta = \ln \gamma \frac{I}{B} - \frac{Kt}{B} \tag{2.7}$$

A plot of ln θ versus t has the slope $\frac{K}{B}$ and thus determines this constant. The determination of I/B involves a slightly different technique which is discussed in the literature.[21]

2.7.2 Perception Thresholds

A number of useful results are obtained if equation 2.7 is solved for t to yield

$$t = \frac{B}{K} \ln \frac{\gamma I}{\theta B} \tag{2.8}$$

If θ in equation 2.8 is taken to be the threshold cupula deflection(i.e. the minimum deflection for which a sensation of rotation occurs), then t may be interpreted as the time from stimulus onset to the end of rotation sensation. Thus 2.8 becomes

$$t_\mu = \frac{B}{K} \ln \frac{\gamma I}{\theta_{min} B} \tag{2.9}$$

Now suppose a stimulus of exactly threshold intensity is applied. The time from stimulus onset to cessation of sensation is then≈ 0. Taking $t_\mu = 0$ in 2.9, we can then solve for θ min to get:

$$\theta_{min} = \frac{I}{B} \gamma_{min} \tag{2.10}$$

Values of θ min for subjective and nystagmus responses to velocity step inputs can be estimated from figure 2.4. This is done by looking at the value for the velocity at zero ordinate for the two cupulograms shown there. γ_{min} is found to be $\approx$ 2.7 deg/sec for subjective response and 9 deg/sec for nystagmus. Assuming a value of 0.1 sec for I/B, θ min is found to be 0.27 degrees and 0.9 degrees respectively.

It can also be shown that the threshold of angular acceleration sensation is given by[21]

$$\alpha_{min} = \frac{\theta_{min}}{I/K} \tag{2.11}$$

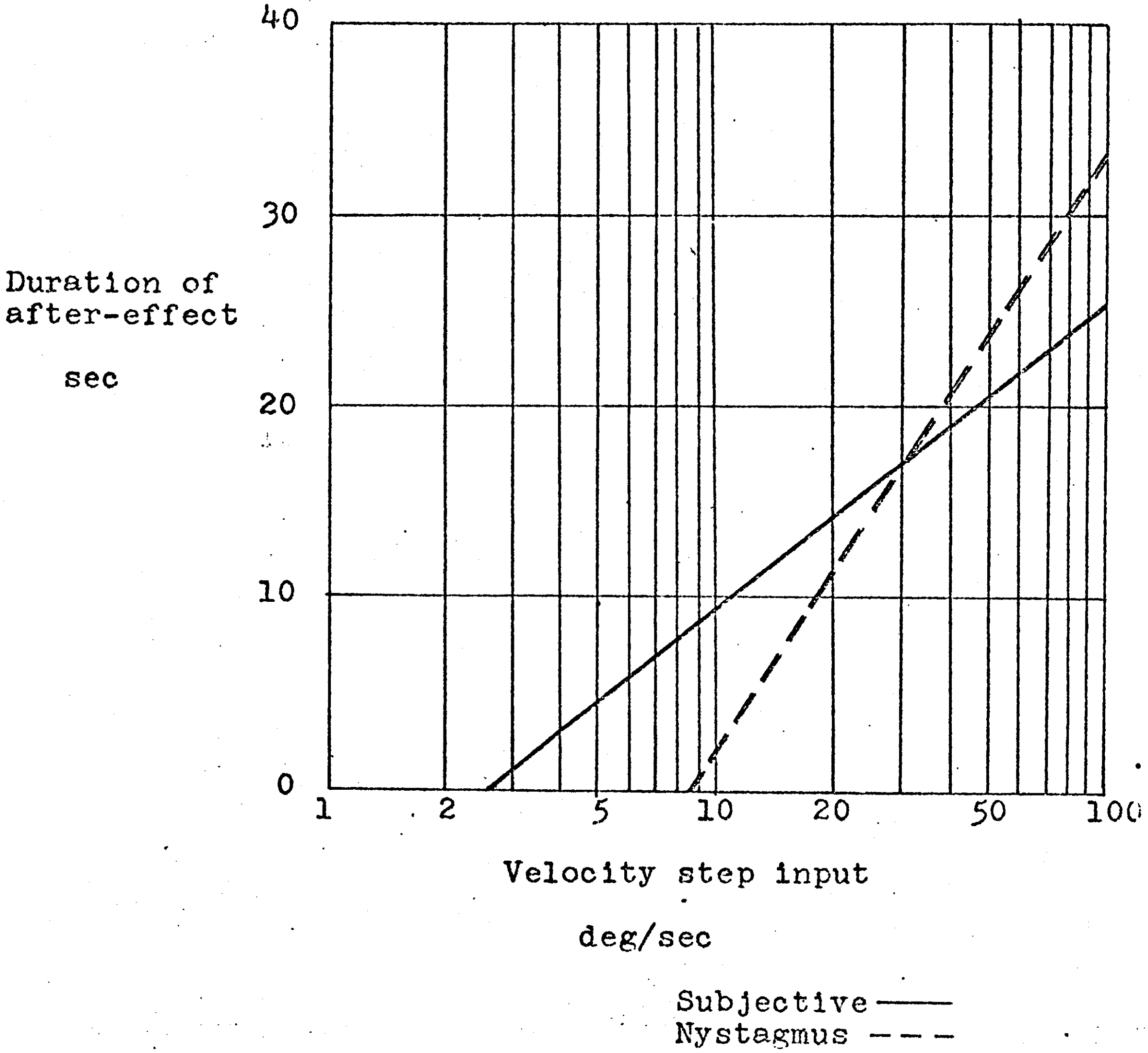


Figure 2.4

Average cupulograms for subjective and nystagmus responses to velocity step input (Modified from 21) where for the nominal values of $\frac{K}{B}$ and $\frac{I}{B}$ given above $I/K = 1$ sec^2. Thus approximate values of α_{min} are easily found to be

$\alpha_{min} = 0.27$ deg/sec^2 for subjective sensation

$\alpha_{min} = 0.9$ deg/sec^2 for nystagmus

These values of acceleration perception thresholds are in rather good agreement with the experimental results of a number of researchers.[4,21] As might be expected, values for nystagmus response are generally much closer to the nominal value above, reflecting the objective nature of nystagmus studies. Subjective response is much more dependent on individual differences and hence yields a larger experimental data spread.

2.7.3 Latency

In some instances, the simple measure of threshold stimulus intensity may not be adequate to describe rotational perception. Low intensity stimuli may, if applied for a sufficient period of time, result in perceived motion. The period of time required in such a circumstance is termed the latency. Indeed, every stimulus intensity has a certain latency period associated with it. The latency concept has a direct parallel, chronaxia, in galvanic stimulation studies which will be discussed in Chapter 3.

In order to obtain an analytic expression for latency times for angular acceleration perception, one begins with equation 2.5, noting once again that $I/B \ll B/K$.

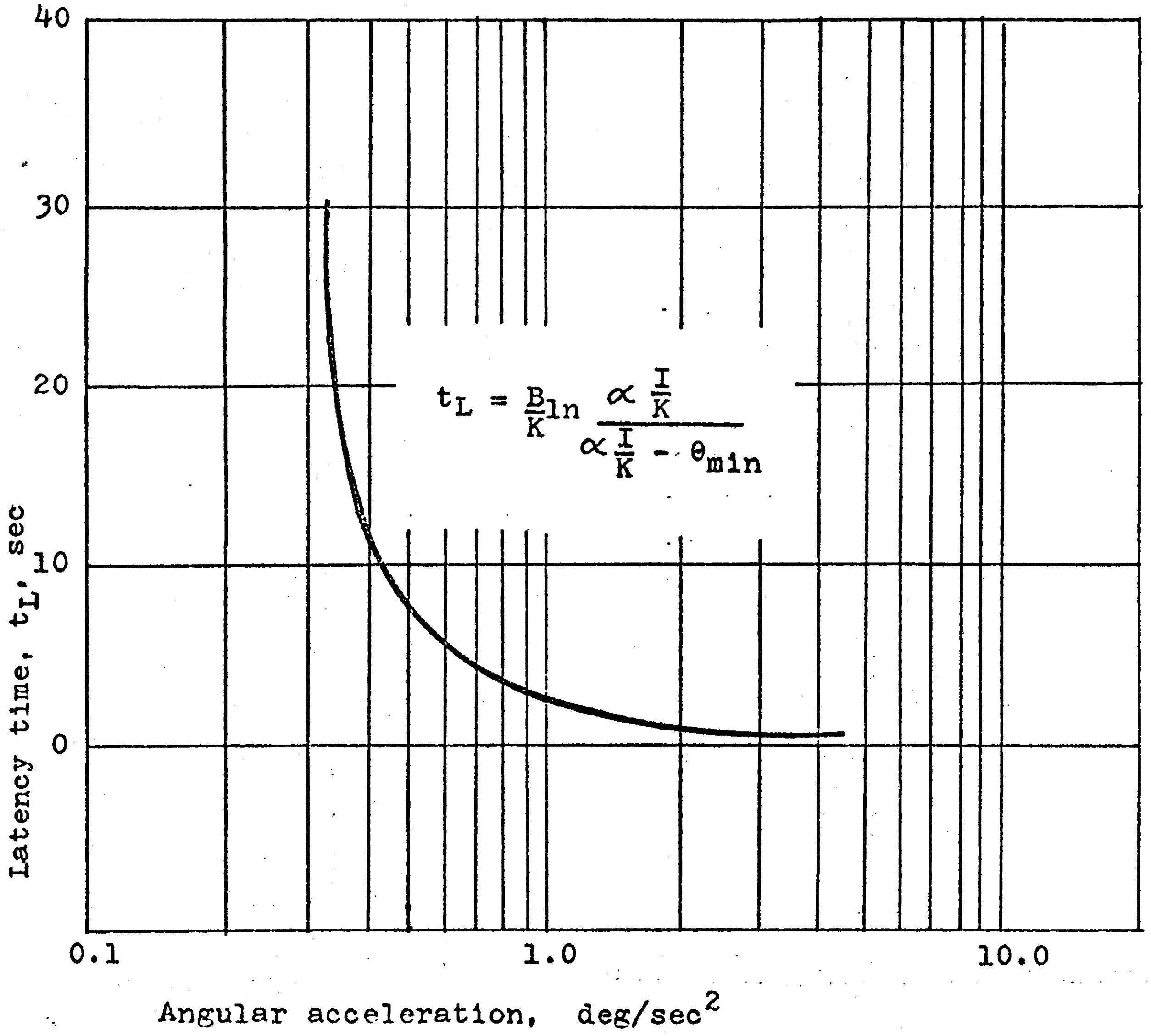


Figure 2.5

Perception latency time vs. angular acceleration for rotation about the vertical axis ($\theta_{min} = 0.25$, $\frac{B}{K} = 8$ sec, $\frac{I}{K} = 0.8$ sec^2) (Modified from 21)

With the latter assumption equation, 2.5 becomes

$$\theta = \alpha \frac{I}{K}(1 - e^{-Kt/B}) \tag{2.12}$$

Letting $\theta = \theta$ min and solving for t yields

$$t = \frac{B}{K} \ln \left[\frac{\alpha \frac{I}{K}}{\alpha \frac{I}{K} - \theta_{min}}\right] \tag{2.13}$$

or the latency time as a function of α. An approximate plot of 2.13 is shown in figure 2.5 with $\theta_{min} = 0.25$ deg. Experimental data often reveals much lower thresholds when sufficient time is allowed for response.[21] Still 2.13 is useful for describing latency.

2.7.4 Response decline with Prolonged or Repeated Stimulation

If stimulation of the semicircular canals continues at a constant level for an extended period(more than several seconds) the sensation of angular velocity gradually decreases and eventually disappears. This phenomenon can be understood if one remembers that the cupula is deflected due to the inertia of the endolymph in the semicircular canals. With a prolonged constant stimulus, the cupula is able to return to its rest position. Figure 2.6 shows the approximate canal response when a term of the form $s/(s + 0.033)$ is added to equation 2.3.[39] This term, which is sometimes called an adaptation, brings the response to approximately below the threshold in thirty seconds as shown in the figure.

Repeated application of the same or similar stimulus

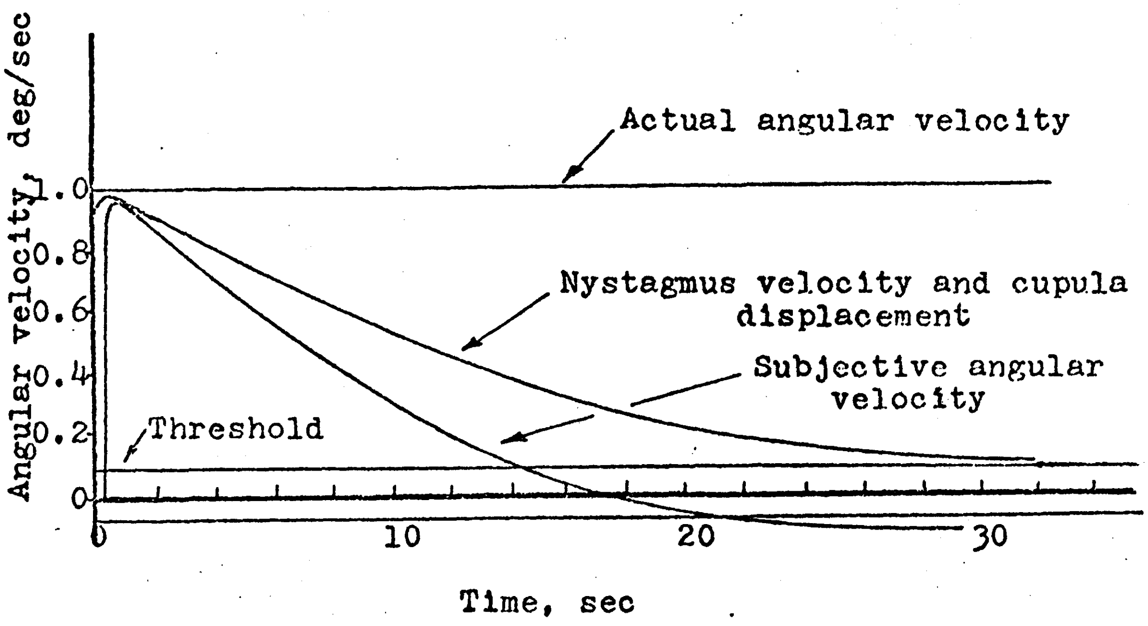


Figure 2.6

Velocity step response of semicircular canal model including adaptation dynamics (39) also results in response decline. This decline, which manifests itself in higher thresholds and increased ratio of adaptation, is most noticeable in pilots and others who undergo regular intense vestibular stimulation.

2.7.5 Caloric Stimulation Model

Steer has proposed a model for caloric stimulation based on theoretical considerations and actual caloric test results. It is outlined briefly here. For further information, the reader is referred to Steer's thesis.[29]

The model, in the Laplace domain, is given by:

$$\frac{\theta_c(s)}{T(s)} = \frac{20K_T/T_1 T_2 T_3 \cos\phi}{(s+\frac{1}{T_1})(s+\frac{1}{T_2})(s+\frac{1}{T_3})} \qquad (2.14)$$

where

$\theta_c(s)$ = cupular displacement due to caloric stimulus

$T(s)$ = temperature at tympanic membrane

T_1 = thermal lag (≈ 25 sec)

T_2 = $B/K = 10$ sec

T_3 = $B/I = 0.1$ sec

ϕ = angle between plane of thermal gradient and the perpendicular to the gravity vector

K_T = system gain

Equation 2.14 may be written as

$$\frac{\theta_c(s)}{T(s)} = \frac{20K_T \cos\phi}{25s+1}\left[\frac{1}{(0.1s+1)(10s+1)}\right] \qquad (2.15)$$

where the term in brackets is recognized as the model, just described, of cupula response to angular stimuli. The caloric model therefore provides a useful comparison of caloric and rotational responses.

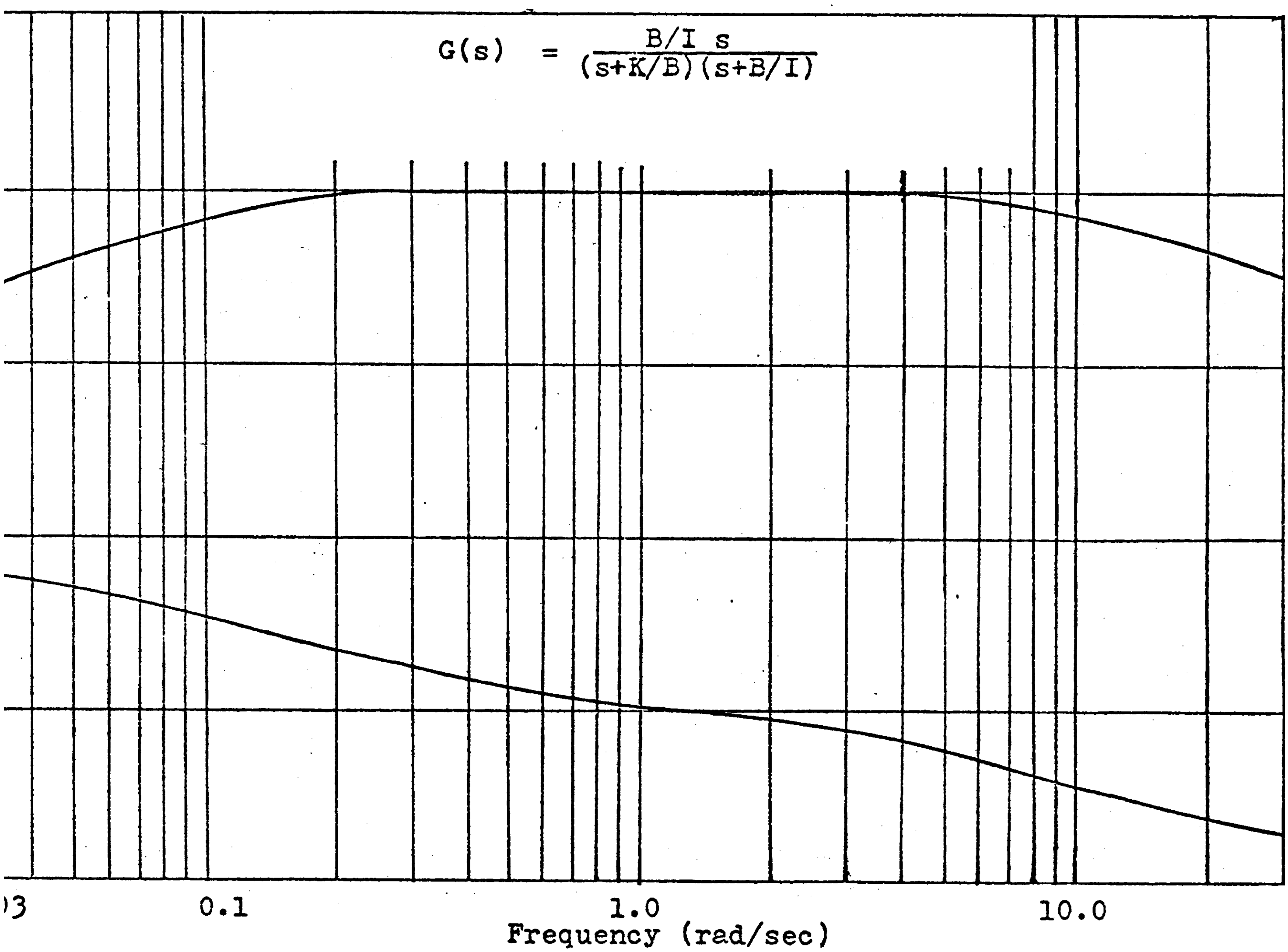


Figure 2.7

requency response of subjective perception model of semicircular canals (1

2.7.6 Subjective Perception Model [19,21]

It is interesting in the present work to consider a model of subjective perception of the semicircular canals. The model is expressed as

$$\frac{\dot{\theta}_p(s)}{\dot{\theta}_i(s)} = \frac{B/I \quad s}{(s + \frac{K}{B})(s + \frac{B}{I})} \qquad (2.16)$$

where

$\dot{\theta}_p(s)$ = Subjective Perception of angulat velocity

$\dot{\theta}_i(s)$ = Input angular velocity

Typical values of the constants are B/I = 10 and K/B = 0.12.

This model is obtained by performing the "subjective" test discussed in section 2.4. A Bode plot of the model is shown in figure 2.7. Note that over the range w = 0.1 to w = 10 rad/second the model indicates subjective perception to be that of angular velocity.

2.8 Comments on Vestibular Models

It must be emphasized that mathematical models of any physiological response are only useful conceptual tools. They are seldom, if ever, totally accurate descriptions of the underlying physiological events. The models discussed in the last section must be viewed in that light.

CHAPTER 3

THE GALVANIC VESTIBULAR REACTION

It has been recognized for some 150 years that passing a direct current between the mastoid processes brings about one or several responses similar to those characteristic of vestibular stimulation. The use of D.C.(galvanic) stimulation in diagnosis and treatment of certain vestibular disorders has been suggested with varying enthusiasm since that time.

This chapter reviews the past research into the galvanic vestibular reaction, discusses the various reported responses, especially those related to the sensation of rotation, and outlines the methods for conducting galvanic stimulation tests.

3.1 Action Site of the Stimulus [14,27]

Shapiro and others report that Jan Perkinje about 1820 found that an electric current passed through the head caused vertigo. It was recognized by Hitzig in 1871 that such a current also elicited eye movements. Breur later noted such a current also stimulated the vestibular system in some manner. A number of persons since have described a variety of effects on the vestibular system and oculomotor response due to galvanic stimulation.

Among the reported reactions are: deviations of the eyes toward the anode, nystagmus with fast phase component toward the cathode, tilting of the body and/or head toward the anode depending on whether the subject is sitting or standing, and subjective sensation of movement, especially rotation.

The degree and direction of these responses are felt to depend, at least qualitatively, on the polarity, points of application and intensity of the galvanic stimulus. Of particular interest in clinical work has been the point of action of the stimulus.

Barany postulated that a cathodic stimulus on the mastoid process increased the catelectrotonus(sensitivity to negative electrical current) in the vestibular nerve thus increasing its excitability. Anodic stimulation, he felt, had a depressing effect on excitation. Brüning opposed this theory, arguing that nerves could only be stimulated by alternating current, and postulated that galvanic current acted directly on the vestibular receptor organs. Hennebert felt that both the vestibular and auditory receptors were affected.

The Bruning theory held that the galvanic current caused an electrokinetic flow in the endolymph of the semicircular canals. Such a flow would be somewhat analogous to the flow due to a thermal gradient set up by caloric stimulation as discussed in Chapter 2.

Most evidence is in support of Barany's theory, however. Marx plugged the semicircular canals of guinea pigs and still obtained a "normal" D.C. reaction. He obtained similar reactions if he destroyed the semicircular canals or the entire labyrinth. Neumann and others found clinical cases where patients had no caloric or rotational responses but did react to galvanic stimulation. Steinhausen was able to demonstrate in experiments with a pike(fish) that the cupula was not deflected due to a galvanic current.

Other researchers, including Spiegal and Scala,[26] have severed the 8th cranial(vestibular and acoustic) nerve and observed the disappearance of galvanic response. Pfaltz and Koiche have reported that brainstem lesions which do not elicit spontaneous nystagmus appear to have little or no influence on a patient's galvanic reaction.[22]

On the basis of the evidence above, it would thus appear that the peripheral vestibular neuron is the action site of the galvanic stimulus. Detailed study of this or other sites on a system level is hindered by a number of factors: difference in conductivity of various tissues, unknown current distributions, changes in current level, and polarization.[14]

Some researchers, including Spiegal,[27] feel that within the vestibular neuron, it is principally the fibers from the maculae(see Chapter 2) which are affected by galvanic current. They point to such indications as eye rolling and head inclination as evidence. Also, using the double galvanic test, which is discussed below, Spiegal and Scala were able to decrease tonic impulses to the forelegs in decerebrate cats by using anodic stimulation.[26] Cathodic stimulation increased muscle tonus thus suggesting a sort of modulating influence by the galvanic stimulus.

The final answer to the point of action of galvanic vestibular stimulation will probably not be available for some time.

3.2 Differing Response to Anodic and Cathodic Stimulation

The differences in response observed for anodic and cathodic stimuli have had several explanations. Those theories mentioned above, Barany's of electrotonus, and Spiegal's of action on the fibers from the maculae, are of a qualitative nature. Another theory, first proposed by Wilson and Pike, is sometimes called the quantitive explanation.[36] This theory holds that the vestibular nerve has two types of endings. One type was considered highly sensitive to anodic stimulus and responsible for eye movements toward the side of the anode. A second, more numerous, but less sensitive type of fiber was felt to respond to cathodic stimulus and to cause contralateral eye movements.

The correctness of any of these theories has yet to be established conclusively, but the idea of a qualitative difference in the two polarities has had the most interest.

3.3 Methods of Stimulation [14,27]

There are several types of galvanic tests which may be performed. The simplest are of the unipolar and bipolar varieties.

In the unipolar test, the stimulating electrode is placed on either the tragus or mastoid and an indifferent electrode is placed on either the forehead or the back of the neck. Bipolar stimulation employs electrodes on both tragi or mastoid processes so that current passes directly through the head. In both tests, the cathode is designated as the stimulating electrode.

Another possible test which is a combination of the two above is the double galvanic method. In this test, electrodes are placed on both mastoids or in the meati of the ear as in the bipolar test. Both electrodes are connected to the stimulus current. An indifferent electrode is placed on the neck, forehead, or abdomen. This method is less specific than the former two.

Pulsed current, which Spiegal calls rhythmic stimulation, has also been shown to bring about nystagmus at pulse frequencies of less than 10 per second. This is not, strictly speaking, galvanic stimulation since it is not a constant stimulus.

A number of interesting items can be learned with the aid of a different type of technique known as the chronaxia test. A general measure of neural threshold, chronaxia compares a standard current intensity acting on a specific nerve with the time required for that current to travel the length of the nerve. The intensity of direct current which will just traverse a nerve given an infinite amount of time is termed a rheobase. In the standard chronaxia test, a current of two rheobase magnitude is applied and the passage time is noted. The time is called the chronaxia for the nerve. The measurement of the response in the case of galvanic vestibular stimulation is the time from application of current until head movement or eye deviation occurs(with errors which can be partially accounted for).

Chronaxia is relatively constant between individuals for a given nerve. The reported values for chronaxia for the vestibular nerve vary considerably, however, from about one millisecond to well over ten milliseconds. This is probably due to difference in experimental techniques.

3.4 Associated Eye Movements

The eye movements associated with galvanic vestibular stimulation have a number of characteristics. One is a shift in mean eye position away from straight ahead toward the side of the anode. Also, beyond a certain intensity threshold, which may vary with mode(anatomical location of electrodes), nystagmus is elicited with fast phase toward the cathode. As mentioned above, Spiegal[27] hypothesizes that the anode has a depressor action on tonic labyrinthine impulses. He feels nystagmus may result from an imbalance in the two vestibular nuclei as a consequence of this depressor effect.

Ruis and Garcia have also noted slow eye movements of a drift nature preceding the onset of nystagmus and at a lower current threshold.[25] These movements appear to be a type of onset phenomenon and disappear with repeated stimulus even if nystagmus persists. They did not use a constant stimulus but instead employed 20 millisecond pulses of from 5-70 volts at a frequency of 5 pulses/second.

The movements are biphasic with a fast first phase lasting about 1-2 seconds. The vertical component was found to be larger than the horizontal component. For long duration pulses, nystagmus was observed but only after the initial biphasic period. Increased stimulus amplitude shortened the nystagmus latency time.

3.5 Eye Movement Monitoring during Galvanic Stimulation [2,3]

A comment on the monitoring of eye movements during galvanic stimulation is of interest. A number of researchers have employed electro-oculography(see Chapter 2) in such experiments and most report that the galvanic current severely alters the corneo retinal potential in one or several ways. All suggest that the photoelectric technique or other which will not be directly influenced by the D.C. current be used in measuring eye movements during galvanic stimulation.

3.6 Other Responses

In addition to eye movement, head inclination and body sway have been used as objective measures of response to galvanic vestibular stimulation. Both of these phenomenon normally exhibit, when present, an inclination toward the side of the body on which the anode is located. They are probably manifestations of the stimulus modulation of tonic impulses to the body musculature as Spiegal demonstrated in the experiment mentioned above. Spiegal also reports that the falling tendency may occur at lower current levels than necessary to elicit nystagmus.

Blonder reports using a version of the falling reaction as a standard measure of galvanic response in clinical tests.[14,27]

3.7 Subjective Sensations

Subjective sensations as a result of galvanic stimulation are often difficult to interpret. Subjects report sensations of sway, both side ways and front ot back, dizziness, and rotation. Also, above some threshold current(which varies with subject), a tingling sensation is experienced under the electrodes with strongest sensation under the cathode.

The nature of the subjective sensation may be related to subject experience and adaptation. For this reason, it may be well to group all such sensations under the admittedly vague heading of disorientation.

Malcik has employed a binaural D.C. stimulation of 3 ma. to 350 pilots in order to simulate illusions such as sway or rotation experienced during flight.[17] His subjects were asked to fly an instrument flight simulator while under the influence of this current. He reports that all experienced illusory sensations to some degree. Those subjects with more instrument experience were able to compensate for the illusions more readily than those with limited instrument practice. Performance also improved for all subjects as habituation developed for the galvanic stimulus. Since the eyes were fixated on instruments, no noticeable nystagmus was observed.

3.8 Low Frequency Sinusoidal Stimulation[10,11,12,13]

In recent years, Dzendolet and his associates have studied the effects of sinusoidal galvanic stimulation on body sway and subjective sensation. The stimulus was applied binaurally at the mastoid processes of blindfolded standing subjects. Eight stimulus frequencies tanging from 0.030 - 4.0 cps were presented in random order. The stimulus amplitude was increased continuously on each run starting from 0 ma. and increasing at a constant rate of 0.0050 ma/second. Objective and subjective responses were determined including thresholds. A plot of the latter is shown in figure 3.1 It is interesting to note the relative

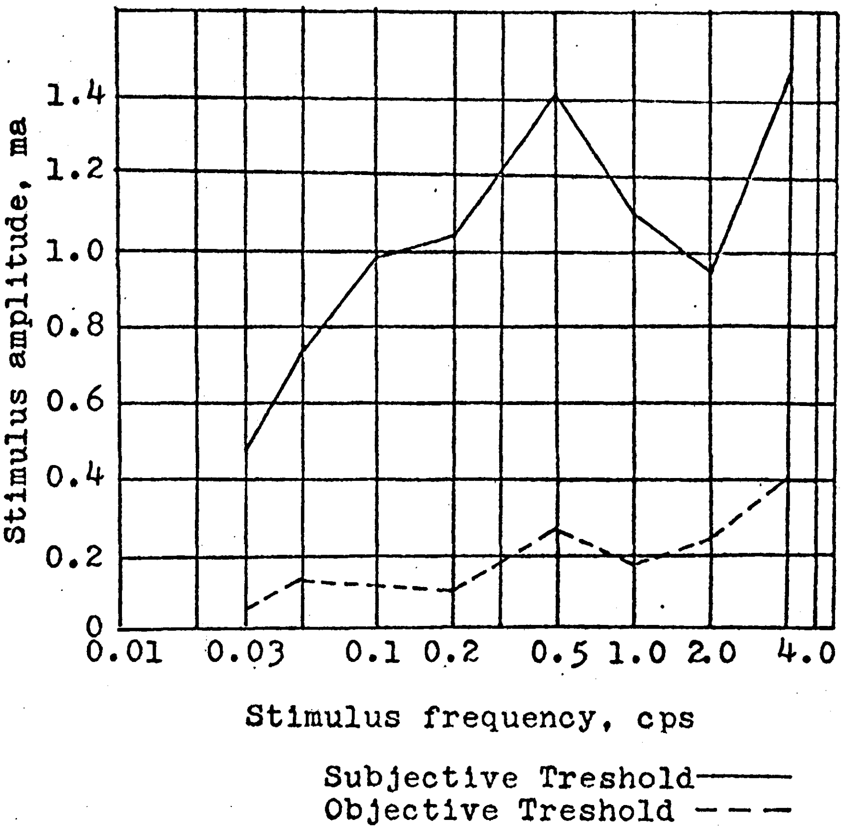


Figure 3.1

Subjective and objective current thresholds for sinusoidal vestibular galvanic stimulation as a function of stimulus frequency (12)

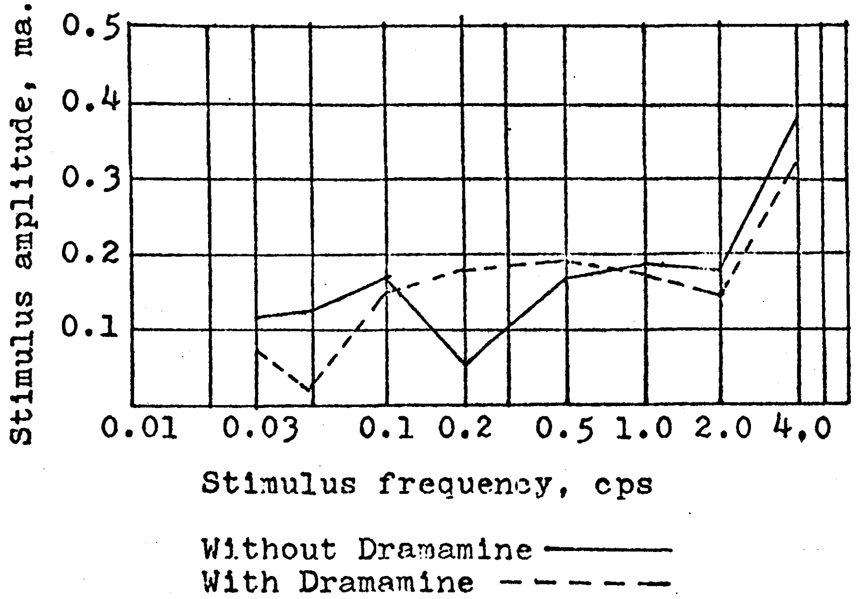


Figure 3.2

The effect of Dramamine on the objective threshold for sinusoidal galvanic vestibular stimulation (13) difference in threshold between subjective sensation and objective response. (The latter is determined from body sway, the former by subject indication) At low frequencies, the objective response threshold is fairly constant at a stimulus of 100μa and increases to about 400μa at 4 cps. Subjective thresholds are all considerably higher varying from 500μa to 1.4 ma over the frequencies used.

The subjective thresholds agree rather well with those reported above for D.C. stimulation. The objective values are considerably lower. The difference in the type of stimulus is undoubtedly a factor in these differences.

Subject sway was found to be proportional to the frequency of the input stimulus. Reported subject sensation varied considerably: oscillation of head and torso, oscillating sideways and back and forth, and a few instances of vertigo. These are consistent with those reported above for direct current stimulation.

An interesting sidelight to this work with possible clinical applications is as follows. These researchers noted that the sinusoidal galvanic stimulus is comparable in some way to the factors causing motion sickness(i.e. slowly oscillating ship or automobile).

In particular, they find a lowered objective threshold for sinusoidal stimulation at a frequency of 0.2 cps. (See figures 3.1 and 3.2) They report the findings of other researchers of a high incidence of motion sickness phenomena(nausea, vomiting, etc.) at frequencies near this value. When they administered dramamine, a common antimotion sickness drug, the threshold at 0.2 cps was raised considerably as shown in figure 3.2. This may indicate that the drug acts on the same site in galvanic stimulation as in motion sickness, though no conclusive evidence exists on the actual site in either instance.

Whether there is any signifance to this comparison is yet to be substantiated. It is nevertheless an interesting observation.

3.9 Summary

This chapter has reviewed the nature and point of action of the galvanic vestibular reaction. At present, no final answer is available concerning the action site of the stimulus though evidence generally points to the peripheral sensory nerve.

Cathodic and anodic stimuli bring about different qualitative responses with those at the anode apparently more significant. Eye deviation and/or nystagmus are usually elicited by the stimulus above a certain intensity level. Nystagmus, when present, has its fast phase directed toward the side of the cathode.

CHAPTER 4

DESCRIPTION OF EXPERIMENTAL METHOD

This chapter discusses the experimental procedures used to study the influence of galvanic vestibular stimulation on the perception of rotation.

4.1 The Basic Experiment

The intent of this research was to study, in a qualitative manner, the relationships between modes of application and intensities of galvanic stimuli and a subjects' perception of rotation. Thus an experiment was sought which would employ both rotatory and galvanic stimuli administered independently of one another.

The experiment which was used consisted of the following. The subject was placed in a darkened Bareny chair and a zero mean random input was applied to the chair. The subject was provided with a three state controller and was given the task of countering any sensations of motion which he experienced. That is if he felt he was moving to the right he should press his controller to the left until he no longer sensed motion and so on. Assuming that the random signal indeed has a zero mean and that the subject has no directional preponderance, one would expect, theoretically, that the subject would counter any motion above his threshold and that the chair would not move more than slightly away from the reference position.

If a galvanic stimulus is applied to the subject together with the random input to the chair, one would expect the subjects' motion sensation to be altered in some manner(On the basis of the discussion in Chapter 3). This approach was adapted with the postulate that the galvanic stimulus would bias the threshold for rotation perception. The measure of response would be the deviation of the chair position over the course of a run.

The experiment thus places the subject in an active role as opposed to the passive role of the similar experiment described in Chapter 2. The three state controller was employed since it appeared important that the subject respond only to a sensation of motion in the clockwise direction and not to the magnitude as he might were a graded controller such as a joy stick used.

The average subject would not be expected to differentiate between various types of angular movement. Hence, the subject's were only asked to counter motion, and not, say, velocity or accelerations which might be vague concepts for some subjects.

Angular accelerations are kept relatively small with these conditions thus no large cupula deflections or extended reactions to any given stimulus are to be expected.

Each subject was to be run with each of the six possible modes, unipolar right cathode and right anode, unipolar left cathode and left anode, and bipolar left cathode and right cathode and at six different intensity levels. The latter number was not completely arbitrary but related to the overall experimental design which will be discussed in the next section.

The lowest intensity level was chosen at 100μa partially due to Dzendolet's reported objective threshold for low frequency sinusoidal vestibular stimulation as discussed in Chapter 2.[12] Successive intensity values were doubled up to a maximum of 3 ma. in order to cover as wide a range as possible and still remain within pain and safety levels.

In addition to six runs with combined rotational and galvanic stimulus, two control runs, one at the beginning and the other at the end of the session were added to make a total of eight runs per subject. The controls were added not only to determine the normal response without current but also to discover, if possible, any overall effect on this norm after the combined experiments.

Eye movements were to be monitored in addition to the subjective response in an attempt to obtain an involuntary measure of response.

4.2 Experimental Design[6,18]

Once the basic experiment was decided upon, a suitable experimental design was required in order to study a number of different variables in a systematic way. A design was sought which would incorporate all of the following features: 1.) all six possible modes of unipolar and bipolar galvanic stimulation, 2.) a number of different intensity levels, 3.) yield as much information as possible about effects of galvanic stimulus, 4.) employ as few subjects as possible, 5.) balanced for the elimination of order effects.

Since there were six possible modes, it was decided arbitrarily to use six intensity levels in the experiments as mentioned above. If each such were run at every mode and intensity, however, thirty-six runs per subject would have been required to include all of the possible combinations. In order to reduce the number of runs required per subject and in order to achieve the randomness of application desired, a slightly modified form of the graeco-latin square experimental design was employed.[6,18]

The graeco-latin square is an extension of the latin square design. An example of a 6x6 latin square is shown in figure 4.1. The rows represent subjects, the columns represent the order of experimental runs, and the letters entered in each position represent six experimental conditions, in this case representing the six modes of galvanic stimulation. Each letter appears only once in each row and each column. In addition, no letter preceeds or follows any other letter more than

A	B	C	D	E	F
B	D	A	F	C	E
C	A	E	B	F	D
D	F	B	E	A	C
E	C	F	A	D	B
F	E	D	C	B	A

Figure 4.1

Completely orthogonal 6X6 Latin Square

	Run Number					
Subject Number	1	2	3	4	5	6
1	AU	BV	CX	DY	EZ	FW
2	BZ	DW	AV	FU	CY	EX
3	CZ	AW	EY	BX	FV	DU
4	DZ	FY	BW	EV	AX	CU
5	EW	CV	FZ	AY	DX	BU
6	FX	EU	DV	CW	BY	AZ

Key

Intensities

U = 100μa
V = 200μa
W = 400μa
X = 800μa
Y = 1.6ma
Z = 3.0ma

Modes

A = Unipolar Right Cathode
B = Unipolar Right Anode
C = Unipolar Left Cathode
D = Unipolar Left Anode
E = Bipolar Left Cathode
F = Bipolar Right Cathode

Figure 4.2

Graeco-Latin Square used in experimental design.

once in the square. An array such as this is said to be completely orthogonalized, which means practically that all the elements are independent. (Another way of viewing this is to consider the six letters to be unit vectors in a six dimensional vector space. If any row or column is considered a six dimensional vector then its inner product with any other row or column will = 0 implying orthogonality in the mathematical sense.)

A graeco-latin square is composed of latin squares imposed one upon the other and allows the introduction of a second set of conditions into an experiment with a fixed number of subjects and runs. In the ideal case, each of the two latin squares would be orthogonal with respect to itself and with respect to the other square. The latter property would require that no pair of conditions, one from each latin square, would appear more than once in the graeco-latin square.

The graeco-latin square used in this thesis is shown in figure 4.2. The letters A-F represent the modes and the letters U-Z represent six intensity levels. The dimension of the square was restrained at 6x6 by the modes as mentioned above. This restraint introduced a slight difficulty however. Euler and others have shown it to be impossible to construct a completely orthogonal graeco-latin square with no repetitions of conditions in all rows and columns.[6]

If two completely orthogonal 6x6 latin squares are imposed one upon the other, a repetition will always occur in some entry.(e.g. the combination BU representing mode B and intensity U or a similar combination would appear more than once in the square) A repetition of conditions is not desirable since each combination of mode and intensity should be present once in the series of experiments.

The solution to this difficulty lies in relaxing the orthogonality condition on one of the squares. In order to accomplish this an assumption was made that the modes, in general, were likely to have a greater effect on the results than the intensities. (This assumption was based on findings reported in the literature and as discussed in Chapter 3). On this premise, the modes were made completely orthogonal in a latin square corresponding to figure 4.1.

The intensity conditions were then added over this square in such a way that no mode-intensity pair was repeated and that the square of intensities was as nearly orthogonal as possible. As shown in figure 4.2, the intensities increase in magnitude as their code letters in the square were also balanced so that the sum of the current given to all subjects as a whole on the first three runs was approximately equal to the total over the last three runs. This was done to avoid a trend in the application of current over all subjects. With these provisions, the design was then considered to be entirely random for the purpose of later data analysis.

The graeco-latin square lends itself will to variance analysis as will be noted in Chapter 5. Other experimental designssuch as balanced incomplete blocks were considered but were rejected since they appeared to offer no advantages over the graeco-latin square for this study.

4.3 Description of Equipment

This section describes the equipment used to rotate, galvanically stimulate and to monitor the responses of the subjects during the experiments described above.

4.3.1 Rotating Chair

The Man Vehicle Laboratory's rotating chair was employed to provide angular motion stimulation about the vertical axis. It is driven by two 15 ft.-lb. torque motors controlled from a pulse width modulated servo system. Details on the chair may be found in Katz's thesis.[16] The command signal consisted of the sum of a zero mean pseudo-random input and the subjects' response stick. The random signal was obtained by summing seven sinusoids of frequencies ranging from 0.1 to 0.61 radians/second and recorded on magnetic tape. The gain of the signal was adjusted as shown in figure 4.7 so that the maximum amplitude deviation caused the chair to move 540 degrees away from a zero reference position with a 150 pound subject in the chair.

In order to counter any motion sensation due to either the random input or the galvanic stimulus, the subject was provided a three state controller which he operated with his right hand. With this controller, the subject was able to apply a step input to the servo system so as to cause the chair to move either CW or CCW. In the middle position, the switch had no effect on chair movement. The amplitude of the step was adjusted so that, in the absence of the random input, it caused a step change in chair position of 540 degrees.

Chair position was monitored with a 20K potentiometer attached through gears to the axis of chair rotation. This potentiometer produces an output of 0.1 volt/radian of chair movement which is scaled so that 0.25 volts = 360 degrees(2π radians).

4.3.2 Galvanic Stimulation Equipment

Galvanic stimulation was applied through two specially designed circular electrodes approximately one inch in diameter affixed to the subjects' mastoid processes. A diagram of one of these electrodes is shown in figure 4.3. A layer of wetted gauze impregnated with electrode paste was included in the electrode in order to avoid metal to skin contact and to obtain a relatively uniform current distribution. The two electrodes were mounted on a standard headband.

A so called indifferent electrode consisting of a 2 inch by 3 inch gauze pad was placed on the back of the

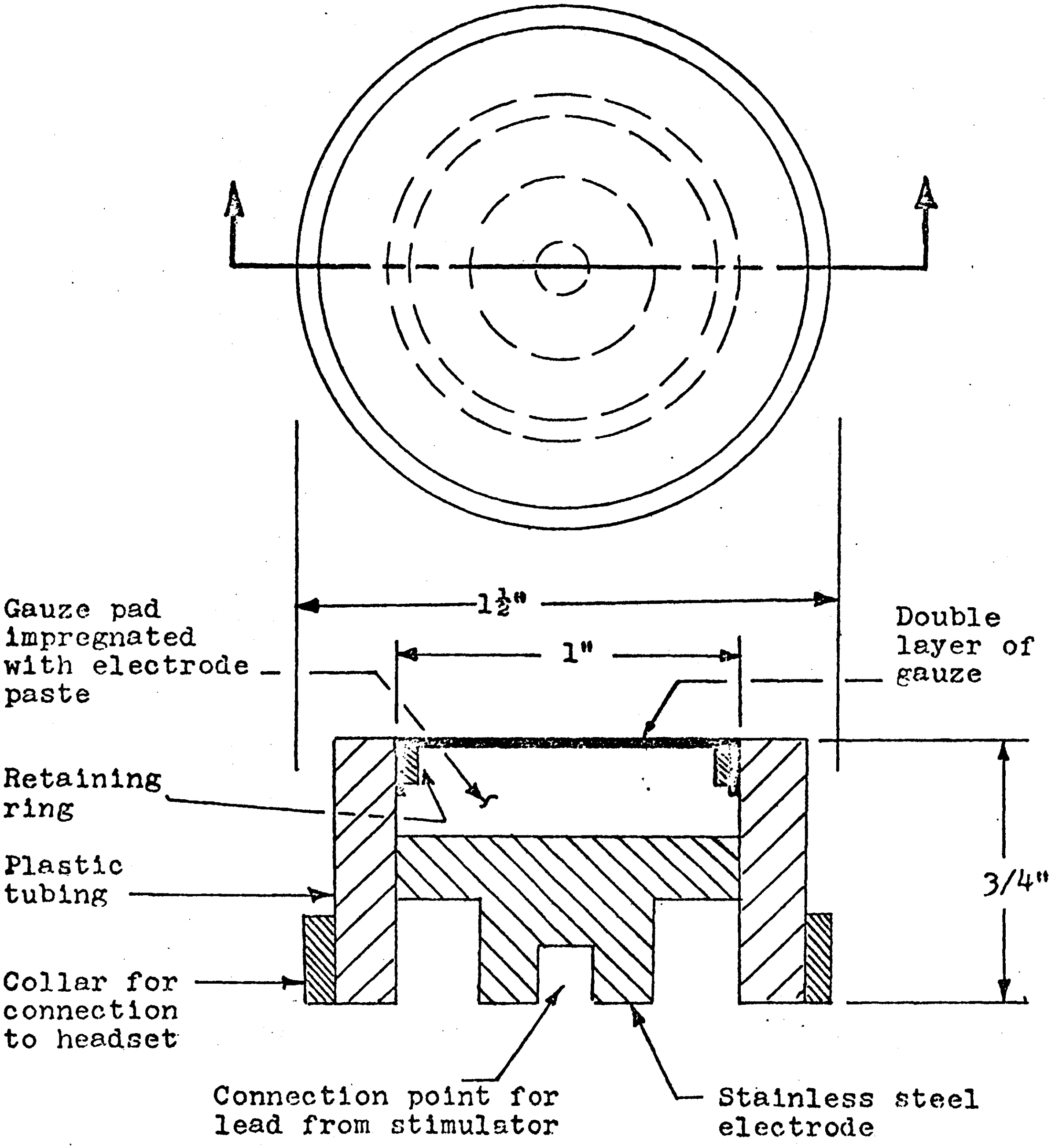


Figure 4.3
Stimulating Electrode
(approximately twice actual size)

subject's neck and held in place with surgical tape. This electrode was used as the common in unipolar tests.

All three contact areas on the subject were treated with electrode paste before the runs in an effort to achieve a nominal inter-electrode D.C. resistance of 2-3K ohms.

The positioning of the three electrodes on the subject is shown in figure 4.4. Figure 4.5 shows a schematic for the stimulus circuitry. D.C. current was obtained from an Electronics for Life Sciences Constant Current Stimulator Model CCS-1A. This stimulator is battery powered and has a maximum output capacity of 10 ma. at 90 volts. Switching was provided between the stimulator and the elctrodes in order to select either bipolar or right or left unipolar connections. Polarity reversal is accomplished at the stimulator, thus allowing for all six possible modes as outlined earlier.

The maximum current to be used was 3 ma., hence the stimulator was fused at 5 ma. The subject was able to disconnect the galvanic stimulus at any time during the experiment by depressing a "panic" button with his left hand. Pressing this button also rang a bell to alert the experimenter to the subject's difficulty.

A 20K potentiometer was added as shown in figure 4.5 to allow gradual application of current during an experimental run because at higher intensities particularly, a step input in current is often discomforting to the subject.

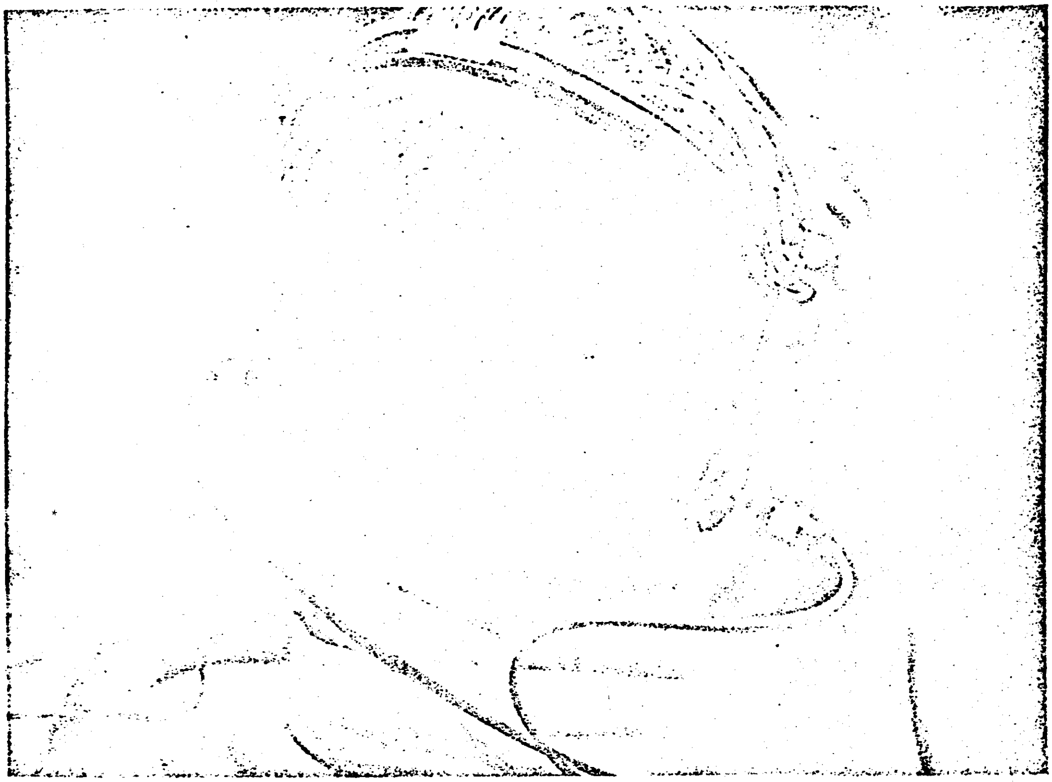


Figure 4.4

Locations of Stimulating Electrodes

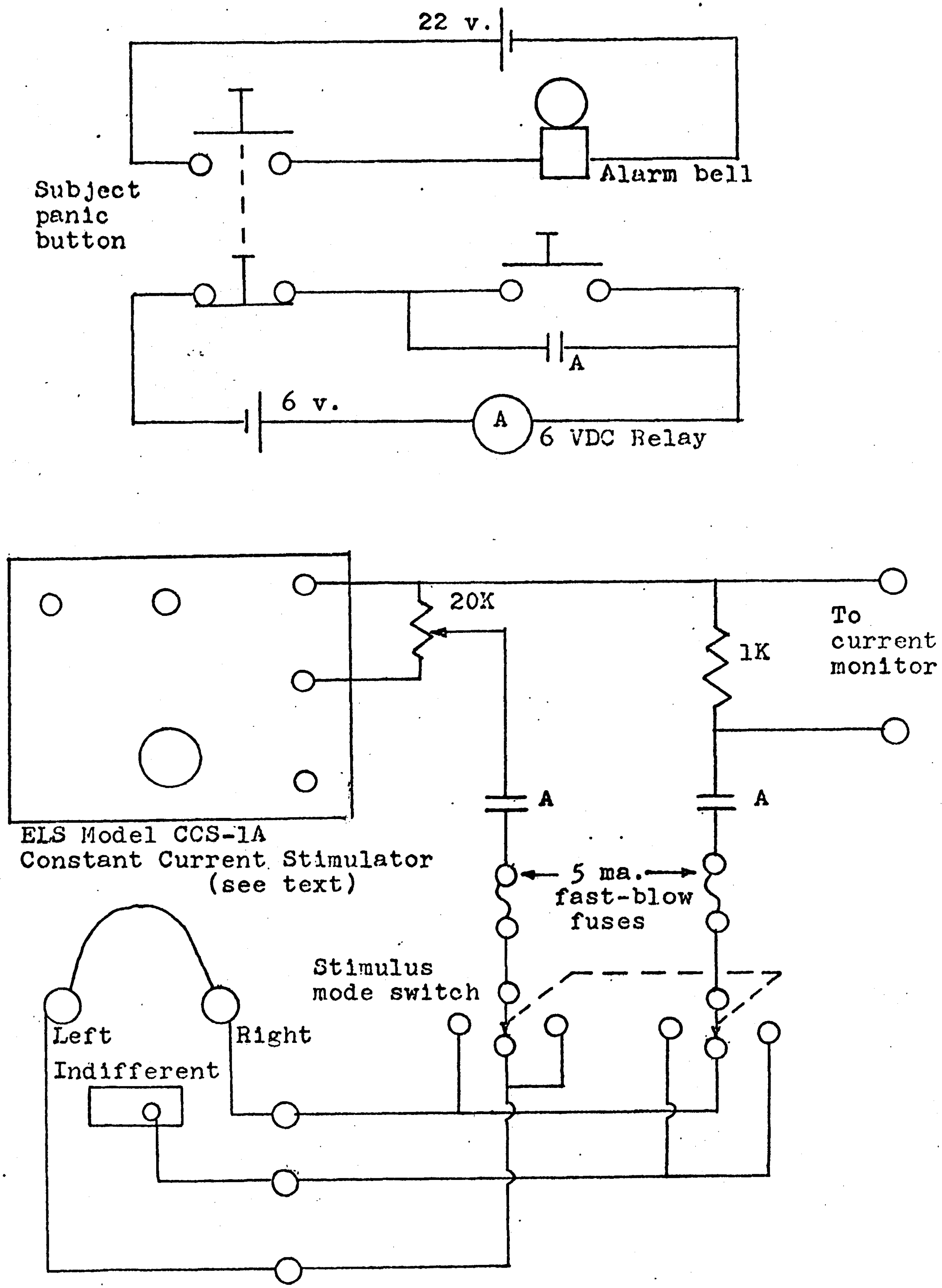


Figure 4.5

Galvanic Stimulus Connections

Current was monitored by measuring the voltage across a 1K ohm resistor in series with the stimulation circuit. The measuring circuit had a floating ground in order to isolate the subject from possible ground loops.

4.3.3 Eye Movement Monitoring

Subject eye movements were monitored using a Biometrics model SG HV - 2 photoelectric eye monitor, the operation of which was discussed in Chapter 2. The positioning of the monitor on the subject is shown in figure 4.6. In order to calibrate the instrument, the following procedure was employed. A white screen with three small black crosses drawn upon it was placed in the subject's line of sight in the rotating chair. The crosses were arranged so that one was directly ahead of the subject and the other two were 15 degrees to either side of this central point. With all lights out, as during the experiment, the screen is invisible. A very dim light, under subject control, was used to make the screen barely visible during calibration. With this light on the subject was asked to look straight, right, and left. The gain of the monitor was adjusted so that 20 degrees of horizontal eye movement = 1 volt. At the conclusion of the calibration, the subject turned off the light and was allowed to adapt to the darkness. The calibration was checked at the end of each run for possible drift or other changes.

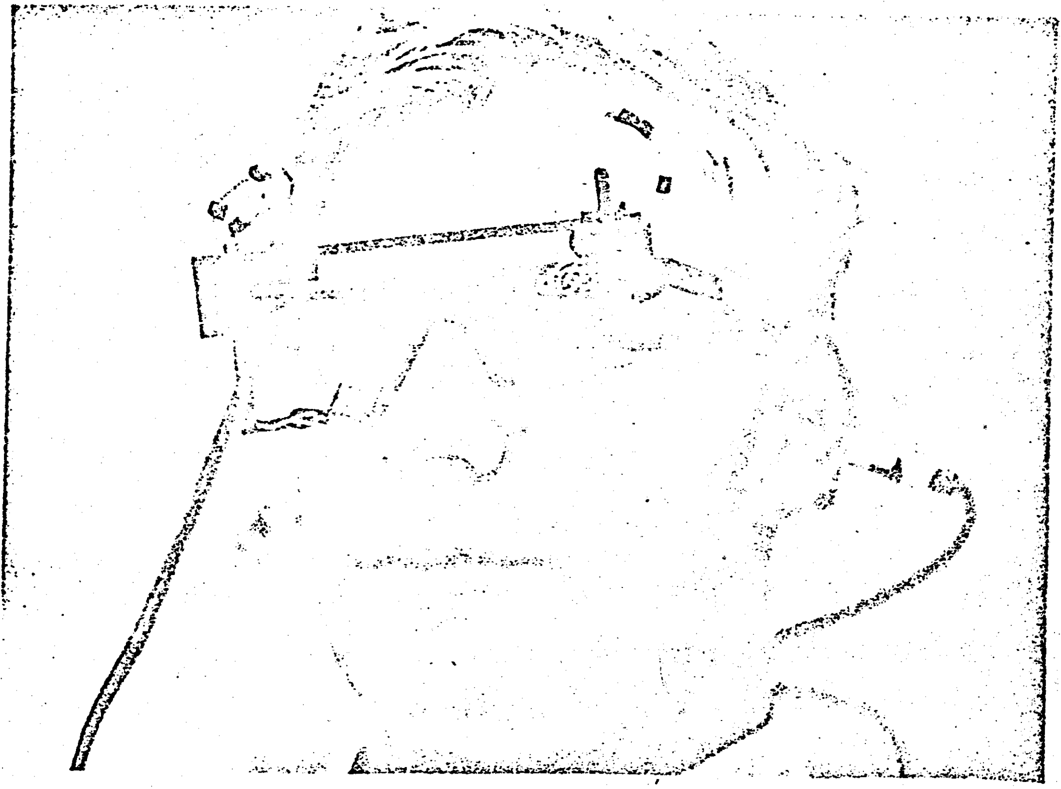


Figure 4.6

Positioning of the Eye Movement Monitor

4.4 Selection of Subjects

Six subjects, five males and one female, were used in the experimental design described above. Each of the subjects underwent a standard clinical vestibular examination in the Otoneurology Laboratory at the Massachusetts Eye and Ear Infirmary. All were judged normal tests for the purposes of this experiment. One showed a slight left directional preponderance but the amount was not considered extreme hence he was retained.

In addition to the normal subjects, one female subject with no vestibular function was run. Her clinical condition was described as neurofibromatosis and she had had a bilateral acoustic neuromas removed surgically.

4.5 Experimental Protocol

Approximately one and one half hours were required to run each subject, including approximately one half hour of subject and equipment preparation.

Subject preparation consisted of mounting the electrodes, checking inter-electrode resistances, calibration of the current monitor, mounting and calibration of the eye movement monitor and general instructions.

The general instructions were consistent from subject to subject and included instructions for the eye movement calibration. A copy of these instructions is given in table 4.1.

A total of eight runs per subject were made. These were an initial control run, six runs with current, and a

1. The chair may rotate. Your job is to stop the movement of the chair by pressing the switch with your right hand. Pushing down the switch on the right will make the chair turn right; pushing down on the left will make it move left. In the center position, there is no effect on chair movement. (demonstrate) So, if you feel the chair is standing still, do not press the switch. If you feel it is turning to the right for example you push the left side of the switch until you feel the turning has stopped and then release the switch. (demonstrate)

2. Keep your eyes looking straight ahead and do not move your head.

3. You may feel a tingling sensation under the electrodes at times. It will not be painful-just disregard it.

4. If you need help, push the alarm button. (demonstrate)

5. (Eye Movement Monitor Calibration) On the card in front of you there are three crosses, one at the center, one to your right, and one to your left. When you are asked to look straight ahead, look at the center cross. Look to the right, straight, or left on command and continue to look at the cross until the next command.

   We will repeat this when the room is dark. There is a small panel light which will allow you to see the crosses. When we have finished with this, turn the light off. (show subject the location of the light switch)

6. Now we will run the chair as before but with the curtains closed and the lights out. Be sure to keep your eyes open looking straight ahead.

Table 4.1

Instructions to subjects prior to experimental runs.

final control run. The modes and intensities for the galvanic stimulation runs were determined from the experimental design and were set manually before each run. Each of the eight runs lasted slightly more than two minutes with a five minute rest period between runs, the latter to reduce the chance of residual effects. During the six runs with galvanic stimulus, the chair motors were started first and the current was then immediately applied by turning the intensity potentiometer up(the 20 K potentiometer is shown in figure 4.5).

No attempt was made to eliminate subject audio cues. Ambient noise level during the experiments was fairly high due to the chair torque motor hum and to a small exhaust fan in the chair. The noise level was deemed high enough to prevent any significant audio cues of motion.

Much has been made of the effect of subject arousal state on the quality of eye movements elicited during vestibular experiment.[7] It was felt initially that the subject's task would maintain a high enough arousal level for this purpose. This may not have been the case in the experiments. Some discussion is given in the next chapter.

4.6 Data Records

Data for each experimental run was recorded on an eight channel Precision Instrument instrumentation recorder model P.S.200A. Five channels of analog data

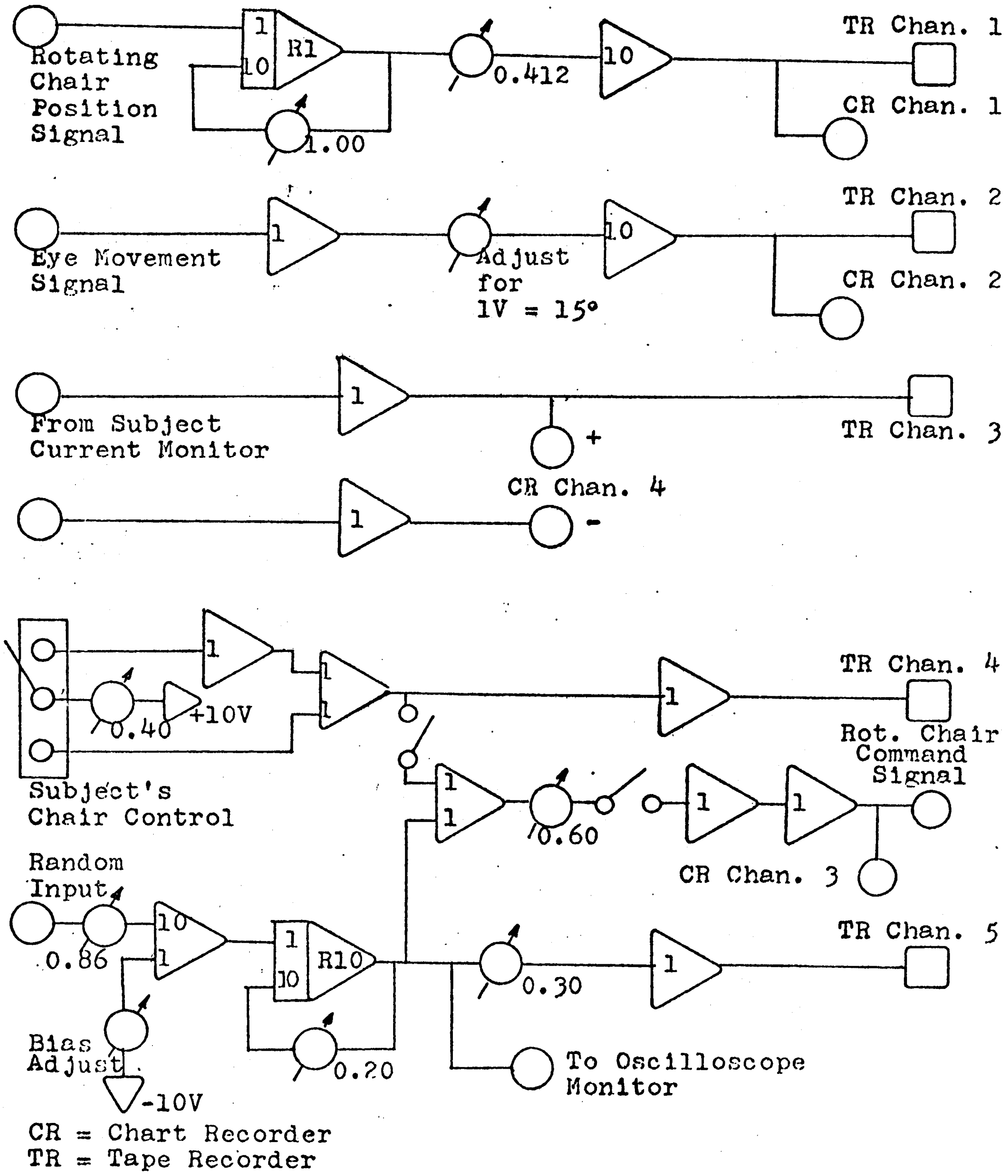


Figure 4.7

Monitoring and command signal connections

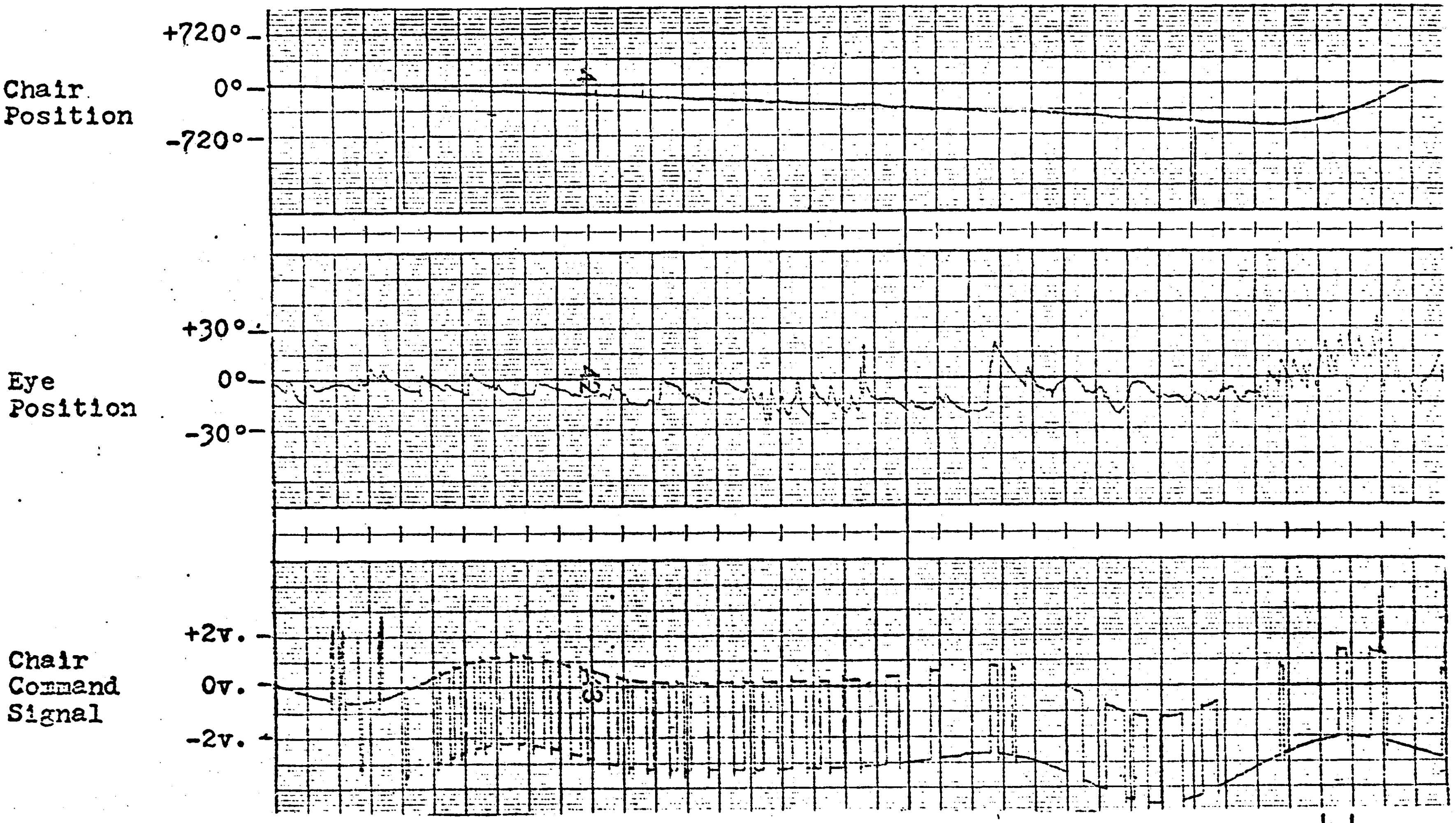


Figure 4.8

Typical Experiment Data
(Galvanic Stimulus: Unipolar Left Anode; 1.6 ma.)

were recorded as shown in figure 4.8. These included 1.) chair position, 2.) eye position, 3.) random input to the chair, 4.) subject's stick control and 5.) stimulating current. The data was simultaneously recorded on a four-channel Brush chart recorder model 240. The random input and subject stick control were combined in order to display all data graphically on the four channels.

The current monitor channel is not shown in figure 4.8 due to space limitations. The galvanic stimulus consisted of unipolar left anode at an intensity of 1-6 ma. Note the right beating nystagmus(toward the cathode) and the leftward drift of the chair as the experiment progresses and the subject's use of right control almost exclusively.

It is also noted that the chair returns toward zero near the end of the run. This occurance was observed in a number of runs but the cause is not clear. It might be an indication of cessation or reversal of the galvanic stimulus effect but this has not been substantiated.

CHAPTER 5

EXPERIMENTAL RESULTS

This chapter presents the results of the experiments performed in Chapter 4. The data analysis techniques are presented first followed by a discussion of the chair movement data. This is followed by a discussion of the eye movement data and the chapter concludes with some brief comments on the responses of the one abnormal subject tested.

5.1 Data Analysis

The experiments described in Chapter 4 produced two types of data: eye position and chair position versus time for each two minute run. In order to estimate the average drift away from the zero reference position, it was decided to calculate the mean value of chair position and of cumulative slow phase eye position over each run. The latter was used since it represents total amplitude of eye deviation during the experimental run.

5.1.1 Method for Determination of Cumulative Slow Phase Eye Position

Cumulative slow phase position was obtained from the original eye data by processing with the hybrid program, MITNYS. This program removes saccades and blinks which may be present in the raw eye position signal and pieces the slow phase portions of the record together to form a continuous cumulative position signal. MITNYS was originally developed for use in on-line vestibular experiments and is discussed in detail elsewhere.[31] It is also discussed briefly in appendix B which also presents a block diagram and a listing of the program.

5.1.2 Determination of Statistics of the Data

The mean, variance, and standard deviation for chair position and cumulative slow phase eye position for each run were calculated using the hybrid program, MAN, which is described in appendix C.

The mean value of position for each run with current was then entered in its respective location in the graeco-latin square used in the experimental design. Mean values for the control runs were also calculated and added in their respective locations at the beginning and end of each subject's data set. These results are given in table 5.1 for chair data and table 5.2 for eye data. All entries represent angular position measured in degrees. The tables also show the data rearranged according to modes and intensities of the galvanic stimulus (recall that these two parameter groups were randomized in the original graeco-latin square).

		Order							
		0	1	2	3	4	5	6	7
Subjects	1	213	62	168	235	-150	225	65	138
	2	-95	231	26	37	77	167	95	-235
	3	193	180	175	182	51	143	153	211
	4	-17	-9	13	4	40	49	7	84
	5	-10	74	179	-296	36	-172	115	77
	6	-2	-108	22	-21	192	157	-308	6

		Modes					
		A	B	C	D	E	F
Intensities	U	62	115	7	153	22	77
	V	37	168	179	-21	40	143
	W	175	4	192	26	74	65
	X	49	51	235	-172	95	-108
	Y	36	157	167	-150	182	13
	Z	-308	231	180	-9	225	-296

Table 5.1

Raw mean chair position data arranged according to subjects vs. order and intensities vs. modes (Orders 0 and 7 represent control runs. All entries are expressed in degrees)

	Order							
Subjects	0	1	2	3	4	5	6	7
1	-263	-221	-20	56	-75	226	-88	-39
2	-22	88	77	-63	12	112	-82	-199
3	49	323	13	90	76	43	-59	180
4	18	53	-124	164	83	41	55	90
5	351	343	311	-199	41	-340	213	427
6	7	48	14	78	-21	13	-66	-197

	Modes					
Intensities	A	B	C	D	E	F
U	-221	213	55	-59	14	12
V	-63	-20	311	78	83	43
W	13	164	-21	77	343	-88
X	41	76	56	-340	-82	48
Y	41	13	112	-75	90	-124
Z	-66	88	323	53	226	-199

Table 5.2

Raw mean eye position data arranged according to subjects vs. order and intensities vs. modes (Orders 0 and 7 represent control runs. All entries are expressed in degrees)

5.1.3 Tests for Significance of Various Parameters

In order to determine which of the parameter groups among subjects, order, modes, and intensities had significant influence on the data, a standard analysis of variance was performed. The analysis of variance is common technique for studying experimental data and is probably familiar to most readers. In brief, it involves operations on a set of data in such a way as to independently estimate the variance of each of the parameter groups contributing to the data. A residual variance is also estimated. This term represents the variance of random error contributions. The residual variance is assumed to be unbiased by differences among the parameters.

To test for possible significance of any parameter group, a null hypothesis is intoduced. This hypotheis assumes that each parameter is normally distributed and that all parameter group means are identical. The variance estimate of each parameter group is then compared with the residual variance estimate. If the ratio of the two estimates is small (more accurately, below a certain F level, to be discussed below) then the null hypothesis holds indicating the parameter group being tested was not a significant factor in the data.

If the variance ratio is large however, the null hypothesis must be rejected. This leads to the conclusion that the mean of the parameter group being tested does differ significantly from the means of the other groups. Thus, this group is concluded to have a significant influence on the results.

The significance level of the variance ratio, VR, is determined with the aid of the so-called F distribution. This distribution is a function of the degrees of freedom of the parameter group and of the residual. It is commonly tabulated in statistical handbooks according to various probability of occurence levels. One has then only to decide how large a chance for error he will allow in establishing significance. The table of F for this probability level will then indicate the variance ratio required for the given degrees of freedom of the parameter and the residual. The .05 probability level is often used in experiments such as the present one and was chosen as the standard here.

The graeco-latin square lends itself well to an analysis of variance study. Two computer programs, ANVAR and ANVAR2, were written to perform this analysis on the experimental data. The two programs are identical except that ANVAR2 takes into account the control runs while ANVAR does not. Both programs are discussed in appendix D.

If the analysis of variance indicates that a certain parameter group has a significant influence on the results, one would then like to know where differences lie within the group. A student "t" test may be used for this purpose.

The "t" test compares the differences between two means with a standard error term derived from the residual variance found in the analysis of variance and also depending upon the number of samples in each of the two means being tested. The standard error term is often called the error variance and the latter term is used here.

The ratio of differences in mean to error variance yields a "t" value. Values of "t" are tabulated according to degrees of freedom of the residual and the percentage probability of occurence. For significance, the ratio in the test must equal or exceed the value of t for the two parameters of the table. .05 is often the standard for the latter.

Two straightforward programs, T TEST and T $TEST_2$, were written to perform the student "t" on the experimental data. They are identical except that T $TEST_2$ makes provisions for control runs while T TEST does not. The two programs are described in Appendix E.

Details on the theory of the analysis of variance and the student "t" test may be found in the references.[6,18]

5.2 Analysis of Chair Position Data

Using the analysis of variance methods discussed above, the chair position data shown in Table 5.1 was studied. Table 5.3 gives the results of performing the analysis of variance on this data without consideration of control runs. The data, as it appears in the graeco-latin square, is at the top of the table, the variance table is in the middle, and the means for each subject, mode, and intensity are at the bottom. Below the table, the error variance is printed out for possible use in a

```
                        Order
Subjects
       =    62=   168=   235=- 150=   225=    65
       =   231=    26=    37=   77=   167=    95
       =   180=   175=   182=   51=   143=   153
       =-    9=    13=     4=   40=    49=     7
       =    74=   179=- 296=    36=- 172=   115
       =-  108=    22=-   21=  192=   157=- 308

SOURCE        DF        SS              VE              VR

MODES          5  = 194547.00   =   38909.50   =        2.67

INTENSITIES    5  =  38393.30   =    7678.65   =        0.53

SUBJECTS       5  = 139206.00   =   27841.20   =        1.91

ORDER          5  =  35478.90   =    7095.78   =        0.49

RESIDUAL      15  = 218361.00   =   14557.40

TOTAL         35  = 625986.00

                    Mean Responses
          SUBJECTS     MODES   INTENSITIES

      1 =   100.8  A =    8.5  U =   72.7
      2 =   105.5  B =  121.0  V =   91.0
      3 =   147.3  C =  160.0  W =   89.3
      4 =    17.3  D =-  28.8  X =   25.0
      5 =-   10.7  E =  106.3  Y =   67.5
      6 =-   11.0  F =-  17.7  Z =    3.8

ERROR VARIANCE=    69.66
```

Table 5.3

Analysis of Variance of Raw Chair Position Data "t" test.

The variance ratio for each parameter group is listed in the variance table under the heading, VR. Each parameter group has five degrees of freedom. The value of F required at 0.95 level for these degrees of freedom is 2.90. It is seen that none of variance ratios equal or exceed this value, hence no conclusion can be drawn concerning significance.

It is useful to note the low value of VR obtained for order. Recall that the graeco-latin square was employed to reduce the effects on the results of order of presentation of the stimuli. A low VR value for order indicates the design has been successful in achieving the goal.

It is also useful to note that the VR value for modes is closest to the required F level. In an attempt to enhance the effects of the modes, a correction of the data to account for subject differences was made. This was accomplished by adding to each subject's data the difference between the overall mean and that subject's mean. For example, the overall mean of the 36 data entries was 58 degrees and the mean of subject 1 is found from Table 5.3 to be 100.8 degrees. The difference between the two values is $58-100.8 \approx -43$ degrees. If -43 degrees is added to each data point from subject 1, the mean of his data will become equal to the overall mean, eliminating the effect of his mean response from the data set.

This procedure was repeated for each of the six subjects. An analysis of variance was then run on the corrected data. The results are given in Table 5.4. Note that the value of VR for subjects has dropped almost to zero(it is not exactly zero due to round-off error). Also the VR value for modes is now 3.01, which is above the required F level of 2.90. The VR for order has not changed appreciably.

Since the modes are now shown to be significant, a t test may be conducted to determine where the actual differences lie. Such a test was conducted using the T TEST program. The results are shown in Table 5.5. Mode 1 is found to differ significantly from mode 3, 2 from 4, 3 from 4, and 3 from 6(Note modes 1,4 and 6 correspond to A,D and F; 2,3, and 5 to B,C and E in the experimental design). In each of these four cases, the difference occurs between an anodic and a cathodic mode. No differences are found between modes of the same polarity.

It may also be noted that the means for the anodic modes have large positive values(121, 172, 107) while the cathodic modes have smaller magnitude and tend to the negative direction(9, -28, -17). This result appears at first to be in agreement with the discussion in Chapter 3 where the anode was reported to have a greater effect than the cathode. If one considers the control runs, however, this result is not as clear.

```
                         Order
Subjects
          =     19=    125=    192=-   193=    182=     22
          =    189=-    16=-     5=     35=    125=     53
          =     91=     86=     93=-    38=     54=     64
          =     32=     54=     45=     81=     90=    115
          =    143=    248=-   227=    105=-   103=    184
          =-    39=     91=     48=    261=    226=-   239

SOURCE          DF          SS                VE              VR

MODES            5  =  208809.00    =   41761.80    =         3.01

INTENSITIES      5  =   40952.20    =    8190.44    =         0.59

SUBJECTS         5  =     670.22    =     134.04    =         0.01

ORDER            5  =   31136.90    =    6227.38    =         0.45

RESIDUAL        15  =  208239.00    =   13882.60

TOTAL           35  =  489807.00

                    Mean Responses
              SUBJECTS   MODES   INTENSITIES

        1 =     57.8 A =      9.3 U =    84.7
        2 =     63.5 B =    121.8 V =    91.8
        3 =     58.3 C =    172.0 W =    90.2
        4 =     69.5 D =-    28.0 X =    25.8
        5 =     58.3 E =    107.2 Y =    68.3
        6 =     58.0 F =-    16.8 Z =     4.7

ERROR VARIANCE=    68.03
```

Table 5.4

Analysis of Variance of Chair Data Corrected for Subject Differences

```
            T TEST

ERROR VARIANCE= 68.03   T(P=0.05)=  2.13

                     M0DES                 INTENSITIES

    =      1.0   =     9.3           =     84.7
    =      2.0   =   121.8           =     91.8
    =      3.0   =   172.0           =     90.2
    =      4.0   =-   28.0           =     25.8
    =      5.0   =   107.2           =     68.3
    =      6.0   =-   16.8           =      4.7


    M= 1 M= 3 T=    2.39
    M= 2 M= 4 T=    2.20
    M= 3 M= 4 T=    2.94
    M= 3 M= 6 T=    2.78*
```

Table 5.5

"t" Test on Chair Data Corrected for Subject Differences

The control run means are both 47 degrees. The mean of all six mode responses taken together is 61 degrees. The proximity of these two values suggests that an inherent bias may be present in the experiment, either due to the equipment or to subject response. If such a bias indeed exists, then correction of the mode means for it would make the magnitude of anodic and cathodic responses approximately equal. One would then conclude that anodic and cathodic stimulus produce approximately the same magnitude of effect.

It was also desired to learn if any of the intensities were significant. The VR value for intensities in both of the above analysis was small however. In order to enhance the intensity effects, the original data was corrected for differences between modes. This correction was made in a manner similar to that for the subjects above except that the overall mean was not used. Hence the mean of each mode after the correction would be ≈ zero.

A difficulty arises here due to the fact that three modes are of one polarity and the other three of the opposite polarity. In order to truly eliminate the mode effects the polarity differences must also be accounted for. This is accomplished by correcting for the expected effects of either the anodic or the cathodic modes.[5] The anodes were chosen arbitrarily and the corrections made by changing the signs of all data obtained during anodic stimulation.(modes B,C,and E). The data then corresponds

```
                      Order
Subjects
     =      53=-    47=-    75=-   121=-   119=     83
     =-    110=     55=     28=     95=-     7=     11
     =-     20=    166=-    76=     70=    161=-   182
     =      20=     31=    117=     66=     40=    153
     =      32=-    19=-   278=     27=-   143=-     6
     =-     90=     84=      8=-    32=-    36=-   317

SOURCE        DF         SS               VE            VR

MODES          5   =-    3942.00    =-     788.40   =-         0.12

INTENSITIES    5   =  209004.00     =   41800.90    =          6.46

SUBJECTS       5   =   87565.70     =   17513.10    =          2.71

ORDER          5   =   37815.30     =    7563.07    =          1.17

RESIDUAL      15   =   97029.70     =    6468.65

TOTAL         35   = 427473.00

                  Mean Responses
         SUBJECTS     MODES   INTENSITIES

     1 =-    37.7 A =-    0.5 U =    93.5
     2 =     12.0 B =-    2.0 V =    32.8
     3 =     19.8 C =     0.0 W =    70.2
     4 =     71.2 D =     0.2 X =-   31.2
     5 =-    64.5 E =-    0.3 Y =-   30.3
     6 =-    63.8 F =     0.3 Z =-  137.3

ERROR VARIANCE=    46.44
```

Table 5.6

Analysis of Variance of Chair Data Corrected for Mode Differences-no controls

```
            T TEST

ERROR VARIANCE= 46.44   T(P=0.05)=  2.13

                    M0DES            INTENSITIES

   =     1.0  =-    0.5          =    93.5
   =     2.0  =-    2.0          =    32.8
   =     3.0  =     0.0          =    70.2
   =     4.0  =     0.2          =-   31.2
   =     5.0  =-    0.3          =-   30.3
   =     6.0  =     0.3          =-  137.3


   S= 1  S= 4  T=   2.69
   S= 1  S= 5  T=   2.67
   S= 1  S= 6  T=   4.97
   S= 2  S= 6  T=   3.67
   S= 3  S= 4  T=   2.18
   S= 3  S= 5  T=   2.17
   S= 3  S= 6  T=   4.47
   S= 4  S= 6  T=   2.29
   S= 5  S= 6  T=   2.31*
```

Table 5.7

"t" Test of Chair Data Corrected for
Mode Differences-no control

to that which might be expected had all cathodic stimuli been used. (Since the mode means have been forced to zero, it makes no difference whether anodic or cathodic modes are changed.)

The corrected data was processed with the analysis of variance program with the results given in Table 5.6. V.R. of the modes is now $\approx$ zero and subject and order V.R.'s are not significant. The VR of the intensities has now become 6.46 however, well above the required 2.90. Thus a "t" test is justified for the intensity data in this form. The results of this test are given in Table 5.7.

The "t" test reveals that intensities 1, 2, and 3 (U, V, and W in the original notation) do not differ from one another but that all differ with one or more of the intensities 4, 5, and 6(X, Y, Z). Intensities 4 and 5 do not differ from one another but both differ from intensity.6.

Some results were obtained if the control were also taken into consideration in this case. These results obtained with the ANVAR 2 and T TEST 2 programs are given in Tables 5.8 and 5.9. Again the analysis of variance finds the intensities to be significant. Due to an increase in error variance, the t test(with 23 degrees of freedom in the residual) indicates differences only between each of the lower three intensities and intensity 6. (Note: The effect of adding the controls

Subjects	Order 0	1	2	3	4	5	6	7
1	166	53	-47	-75	-121	-119	83	91
2	-142	-110	55	28	95	-7	11	-282
3	146	-20	166	-76	70	161	-182	164
4	-64	20	31	117	66	40	153	37
5	-57	32	-19	-278	27	-143	-6	30
6	-49	-90	84	8	-32	-36	-317	41

```
SOURCE         DF         SS             VE              VR

MODES           7   =-    717.19   =-    102.46   =-       0.01

INTENSITIES     5   = 211136.00    =   42227.10   =        3.49

SUBJECTS        5   =  97310.20    =   19462.00   =        1.61

ORDER           7   =  41040.10    =    5862.88   =        0.49

RESIDUAL       23   = 278269.00    =   12098.60

TOTAL          47   = 627037.00
```

Mean Responses

```
   Subjects          Modes          Intensities
 =         3.88   =-        0.50   =      93.50
 =-       44.00   =-        2.00   =      32.83
 =        53.63   =         0.00   =      70.17
 =        50.00   =         0.17   =-     31.17
 =-       51.75   =-        0.33   =-     30.33
 =-       48.88   =         0.33   =-    137.33*
```

Error Variance = 63.51

Table 5.8

Analysis of Variance of Chair Data Corrected for Mode Differences-with control runs

```
            T TEST

ERROR VARIANCE= 63.51  T(P=0.05)=  2.07

                     M0DES              INTENSITIES

   =      0.0   =     0.0         =     0.0
   =      1.0   =-    0.5         =    93.5
   =      2.0   =-    2.0         =    32.8
   =      3.0   =     0.0         =    70.2
   =      4.0   =     0.2         =-   31.2
   =      5.0   =-    0.3         =-   30.3
   =      6.0   =     0.3         =-  137.3
   =      7.0   =     6.7         =     0.0


   S= 1 S= 6 T=    3.64
   S= 2 S= 6 T=    2.68
   S= 3 S= 6 T=    3.27*
```

Table 5.9

"t" Test of Chair Data Corrected for
Mode Differences-with control runs

could be predicted from the original considerations of the analysis of variance. One purpose of the control runs is to establish a subject norm and possible order effects over the course of an experiment. Thus their addition to the analysis of variance would be expected to decrease subject and order effects. At the same time, they add to the overall sum of squares which in turn increases the residual term. Thus all V.R. values are generally lower and the error variance for use in the "t" test becomes larger.)

The results with and without control both strongly suggest that the lower three intensities used in the experiments lie at or below the threshold for the galvanic reaction under the given experimental conditions. The average of the means of these three intensities is 66 degrees which is close to the value of 47 degrees obtained for the control runs. These two values and the value obtained for the overall mean of the modes above are all approximately the same, thus further substantiating the indication that an inherent bias was present in the experiment.

The various results above may be summarized as follows: Significant differences were found between anodic and cathodic mode effects, with anodic stimuli seemingly producing larger effects. If control runs are taken into account, the effects of the two mode types become nearly equal. Intensities below the 800μa level,

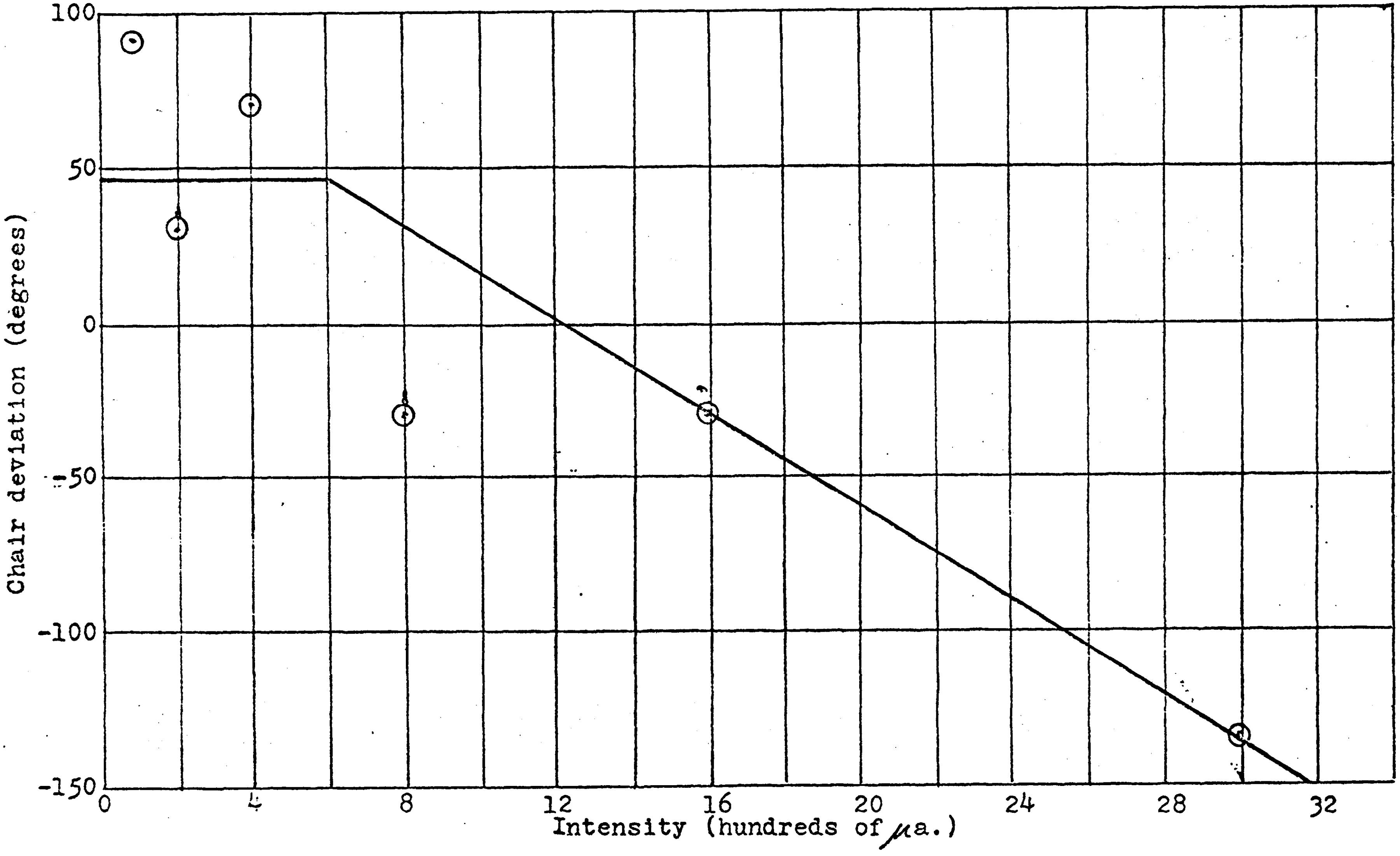


Figure 5.1

Chair deviation versus galvanic stimulus intensity appear to have no effect on the results with responses being approximately the same as for the control runs. At intensity levels at and above 800 a significant effects were apparent. A threshold for current effect between 400 and 800 a was thus suggested. A plot of these results is shown in Figure 5.1.

The plot shows the apparent bias below the threshold of the current effect. The bias is chosen somewhat arbitrarily at 47 degrees, the mean of the control runs. The means of the three intensities below threshold are shown scattered about this value. The threshold is also set somewhat arbitrarily at 600μa. A least mean squared linear plot is then made through this point and the three intensity means above threshold. The line was forced to pass through the 600μa point.

5.3 Analysis of Eye Position Data

The mean cumulative slow phase eye position data from the experiments is given in Table 5.2. This data was processed with the ANVAR program and the results are shown in Table 5.10. The F value required for significance is again 2.90. None of the variance ratios equals or surpasses the value though, as in the raw chair position data, the VR for modes is highest at 2.13. Corrections similar to those used to enhance the chair data were employed on the eye data but failed to improve the significance of any of the parameter groups. Thus no definite conclusions may be drawn concerning the influence

```
                           Order
Subjects
          =-  221=-   20=    56=-   75=   226=-   88
          =    88=    77=-   63=    12=   112=-   82
          =   323=    13=    90=    76=    43=-   59
          =    53=-  124=   164=    83=    41=    55
          =   343=   311=-  199=    41=-  340=   213
          =    48=    14=    78=-   21=    13=-   66

SOURCE        DF        SS               VE              VR

MODES          5  = 237156.00   =   47431.20   =        2.13

INTENSITIES    5  =  67200.20   =   13440.10   =        0.60

SUBJECTS       5  =  40046.60   =    8009.31   =        0.36

ORDER          5  =  44740.90   =    8948.17   =        0.40

RESIDUAL      15  = 334277.00   =   22285.20

TOTAL         35  = 723421.00

                     Mean Responses
          SUBJECTS    MODES   INTENSITIES

       1 =-   20.3 A =-   42.5 U =     2.3
       2 =    24.0 B =    89.0 V =    72.0
       3 =    81.0 C =   139.3 W =    81.3
       4 =    45.3 D =-   44.3 X =-   33.5
       5 =    61.5 E =   112.3 Y =     9.5
       6 =    11.0 F =-   51.3 Z =    70.8

ERROR VARIANCE=   86.19
```

Table 5.10

Analysis of Variance of Raw Eye Position Data of the experimental conditions on eye movements.

One interesting observation can be made on the eye data however. The modes had the highest VR and a comparison of the means of each mode with the corresponding means in the chair data analysis certain similarities can be noted. All right cathodic modes have negative mean responses while all right anodic modes have positive mean responses. In addition, the anodic effects have larger magnitudes than the cathodic as in the chair data. This suggests that a similar net effect due to modes is being observed in both chair and eye movement data.

The peculiarities of the experimental scheme may well have masked the eye movement data. Only relatively low angular accelerations were present which would naturally decrease eye deviations due to rotation. Eye drift(other than that due to the galvanic stimulus) may have decreased the ability to measure the deviations due to the current. It is possible that a fixation point might aid this latter problem.

Despite the inability to find significance in the eye movement data, the results nevertheless appear to be in definite pattern. Additional experiments would, therefore, seem warranted to further uncover the effects of the current on eye movements.

5.4 Subject's Reported Sensations

The subjects reported several sensations during the experiments. These included disorientation, head tilt, and one report of the sensation of "spinning in two directions simultaneously." Several subjects also reported an after effect following stimulation at 3 ma. This manifested itself in a spinning sensation but died out before the beginning of the next run.

Subjects complained somewhat about the electrode head band which became painful when worn for a long period.

5.5 Comments on One Abnormal Subject

One abnormal subject was also run on the experiment under protocol #1. The subject was an eighteen year old female with Von Recklinhausens' disease(neurofibromatosis) who had had bilateral acoustic neuromas removed surgically. She reported no sensation of rotation during any of the experimental runs. The chair position followed the random signal almost exactly. Her only indication of current effect came at the 3 ma. level at which she repeatedly was unable to tolerate the skin effects of the stimulus and terminated the run by pressing the panic button.

Eye movements displayed large right beating nystagmus at the onset of the experiment. Nystagmus remained right beating on all runs but decreased markedly in amplitude. The large deviations at the beginning were attributed to subject apprehension which apparently subsided as the experiment period wore on.

The results for this subject then indicated that galvanic stimulation does not produce sensation of rotation or disorientation when both vestibular nerves have been sectioned.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The object of this thesis was to determine the gross influence of galvanic vestibular stimulation on the perception of rotation and on eye movements. The intent was to determine which parameters might effect these phenomena and to lay the groundwork for future study in this area, particularly in clinical application. In order to accomplish this, the effects of stimulation modes and intensities on subject threshold for motion sensation and eye movements were examined.

Modes (the various electrode combinations) were found to be significant only with reversed polarities. Whereas quantitative differences in effect between anodic and cathodic stimulation had been reported in the literature no such differences were found in the present experiments when correcting for reversal of polarity and the control bias. After these corrections, anodic and cathodic stimulation produced effects of opposite sign but of the same magnitude.

Similarly, differences in magnitude of effect had been reported between unipolar and bipolar stimulation. No such differences were found in the present work.

The threshold for intensity effect in the experiments was found to lie at approximately 600μa. Runs with current below this level gave results no different than those of the control runs. Above 600μa, the current acts in an apparent linear manner to bias the threshold of rotation perception.

With a five minute rest period between runs, no order effects were observed.

Analysis of eye movements suggested results similar to those of the voluntary responses but not at statistically significant levels.

One abnormal subject with peripheral vestibular nerves destroyed was run on the experimental set-up. No reaction could be obtained with or without galvanic stimulus. Thus, for this subject, absence of the peripheral nerve implies absence of the galvanic reaction. Thus the action site of the stimulus appears to be distal to the brain stem though the exact point remains to be established.

The experimental results are in apparent agreement with the findings of Mirchandani that all persons, even so called vestibularly "normal" subjects, exhibit a slight directional preponderance over a period of time. In the present case this was manifested in a consistent chair drift away from a zero reference position during control runs and during runs with current but below threshold for current effect. The drift in each case was to the right, the same as in Mirchandani's experiments.

The results of this research indicate possible extensions of the subjective perception model of the semicircular canals, discussed in Chapter 2. The proposed additions to the model are shown in figure 6.1. These include a threshold, a gain, K_G, and an as yet unknown dynamic ter K(s) to reflect possible transient or response decline phenomena.

The galvanic stimulus has an apparent additive effect on perception of rotation. The best estimate of the action site at present indicates that it is probably central to the hair cells in the macula of the semicircular canals. The proposed addition to the model reflects these considerations by making the galvanic stimulus response terms additive with the output of the existing perception model but before the central nervous system. The evaluation of K(s) and exact determination of the threshold and K_G will be required in future work.

A number of topics related to galvanic vestibular stimulation deserve future attention.

The threshold and gain for intensity effects should be established more accurately by more extensive testing of several subjects under fewer conditions. One means of accomplishing this is an alternative form of the experiment above with the subject in a passive role.

Various transient analyses might also be useful. In particular, step inputs in rotating chair velocity in the presence of galvanic stimulation might yield

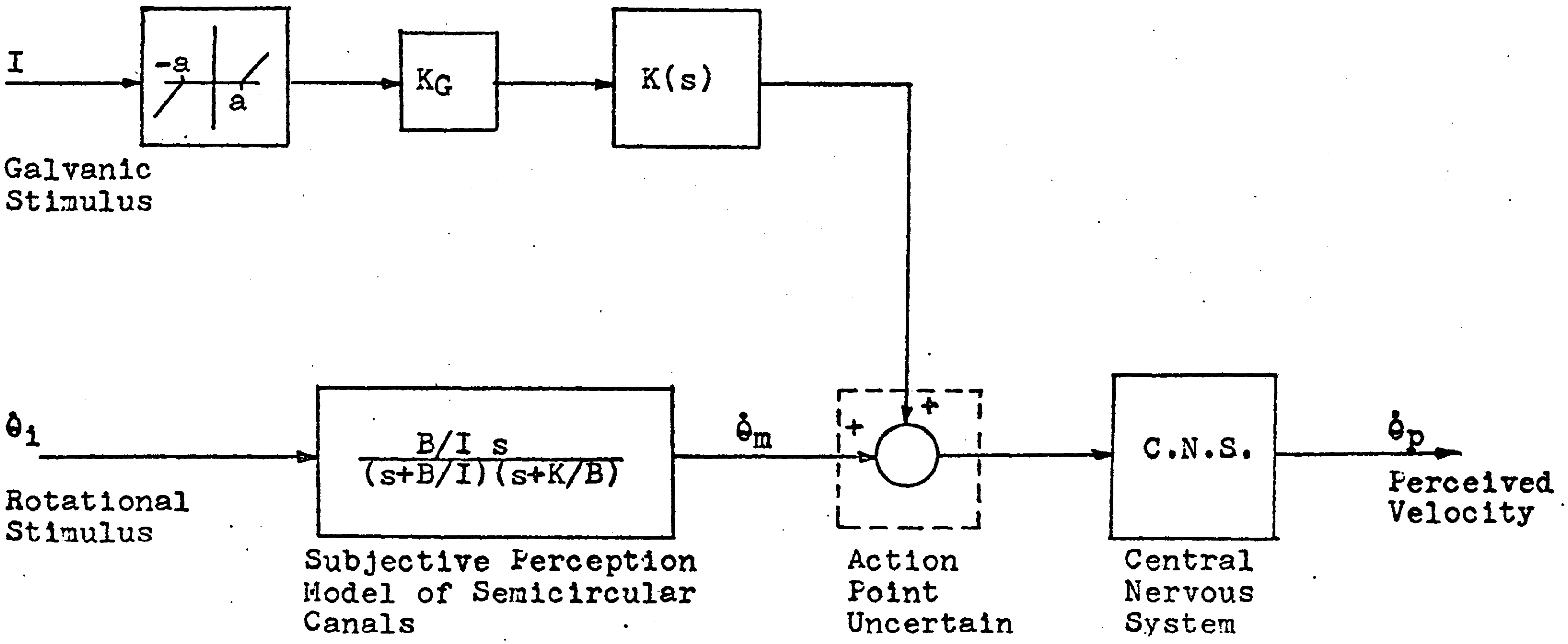


Figure 6.1

Proposed extension of subjective perception model
to include galvanic stimulus

information on response latency times. Chronaxia study might also be further considered. As pointed out in Chapter 3, results have not been consistent between researchers for vestibular nerve chronaxia. If a repeatable method of performing this test were available it might become useful clinically.

The effects of galvanic stimulation on posture as discussed in Chapter 3 might also be a particularly fruitful area for future consideration.

An important consideration for future work is the eye movement response to galvanic stimulation. The experiments performed here indicated that eye movements might provide useful quantitative measures of rotation sensation if signal to noise ratios were improved. A possible means of improving this ratio would be to provide a fixation point, either visual or propriocceptive (such as asking the subject to "look" at his outstretched thumb).

Eye movements, if shown to be a consistent good indication of the galvanic vestibular reaction would be much more practical to use in a clinical test as compared with the rotational tests employed here.

APPENDIX A

COMPUTATION EQUIPMENT USED IN DATA ANALYSIS

All data analysis for this thesis was performed on the MIT Man Vehicle Laboratory hybrid computer facility. This equipment consists of a Digital Equipment Corporation PDP-8 digital computer interfaced to a GPS model 290 T analog computer. The PDP-8 has a 12 bit, fixed word length, 1½ second cycle time, and $4{,}096_{10}$ memory locations. Programs are written and stored using a modified version of the DEC tape programming system supplied by the manufacturer.

The analog machine uses a 10 volt reference. There are 7 A/D and 8 D/A channels each with a range of ±10 volts. Sampling rate is determined by a real time clock actuating a program interupt line at the analog machine.

APPENDIX B

MITNYS, A HYBRID PROGRAM TO DETERMINE CUMULATIVE SLOW PHASE OF NYSTAGMUS

The eye movement data obtained during the experiments described in this thesis was processed using the hybrid program, MITNYS, the digital portion of which is written in PAL, the assembly language for the PDP-8 computer.

MITNYS receives the raw analog eye movement data, removes saccades and blinks which may be present, and pieces the slow phase eye movements together to form a cumulative slow phase output. This output may be thought of as the total amplitude of slow phase eye movements during the experiment.

In addition, the program differentiates this output to obtain slow phase velocity, however, this was not required in the present research.

A simplified block diagram for MITNYS is given in figure B.1, and an annotated listing follows. The required analog connections are shown in figure B.2. A complete discussion of the algorithm is somewhat involved and is omitted here. It has been reported elsewhere for those who may be interested.[31]

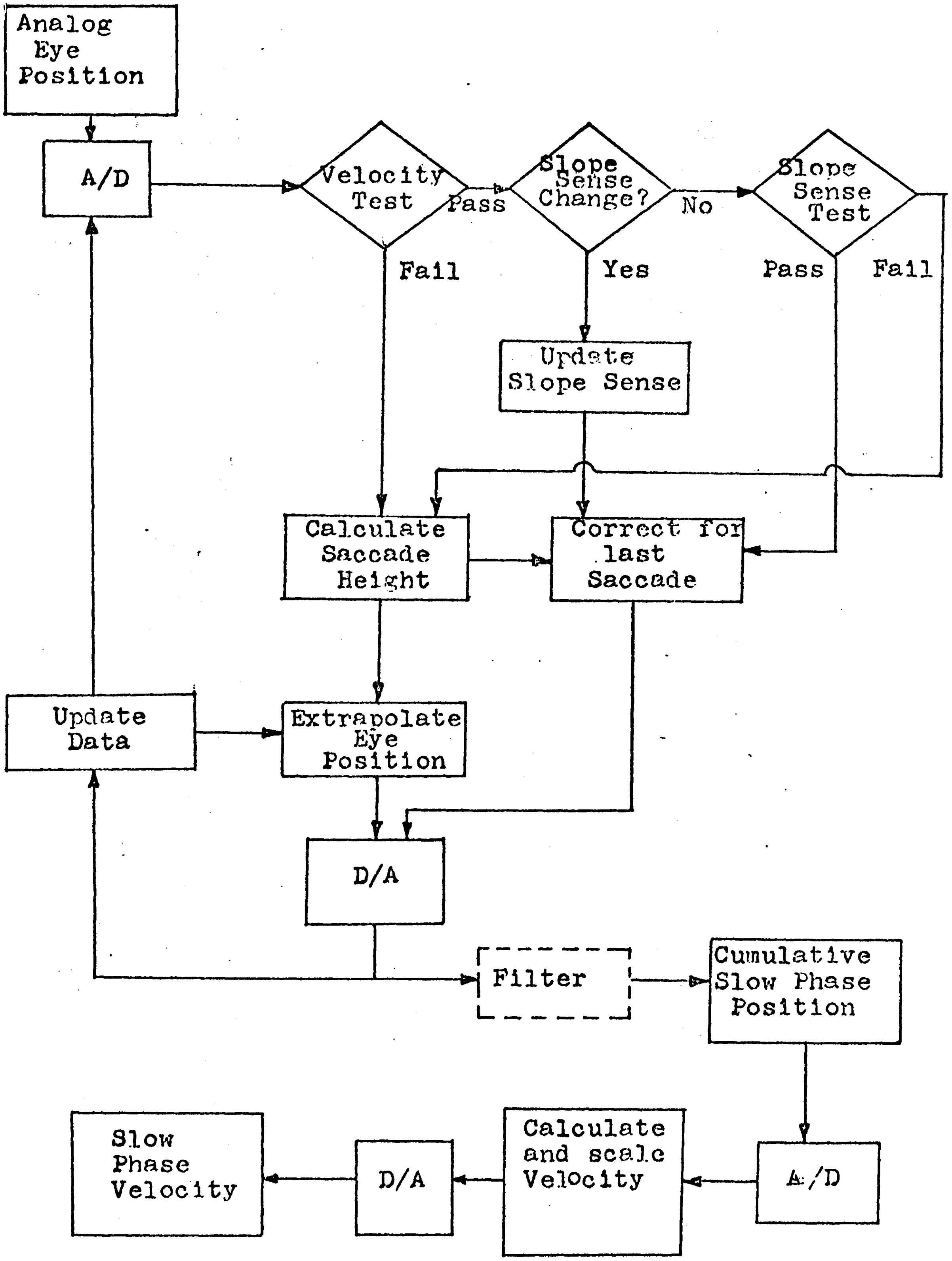


Figure B.1

Simplified block diagram for the hybrid program MITNYS

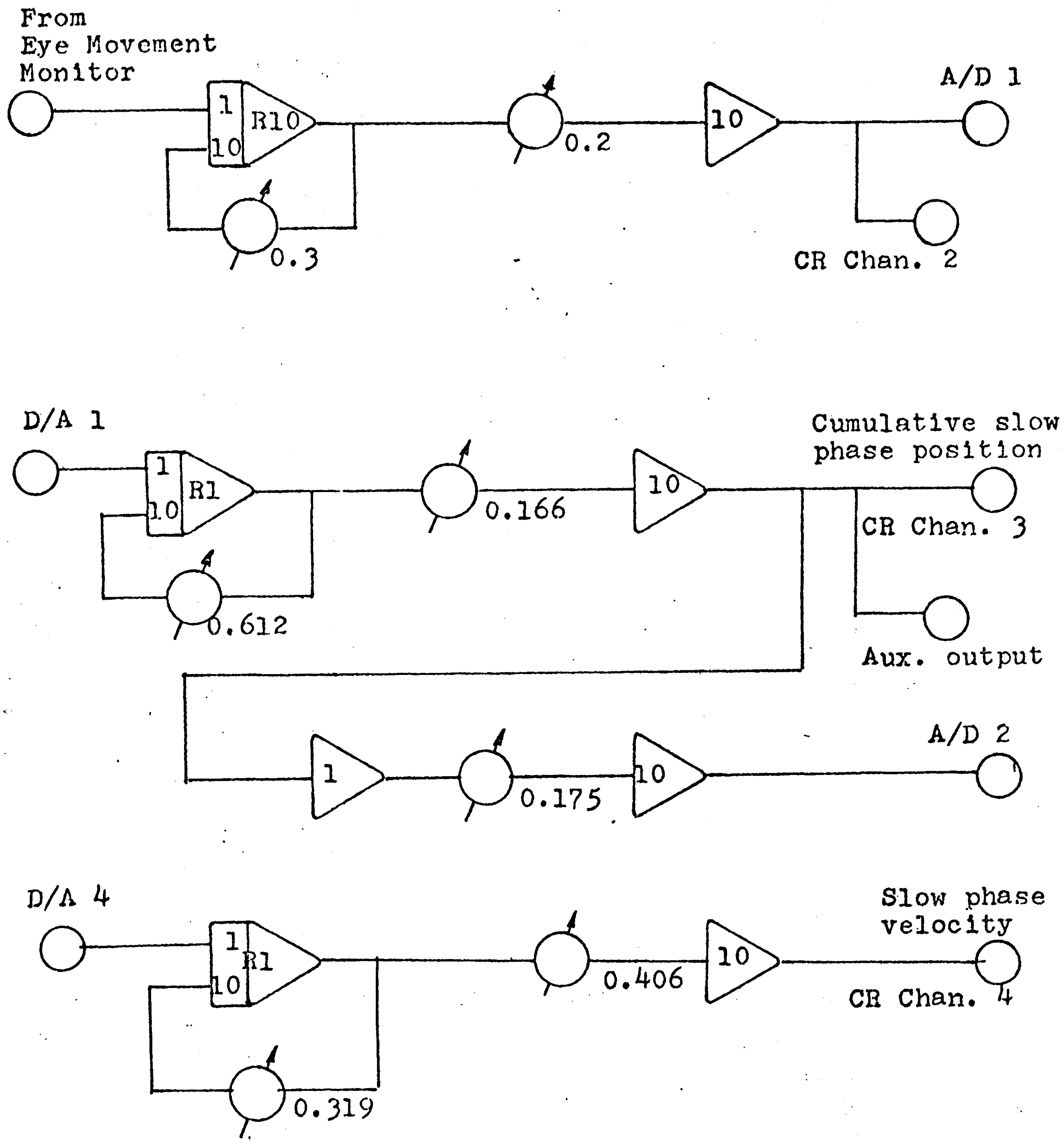


Figure B.2

Analog Connections for the hybrid program, MITNYS

```
                *200         /MITNYS-DOUBLE PRECISION
                             /ON-LINE NYSTAGMUS PROCESSOR

                             /MAN-VEHICLE LAB, MIT, FEBRUARY, 1970

                                 /INPUT CALIBRATION: 1V = 15DEG
                                 /SAMP RATE = 32 PER SEC


0200  7200       START,CLA /INITIALIZE CONSTANTS
0201  3040             DCA SAMP0
0202  3032             DCA APP0A
0203  3033             DCA APP0B
0204  3044             DCA TEMP1
0205  3047             DCA SLOPE
0206  3052             DCA SS
0207  1021             TAD B
0210  3055             DCA CNTR1
0211  1022             TAD C
0212  3056             DCA CNTR2

0213  7604         TOP,LAS /PAUSE IF AC0=1
0214  7510             SPA
0215  5200             JMP START
0216  7604             LAS
0217  3020             DCA A/ SET VELOCITY CRITERIA;
0220  6454             CLAF                /0020 = 50 DEG PER SEC
0221  6461             SNAF
0222  7610             SKP CLA
0223  5221             JMP .-2
0224  6422             DACG
0225  6545             ADCC ADIC/SAMPLE AMPLITUDE
0226  6532             ADCV
0227  6531             ADSF
0230  5227             JMP .-1
0231  6534             ADRB
0232  3037             DCA SAMP1
0233  6544         SPV,ADIC /SAMPLE CUMULATIVE POSITION
0234  6532             ADCV
0235  6531             ADSF
0236  5235             JMP .-1
0237  6534             ADRB
0240  3063             DCA POS1
0241  2060             ISZ CNTR4
0242  5273             JMP DIF
0243  1025             TAD F
0244  3060             DCA CNTR4
0245  1064             TAD POS0 /DETERMINE SLOW PHASE VELOCITY
0246  7041             CIA
0247  1063             TAD POS1
0250  3065             DCA VEL
0251  1065             TAD VEL
0252  7104             CLL RAL
```

```
0253   7204        CLA RAL
0254   3061        DCA SD1
0255   1065        TAD VEL
0256   7510        SGEZ
0257   7041        CIA
0260   7106        CLL RTL
0261   3062        DCA V1
0262   1061        TAD SD1
0263   7110        CLL RAR
0264   7620        SNL CLA
0265   5473        JMP I PVL
0266   1062        TAD V1
0267   7041        CIA
0270   3062        DCA V1
0271   1063     VL,TAD POS1
0272   3064        DCA POS0
0273   1040    DIF,TAD SAMP0 /CALCULATE AMPLITUDE DIFFERENCE
0274   7041        CIA
0275   1037        TAD SAMP1
0276   3043        DCA DIF1
0277   1043        TAD DIF1
0300   7104        CLL RAL
0301   7204        CLA RAL
0302   3050        DCA SIGN
0303   1043    CHK,TAD DIF1 /VELOCITY CRITERIA
0304   7540        SLEZ
0305   7041        CIA
0306   1020        TAD A
0307   7710        SGEZ CLA
0310   5476        JMP I PEPK
0311   1053        TAD WAIT
0312   7640        SZA CLA
0313   5507        JMP I PST
0314   2057        ISZ CNTR3
0315   5477        JMP I PLOK
0316   2053        ISZ WAIT
0317   1052     ST,TAD SS
0320   7640        SZA CLA
0321   5500        JMP I PSET
0322   1043        TAD DIF1 /TEST FOR EXTREMUM
0323   7540        SLEZ
0324   7041        CIA
0325   1026        TAD Q
0326   7710        SGEZ CLA
0327   5466        JMP I POK
0330   2052        ISZ SS
0331   5466        JMP I POK
0332   1054    SET,TAD KEY
0333   7640        SZA CLA
0334   5503        JMP I PSN
0335   1032        TAD APP0A
0336   3051        DCA SEMP
0337   2054        ISZ KEY
0340   2055     SN,ISZ CNTR1
```

```
0341   5466        JMP I POK
0342   1051        TAD SEMP /UPDATE SLOPE SENSE
0343   7041        CIA
0344   1032        TAD APP0A
0345   7104        CLL RAL
0346   7204        CLA RAL
0347   3047        DCA SLOPE
0350   3053        DCA WAIT
0351   3052        DCA SS
0352   3054        DCA KEY
0353   1024        TAD E
0354   3057        DCA CNTR3
0355   1021        TAD B
0356   3055        DCA CNTR1
0357   5466        JMP I POK
0360   1024   EPK, TAD E
0361   3057        DCA CNTR3
0362   5475        JMP I PEPL
0363   1054   LOK, TAD KEY /SLOPE SENSE CRITERIA
0364   7640        SZA CLA
0365   5466        JMP I POK
0366   1047        TAD SLOPE
0367   1050        TAD SIGN
0370   7110        CLL RAR
0371   7620        SNL CLA
0372   5466        JMP I POK
0373   1041   EPL, TAD DEL1 /EXTRAPOLATE POSITION
0374   1042        TAD DEL2
0375   4110        JMS RUN
0376   4144        JMS APP
0377   2106        ISZ DF
0400   5502        JMP I PFT
0401   1106    OK, TAD DF /BOTH TESTS PASSED; SCALE SAMPLE
0402   7650        SNA CLA
0403   5501        JMP I PGO
0404   1041        TAD DEL1
0405   1042        TAD DEL2
0406   4110        JMS RUN
0407   4144        JMS APP
0410   1037        TAD SAMP1
0411   4110        JMS RUN
0412   1034        TAD EXTRA
0413   7040        CMA
0414   3034        DCA EXTRA
0415   1035        TAD EXTRB
0416   7141        CLL CIA
0417   3035        DCA EXTRB
0420   7004        RAL
0421   1034        TAD EXTRA
0422   3034        DCA EXTRA
0423   1035        TAD EXTRB
0424   1031        TAD APP1B
0425   3046        DCA JUMPB
0426   7004        RAL
```

```
0427  1034        TAD EXTRA
0430  1030        TAD APP1A
0431  3045        DCA JUMPA
0432  3106        DCA DF
0433  5502        JMP I PFT
0434  1037     GO,TAD SAMP1
0435  4110        JMS RUN
0436  1035        TAD EXTRB
0437  1046        TAD JUMPB
0440  3031        DCA APP1B
0441  7004        RAL
0442  1034        TAD EXTRA
0443  1045        TAD JUMPA
0444  3030        DCA APP1A
0445  1032     FT,TAD APP0A
0446  7040        CMA
0447  1030        TAD APP1A
0450  3034        DCA EXTRA
0451  3036        DCA LINK
0452  7100        CLL
0453  1033        TAD APP0B
0454  7041        CIA
0455  7430        SZL
0456  2036        ISZ LINK
0457  7100        CLL
0460  1031        TAD APP1B
0461  7421        MQL
0462  7004        RAL
0463  1036        TAD LINK
0464  1034        TAD EXTRA
0465  7413        SHL
0466  0001        0001
0467  3041        DCA DEL1
0470  1030        TAD APP1A
0471  3032        DCA APP0A
0472  1031        TAD APP1B
0473  3033        DCA APP0B
0474  1041    FIX,TAD DEL1 /LIM ERR IN 1ST DIF
0475  7540        SLEZ
0476  7041        CIA
0477  1020        TAD A
0500  7710        SGEZ CLA
0501  7610        SKP CLA
0502  5467        JMP I PUP
0503  1047        TAD SLOPE
0504  7650        SNA CLA
0505  5470        JMP I PCS
0506  1020        TAD A
0507  3041        CIA
0510  3041        DCA DEL1
0511  5467        JMP I PUP
0512  1020     CS,TAD A
0513  3041        DCA DEL1
0514  1044     UP,TAD TEMP1 /UPDATE DIFFERENCE TABLE
```

```
0515  7041       CIA
0516  1041       TAD DEL1
0517  3042       DCA DEL2
0520  1041       TAD DEL1
0521  3044       DCA TEMP1
0522  2056    IN,ISZ CNTR2 /CONVERT DATA
0523  5474       JMP I POUT
0524  1022       TAD C
0525  3056       DCA CNTR2
0526  1032       TAD APP0A
0527  7540       SLEZ
0530  7041       CIA
0531  1023       TAD D
0532  7740       SLEZ CLA
0533  5472       JMP I PRS
0534  3045       DCA JUMPA /RESET CUM POS IF OVERFLOW
0535  3046       DCA JUMPB
0536  3032       DCA APP0A
0537  3033       DCA APP0B
0540  1032    RS,TAD APP0A
0541  6552       DAL1
0542  7200       CLA

0543  1043       TAD DIF1
0544  6554       DAL2
0545  7200       CLA
0546  1055       TAD CNTR1
0547  6562       DAL3
0550  7200       CLA
0551  1062       TAD V1
0552  6564       DAL4
0553  7200       CLA
0554  1047       TAD SLOPE
0555  6572       DAL5
0556  7200       CLA
0557  1037   OUT,TAD SAMP1
0560  3040       DCA SAMP0
0561  6435       LASL /CHK SENSE LINE 12 FOR MANUAL
0562  7110       CLL RAR                  /SLOPE CORRECTION
0563  7620       SNL CLA
0564  5427       JMP I PKO
0565  1047       TAD SLOPE
0566  7001       IAC
0567  7110       CLL RAR
0570  7204       CLA RAL
0571  3047       DCA SLOPE
0572  5505    KO,JMP I PTOP

              *20

0020  0000  A,0
0021  7774  B,7774
0022  7774  C,7774
0023  3750  D,3750
```

```
0024   7770   E,7770
0025   7776   F,7776
0026   0001   Q,0001
0027   0572   PKO,KO
0030   0000   APP1A,0
0031   0000   APP1B,0
0032   0000   APP0A,0
0033   0000   APP0B,0
0034   0000   EXTRA,0
0035   0000   EXTRB,0
0036   0000   LINK,0
0037   0000   SAMP1,0
0040   0000   SAMP0,0
0041   0000   DEL1,0
0042   0000   DEL2,0
0043   0000   DIF1,0
0044   0000   TEMP1,0
0045   0000   JUMPA,0
0046   0000   JUMPB,0
0047   0000   SLOPE,0
0050   0000   SIGN,0
0051   0000   SEMP,0
0052   0000   SS,0
0053   0000   WAIT,0
0054   0000   KEY,0
0055   0000   CNTR1,0
0056   0000   CNTR2,0
0057   0000   CNTR3,0
0060   0000   CNTR4,0
0061   0000   SD1,0
0062   0000   V1,0
0063   0000   POS1,0
0064   0000   POS0,0
0065   0000   VEL,0
0066   0401   POK,OK
0067   0514   PUP,UP
0070   0512   PCS,CS
0071   0522   PIN,IN
0072   0540   PRS,RS
0073   0271   PVL,VL
0074   0557   POUT,OUT
0075   0373   PEPL,EPL
0076   0360   PEPK,EPK
0077   0363   PLOK,LOK
0100   0332   PSET,SET
0101   0434   PGO,GO
0102   0445   PFT,FT
0103   0340   PSN,SN
0104   0000   EX1,0
0105   0213   PTOP,TOP
0106   0000   DF,0
0107   0317   PST,ST
0110   0000   RUN,0 /SCALING SUBROUTINE
0111   3104   DCA EX1
```

```
0112  1104  TAD EX1
0113  7500  SLZ
0114  5120  JMP MS
0115  7041  CIA
0116  3104  DCA EX1
0117  2036  ISZ LINK
0120  7200  MS,CLA
0121  1104  TAD EX1
0122  7415  ASR
0123  0001  0001
0124  3034  DCA EXTRA
0125  7501  MQA
0126  3035  DCA EXTRB
0127  1036  TAD LINK
0130  7450  SNA
0131  5143  JMP OT
0132  1034  TAD EXTRA
0133  7040  CMA
0134  3034  DCA EXTRA
0135  1034  TAD EXTRA
0136  7141  CLL CIA
0137  3035  DCA EXTRB
0140  7004  RAL
0141  1034  TAD EXTRA
0142  3034  DCA EXTRA
0143  5510  OT,JMP I RUN
0144  0000  APP,0 /EXTRAPOLATION SUBROUTINE
0145  1035  TAD EXTRB
0146  1033  TAD APP0B
0147  3031  DCA APP1B
0150  7004  RAL
0151  1034  TAD EXTRA
0152  1032  TAD APP0A
0153  3030  DCA APP1A
0154  3036  DCA LINK
0155  5544  JMP I APP
A        0020
APP      0144
APP0A    0032
APP0B    0033
APP1A    0030
APP1B    0031
B        0021
C        0022
CHK      0303
CNTR1    0055
CNTR2    0056
CNTR3    0057
CNTR4    0060
CS       0512
D        0023
DEL1     0041
DEL2     0042
DF       0106
```

```
DIF      0273
DIF1     0043
E        0024
EPK      0360
EPL      0373
EXTRA    0034
EXTRB    0035
EX1      0104
F        0025
FIX      0474
FT       0445
GO       0434
IN       0522
JUMPA    0045
JUMPB    0046
KEY      0054
KO       0572
LINK     0036
LOK      0363
MS       0120
OK       0401
OT       0143
OUT      0557
PCS      0070
PEPK     0076
PEPL     0075
PFT      0102
PGO      0101
PIN      0071
PKO      0027
PLOK     0077
POK      0066
POS0     0064
POS1     0063
POUT     0074
PRS      0072
PSET     0100
PSN      0103
PST      0107
PTOP     0105
PUP      0067
PVL      0073
Q        0026
RS       0540
RUN      0110
SAMP0    0040
SAMP1    0037
SD1      0061
SEMP     0051
SET      0332
SIGN     0050
SLOPE    0047
SN       0340
SPV      0233
SS       0052
ST       0317
START    0200
TEMP1    0044
TOP      0213
UP       0514
VEL      0065
VL       0271
V1       0062
WAIT     0053
```

APPENDIX C

MAN, A HYBRID PROGRAM TO CALCULATE STATISTICS OF EXPERIMENTAL DATA

This program was used to determine the statistics of the slow phase eye position as determined by the hybrid program MITNYS(see appendix B) and of chair position for each experimental run. The digital portion of MAN is written in PAL, the PDP-8 assembly language. Analog chair or eye position is scaled with the analog machine such that 1 volt = 72 degrees. For each run, 128 seconds of data is sampled once per second, the first sample corresponding to the instant just after all stimuli have been applied. These samples are stored in memory. At the completion of sampling, the digital machine calculates the mean, variance, and standard deviation of the sampled data according to the following algorithms where θ indicated angular position and T = sampling period.

$$\text{Mean:} \quad \overline{\theta} = \frac{1}{N}\sum_{n=1}^{N} \theta(nT) \qquad \text{(C.1)}$$

$$\text{Variance:} \quad \sigma_{\theta}^{2} = \frac{1}{N}\sum_{n=1}^{N} \theta^{2}(nT) - (\overline{\theta})^{2} \qquad \text{(C.2)}$$

$$\text{Standard Deviation:} \quad \sigma_{\theta} = \sqrt{\frac{1}{N}\sum_{n=1}^{N} \theta^{2}(nT) - (\overline{\theta})^{2}} \qquad \text{(C.3)}$$

The results of the calculations are outputted in two ways. The mean and standard deviation are converted to analog signals for possible display. All three of the statistics are also outputted on the teletype in digital form.

The format for this latter output is shown below:

```
GALVANIC STIMULATION DATA
SUBJECT #X    RUN #X
CHAIR(EYE) POSITION MEAN = XXXX.X DEGREES
VARIANCE = XXXXXX.XX DEGREES SQUARED
STANDARD DEVIATION = XXXX.X DEGREES
```

The subject number, run number and specification of eye or chair data are determined manually on the switch register prior to each set of calculations.

The square root routine necessary for determination of the standard deviation and the scaled decimal output routine are calculated by the utility subroutine SUBTAB, written by N.A.J. Van Houtte. A listing of SUBTAB may be found in his thesis.

An annotated listing of MAN follows.

```
                *200
                        /MEAN AND VARIANCE PROGRAM
                        /MIT MAN-VEHICLE LAB, DECEMBER 1969

                             /THIS PROGRAM TO BE OPERATED IN
                             /CONJUNCTION WITH THE UTILITY
                             /PROGRAM "SUBTAB"

                             /SAMP RATE = 1 PER SEC
                             /CHAIR CALIBRATION: 1V=72 DEG
                             /EYE CALIBRATION: 1V=72 DEG

0200   7604       LAS /SET NUMBER OF SAMPLES
0201   7041       CIA
0202   3043       DCA A
0203   7402       HLT

0204   7604   STR,LAS
0205   7104       CLL RAL
0206   7100       CLL
0207   7415       ASR
0210   0003       0003
0211   3020       DCA H /STORE SUBJECT NO. FROM SR6-SR8
0212   7421       MQL
0213   7604       LAS
0214   7415       ASR
0215   0002       0002
0216   7200       CLA
0217   7413       SHL
0220   0002       0002
0221   3021       DCA J /STORE RUN NO. FROM SR9-SR11
0222   7604       LAS
0223   7104       CLL RAL
0224   7104       CLL RAL
0225   7204       CLA RAL
0226   3022       DCA KEY /STORE DATA INDEX FROM AC1; 0=CHAIR; 1=EYE
0227   1045       TAD PLIST /INITIALIZE SAMPLE LIST
0230   3010       DCA 10
0231   1043       TAD A
0232   3023       DCA CNTR1

0233   7604   TOP,LAS /RESTART IF AC0=1
0234   7710       SPA CLA
0235   5204       JMP STR
0236   6552       DAL1 /CLEAR DIGITAL TO ANALOG CHANNELS
0237   6554       DAL2
0240   6551       DACX
0241   6454       CLAF /READ IN DATA
0242   6461       SNAF
0243   7610       SKP CLA
0244   5242       JMP .-2
0245   6545       ADCC ADIC
0246   6532       ADCV
```

```
0247  6531        ADSF
0250  5247        JMP .-1
0251  6534        ADRB
0252  3410        DCA I 10
0253  2023        ISZ CNTR1
0254  5446        JMP I PTOP
0255  7402        HLT

0256  1043     MN,TAD A
0257  3023        DCA CNTR1
0260  1045        TAD PLIST
0261  3010        DCA 10
0262  3025        DCA HIGH
0263  3024        DCA LOW
0264  3026        DCA UP
0265  3027        DCA MID
0266  3030        DCA DOWN

0267  7604    MAV,LAS /RECALCULATE MEAN IF AC0=1
0270  7710        SPA CLA
0271  5256        JMP MN
0272  1410        TAD I 10 /CALCULATE SUM OF SAMPLES
0273  3031        DCA SAMP
0274  1031        TAD SAMP
0275  7710        SPA CLA
0276  7040        CMA
0277  1025        TAD HIGH
0300  3025        DCA HIGH
0301  7100        CLL
0302  1031        TAD SAMP
0303  1024        TAD LOW
0304  3024        DCA LOW
0305  7430        SZL
0306  2025        ISZ HIGH
0307  7000        NOP
0310  1031        TAD SAMP /SQUARE CURRENT SAMPLE
0311  4076        JMS SQ
0312  3035        DCA SSHI
0313  7501        MQA
0314  3036        DCA SSLO
0315  1030        TAD DOWN /CALCULATE SUM OF SQUARED TERMS
0316  1036        TAD SSLO
0317  3030        DCA DOWN
0320  7004        RAL
0321  1035        TAD SSHI
0322  1027        TAD MID
0323  3027        DCA MID
0324  7004        RAL
0325  1026        TAD UP
0326  3026        DCA UP
0327  2023        ISZ CNTR1
0330  5447        JMP I PMAV
0331  1024        TAD LOW /CALCULATE MEAN
0332  7421        MQL
```

```
0333  1025      TAD HIGH
0334  7415      ASR
0335  0006      0006
0336  7701      CLA MQA
0337  3034      DCA MEAN
0340  1030      TAD DOWN /CALCULATE MEAN SQUARE
0341  7421      MQL
0342  1027      TAD MID
0343  7415      ASR
0344  0006      0006
0345  7701      CLA MQA
0346  3033      DCA MSLO
0347  1027      TAD MID
0350  7421      MQL
0351  1026      TAD UP
0352  7415      ASR
0353  0006      0006
0354  7701      CLA MQA
0355  3032      DCA MSHI
0356  1034      TAD MEAN /SQUARE MEAN
0357  4076      JMS SQ
0360  3037      DCA SQMNH
0361  7501      MQA
0362  3040      DCA SQMNL
0363  1037      TAD SQMNH /CALCULATE VARIANCE
0364  7040      CMA
0365  3037      DCA SQMNH
0366  1040      TAD SQMNL
0367  7141      CLL CIA
0370  3040      DCA SQMNL
0371  7004      RAL
0372  1037      TAD SQMNH
0373  3037      DCA SQMNH
0374  1040      TAD SQMNL
0375  1033      TAD MSLO
0376  3042      DCA VARB
0377  7004      RAL
0400  1037      TAD SQMNH
0401  1032      TAD MSHI
0402  3041      DCA VARA
0403  1041      TAD VARA /CALCULATE STANDARD DEVIATION
0404  7510      SGEZ
0405  5211      JMP .+4
0406  7421      MQL
0407  1042      TAD VARB
0410  4471      JMS I PSQRT
0411  3044      DCA SIGMA
0412  1034      TAD MEAN /CONVERT RESULTS FOR ANALOG DISPLAY
0413  6552      DAL1
0414  7200      CLA
0415  1044      TAD SIGMA
0416  6554      DAL2
0417  7200      CLA
0420  6551      DACX
```

```
0421  1051      TAD POUT1
0422  4124      JMS PRINT /TYPE "GALVANIC STIMULATION DATA"
0423  1052      TAD POUT2
0424  4124      JMS PRINT
0425  1020      TAD H
0426  1065      TAD C60
0427  4106      JMS TYPE /TYPE "SUBJECT # 00"
0430  1053      TAD POUT3
0431  4124      JMS PRINT
0432  1021      TAD J
0433  1065      TAD C60
0434  4106      JMS TYPE /TYPE "RUN # 0"
0435  1022      TAD KEY
0436  7640      SZA CLA
0437  5463      JMP I PEYE
0440  1054  CHR,TAD POUT4A
0441  4124      JMS PRINT
0442  5464      JMP I PDEG
0443  1055  EYE,TAD POUT4B
0444  4124      JMS PRINT
0445  1056  DEG,TAD POUT4
0446  4124      JMS PRINT
0447  1066      TAD SPEC1
0450  3470      DCA I PSPEC
0451  1074      TAD FACI1
0452  4473      JMS I PFACI
0453  7421      MQL
0454  1034      TAD MEAN
0455  4472      JMS I PPRNTQ
0456  1057      TAD POUT5
0457  4124      JMS PRINT /TYPE "EYE (CHAIR) POSITION MEAN
0460  1060      TAD POUT6                  /= XX DEGREES
0461  4124      JMS PRINT
0462  1067      TAD SPEC2
0463  3470      DCA I PSPEC
0464  1075      TAD FACI2
0465  4473      JMS I PFACI
0466  1042      TAD VARB
0467  7421      MQL
0470  1041      TAD VARA
0471  4472      JMS I PPRNTQ
0472  1057      TAD POUT5
0473  4124      JMS PRINT
0474  1061      TAD POUT7
0475  4124      JMS PRINT /TYPE "VARIANCE = XX DEGREES SQUARED"
0476  1062      TAD POUT8
0477  4124      JMS PRINT
0500  1066      TAD SPEC1
0501  3470      DCA I PSPEC
0502  1074      TAD FACI1
0503  4473      JMS I PFACI
0504  7421      MQL
0505  1044      TAD SIGMA
```

```
0506  4472      JMS I PPRNTQ
0507  1057      TAD POUT5 /TYPE "STANDARD DEVIATION = XX DEGREES"
0510  4124      JMS PRINT
0511  7402      HLT

0512  5450      JMP I PSTR

0513  3636  OUT1,3636 /CRLF,CRLF
0514  3607       3607 /CRLF,G
0515  0114       0114 /AL
0516  2601       2601 /VA
0517  1611       1611 /NI
0520  0340       0340 /C
0521  2324       2324 /ST
0522  1115       1115 /IM
0523  2514       2514 /UL
0524  0124       0124 /AT
0525  1117       1117 /IO
0526  1640       1640 /N
0527  0401       0401 /DA
0530  2401       2401 /TA
0531  0000       0000 /00

0532  3623  OUT2,3623 /CRLF,S
0533  2502       2502 /UB
0534  1205       1205 /JE
0535  0324       0324 /CT
0536  4043       4043 / #
0537  4000       4000 /
0540  0000       0000 /00

0541  4040  OUT3,4040 /
0542  2225       2225 /RU
0543  1640       1640 /N
0544  4340       4340 /#
0545  0000       0000 /00

0546  3603  OUT4A,3603 /CRLF,C
0547  1001       1001 /HA
0550  1122       1122 /IR
0551  0000       0000 /00

0552  3605  OUT4B,3605 /CRLF,E
0553  3105       3105 /YE
0554  0000       0000 /00

0555  4020  OUT4,4020 / P
0556  1723       1723 /OS
0557  1124       1124 /IT
0560  1117       1117 /IO
0561  1640       1640 /N
0562  1505       1505 /ME
0563  0116       0116 /AN
0564  4075       4075 / =
```

```
0565  4000         4000 /
0566  0000         0000 /00

0567  4004   OUT5,4004 / D
0570  0507         0507 /EG
0571  2205         2205 /RE
0572  0523         0523 /ES
0573  0000         0000 /00

0574  3626   OUT6,3626 /CRLF,V
0575  0122         0122 /AR
0576  1101         1101 /IA
0577  1603         1603 /NC
0600  0540         0540 /E
0601  7540         7540 /=
0602  0000         0000 /00

0603  4023   OUT7,4023 / S
0604  2125         2125 /QU
0605  0122         0122 /AR
0606  0504         0504 /ED
0607  0000         0000 /00

0610  3623   OUT8,3623 /CRLF,S
0611  2401         2401 /TA
0612  1604         1604 /ND
0613  0122         0122 /AR
0614  0440         0440 /D
0615  0405         0405 /DE
0616  2611         2611 /VI
0617  0124         0124 /AT
0620  1117         1117 /IO
0621  1640         1640 /N
0622  7540         7540 /=
0623  0000         0000 /00

             *20

0020  0000   H,0
0021  0000   J,0
0022  0000   KEY,0
0023  0000   CNTR1,0
0024  0000   LOW,0
0025  0000   HIGH,0
0026  0000   UP,0
0027  0000   MID,0
0030  0000   DOWN,0
0031  0000   SAMP,0
0032  0000   MSHI,0
0033  0000   MSLO,0
0034  0000   MEAN,0
0035  0000   SSHI,0
0036  0000   SSLO,0
0037  0000   SQMNH,0
```

```
0040   0000   SQMNL,0
0041   0000   VARA,0
0042   0000   VARB,0
0043   0000   A,0
0044   0000   SIGMA,0
0045   1177   PLIST,LIST-1
0046   0233   PTOP,TOP
0047   0267   PMAV,MAV
0050   0204   PSTR,STR
0051   0513   POUT1,OUT1
0052   0532   POUT2,OUT2
0053   0541   POUT3,OUT3
0054   0546   POUT4A,OUT4A
0055   0552   POUT4B,OUT4B
0056   0555   POUT4,OUT4
0057   0567   POUT5,OUT5
0060   0574   POUT6,OUT6
0061   0603   POUT7,OUT7
0062   0610   POUT8,OUT8
0063   0443   PEYE,EYE
0064   0445   PDEG,DEG
0065   0060   C60,60
0066   4401   SPEC1,4401
0067   4701   SPEC2,4701
0070   5100   PSPEC,5100
0071   7510   PSQRT,7510
0072   5114   PPRNTQ,5114
0073   5155   PFACI,5155
0074   1320   FACI1,1320 /= 720(10)
0075   2014   FACI2,2014 /= 1036(10)

0076   0000   SQ,0 /SQUARING SUBROUTINE
0077   7510   SPA
0100   7041   CIA
0101   3104   DCA .+3
0102   1104   TAD .+2
0103   7425   MQL MUY
0104   0000   0
0105   5476   JMP I SQ

0106   0000   TYPE,0 /TYPE SUBROUTINE
0107   6046   TLS
0110   6041   TSF
0111   5110   JMP .-1
0112   7200   CLA
0113   5506   JMP I TYPE

0114   0000   CRLF,0 /CARRIAGE RETURN LINE FEED SUBROUTINE
0115   1122   TAD K215
0116   4106   JMS TYPE
0117   1123   TAD K212
0120   4106   JMS TYPE
0121   5514   JMP I CRLF
0122   0215   K215,215
```

```
0123  0212  K212,212

0124  0000  PRINT,0 /MESSAGE UNPACK AND DECODE SUBROUTINE
0125  3134  DCA PDEX
0126  1534  TAD I PDEX
0127  2134  ISZ PDEX
0130  7450  SNA
0131  5524  JMP I PRINT
0132  4135  JMS DECODE
0133  5126  JMP .-5
0134  0000  PDEX,0
0135  0000  DECODE,0
0136  3147  DCA PACK
0137  1147  TAD PACK
0140  7012  RTR
0141  7012  RTR
0142  7012  RTR
0143  4150  JMS OUTPT
0144  1147  TAD PACK
0145  4150  JMS OUTPT
0146  5535  JMP I DECODE
0147  0000  PACK,0
0150  0000  OUTPT,0
0151  0167  AND C0077
0152  7450  SNA
0153  5550  JMP I OUTPT
0154  1170  TAD C7742 /CRLF
0155  7440  SZA
0156  5161  JMP .+3
0157  4114  JMS CRLF
0160  5550  JMP I OUTPT
0161  1171  TAD M2
0162  7500  SMA
0163  1172  TAD M100
0164  1173  TAD C340
0165  4106  JMS TYPE
0166  5550  JMP I OUTPT
0167  0077  C0077,77
0170  7742  C7742,7742
0171  7776  M2,7776
0172  7700  M100,7700
0173  0340  C340,340

            *1200

1200  0000  LIST,0 /CURRENT SAMPLE LIST
```

```
A         0043
CHR       0440
CNTR1     0023
CRLF      0114
C0077     0167
C340      0173
C60       0065
C7742     0170
DECODE    0135
DEG       0445
DOWN      0030
EYE       0443
FACI1     0074
FACI2     0075
H         0020
HIGH      0025
J         0021
KEY       0022
K212      0123
K215      0122
LIST      1200
LOW       0024
MAV       0267
MEAN      0034
MID       0027
MN        0256
MSHI      0032
MSLO      0033
M100      0172
M2        0171
OUTPT     0150
OUT1      0513
OUT2      0532
OUT3      0541
OUT4      0555
OUT4A     0546
OUT4B     0552
OUT5      0567
OUT6      0574
OUT7      0603
OUT8      0610
PACK      0147
PDEG      0064
PDEX      0134
PEYE      0063
PFACI     0073
PLIST     0045
PMAV      0047
POUT1     0051
POUT2     0052
POUT3     0053
POUT4     0056
POUT4A    0054
POUT4B    0055
POUT5     0057
POUT6     0060
POUT7     0061
POUT8     0062
PPRNTQ    0072
PRINT     0124
PSPEC     0070
PSQRT     0071
PSTR      0050
PTOP      0046
SAMP      0031
SIGMA     0044
SPEC1     0066
SPEC2     0067
SQ        0076
SQMNH     0037
SQMNL     0040
SSHI      0035
SSLO      0036
STR       0204
TOP       0233
TYPE      0106
UP        0026
VARA      0041
VARB      0042
```

APPENDIX D

ANVAR AND ANVAR 2 PROGRAMS TO CALCULATE ANALYSIS OF VARIANCE

These programs are used to determine the possible significance of the various experimental parameters by performing a standard analysis of variance on data entered in the Graeco-Latin experimental design. The two programs are similar except that ANVAR 2 takes into account the control runs while ANVAR does not. Both programs are written in the conversational programming language FOCAL which was modified slightly so that data could be read in on prepunched paper tape.

A standard analysis of variance algorithm is employed.[18] For a 6x6 square[A]each data entry(here chair or eye mean position) may be represented as a_{ij} where i = row and j = column in the square $i, j = 1,6$. This original square of data is arranged so that rows represent subjects and columns represent order. For convenience, this square was mapped into a second square[B]with rows representing intensities and columns representing modes. Each entry in the second square may be represented by a term b_{ij} where $i, j = 1,6$.

Calculations performed are then as follows for ANVAR(ANVAR 2 is similar).

Total Sum: $X = \sum_{i=1}^{6} \sum_{j=1}^{6} a_{ij}$ (D.1)

Correction Factor: $Z = (X/36)^2$ (D.2)

Total Sum of Squares: $Y = \left(\sum_{i=1}^{6} \sum_{j=1}^{6} a_{ij}^2 \right) - CF$ (D.3)

Sum for Each Subject: $R_i = \sum_{j=1}^{6} a_{ij};\ i = 1,6$ (D.4)

Sum for Each Order: $C_i = \sum_{i=1}^{6} a_{ij};\ j = 1,6$ (D.5)

Sum for Each Intensity: $S_i = \sum_{j=1}^{6} b_{ij};\ i = 1,6$ (D.6)

Sum for Each Mode: $M_i = \sum_{i=1}^{6} b_{ij};\ j = 1,6$ (D.7)

Sum of Squares:

Between Subjects: $P = \sum_{i=1}^{6} (R_i)^2/6 - Z$ (D.6)

Between Order: $C = \sum_{i=1}^{6} (C_i)^2/6 - Z$ (D.7)

Between Modes: $M = \sum_{i=1}^{6} (M_i)^2/6 - Z$ (D.8)

Between Intensities: $L = \sum_{i=1}^{6} (S_i)^2/6 - Z$ (D.8)

Residual Sum of Squares: $R = T - P - C - M - L$ (D.10)

Variance Estimates:

Subjects: $= \frac{P}{5}$

Order: $= \frac{C}{5}$

Variance Estimates (continued):

Modes: $= \frac{M}{5}$

Intensities: $= \frac{L}{5}$

Residual: $W = \frac{R}{15}$

Variance Ratios:

Subjects: $P/5W$

Order: $C/5W$

Modes: $M/5W$

Intensities: $L/5W$

Error Variance(for T Test)

$$EV = \sqrt{W\left(\frac{1}{6} + \frac{1}{6}\right)} = \sqrt{W/3} \qquad (D.11)$$

The variance ratios obtained form ANVAR and ANVAR 2 may be used with a standard F test to determine significance of the various parameters as discussed in the text. The error variance is calculated for possible use in a standard student t test if the F test indicates significance of a certain parameter.

Listings of ANVAR and ANVAR 2 follow.

```
C-FOCAL,1969

01.10 E
01.20 F I=1,36;A V(I)
01.30 F I=1,36;A U(I)
01.40 F I=1,36;S X=X+V(I);S Y=Y+V(I)↑2;S Z=(X/6)↑2;S T=Y-Z
01.50 F I=1,6;D 4
01.60 F I=1,6;D 6
01.70 S M=M-Z;S L=L-Z;S P=P-Z;S C=C-Z;S R=T-M-L-P-C;S W=R/15

02.10 F I=1,6;D 7
02.40 T !!,"      SOURCE      DF         SS              VE            VR"
02.41 T %8.02,!!,"      MODES           5  ",M,"   ",M/5,"   ",M/5*W,!!
02.51 T %8.02,"      INTENSITIES  5  ",L,"   ",L/5,"   ",L/5*W,!!
02.61 T %8.02,"      SUBJECTS     5  ",P,"   ",P/5,"   ",P/5*W,!!
02.71 T %8.02,"      ORDER        5  ",C,"   ",C/5,"   ",C/5*W,!!
02.81 T %8.02,"      RESIDUAL    15  ",R,"   ",W,!!
02.90 T %8.02,"      TOTAL       35  ",T,!!
02.91 T !,"                SUBJECTS   MODES  INTENSITIES",!
02.92 F I=1,6;D 8
02.93 T %6.02,!!,"      ERROR VARIANCE",FSQT(W/3),!!
02.95 Q

04.10 F J=<(I-1)*6+1>,<(I-1)*6+6>;S R(I)=R(I)+V(J);S S(I)=S(I)+U(J)
04.20 F J=0,5;S C(I)=C(I)+V(I+J*6);S M(I)=M(I)+U(I+J*6)

06.10 S M=M+M(I)↑2/6;S L=L+S(I)↑2/6;S P=P+R(I)↑2/6;S C=C+C(I)↑2/6

07.10 T !,"                  ";F J=<(I-1)*6+1>,<(I-1)*6+6>;T %4,V(J)

08.10 T %5.01,!,"               ",R(I)/6,"   ",M(I)/6,"   ",S(I)/6
```

ANVAR, Analysis of Variance program for a 6X6 Graeco-Latin Square

```
C-FOCAL,1969

01.10 E
01.20 F I=1,48;A V(I)
01.30 F I=1,36;A U(I)
01.40 F I=1,48;S X=X+V(I);S Y=Y+V(I)↑2;S Z=(X↑2)/48;S T=Y-Z
01.50 F I=1,6;D 4
01.60 F I=1,8;S M=M+M(I)↑2/6;S C=C+C(I)↑2/6
01.65 F I=1,6;S P=P+R(I)↑2/8;S L=L+S(I)↑2/6
01.70 S M=M-Z;S L=L-Z;S P=P-Z;S C=C-Z;S R=T-M-L-P-C;S W=R/23

02.40 T !!,"     SOURCE     DF       SS            VE          VR"
02.41 T %8.02,!!,"     MODES        7  ",M,"  ",M/7,"   ",M/7*W,!!
02.51 T %8.02,"     INTENSITIES  5  ",L,"  ",L/5,"  ",L/5*W,!!
02.61 T %8.02,"     SUBJECTS     5  ",P,"  ",P/5,"  ",P/5*W,!!
02.71 T %8.02,"     ORDER        7  ",C,"  ",C/7,"  ",C/7*W,!!
02.81 T %8.02,"     RESIDUAL    23  ",R,"  ",W,!!
02.90 T %8.02,"     TOTAL       47  ",T,!!
02.91 F I=1,6;T%5.01,!,"          ",R(I)/8," ",M(I+1)/6,"  ",S(I)/6
02.95 Q

04.10 F J=<(I-1)*8+1>,<(I-1)*8+8>;S R(I)=R(I)+V(J)
04.20 F J=1,8;S C(J)=C(J)+V(J+(I-1)*8);S M(1)=C(1);S M(8)=C(8)
04.30 F J=<(I-1)*6+1>,<(I-1)*6+6>;S S(I)=S(I)+U(J)
04.40 F J=0,5;S M(I+1)=M(I+1)+U(I+J*6)
```

ANVAR2, Analysis of Variance program for a 6X6 Graeco-Latin Square + two control runs per subject

APPENDIX E

T TEST AND T TEST 2

PROGRAMS TO PERFORM STUDENT T TEST

This program is a simple implementation of the student t test in order to determine where the significant differences between means lie. T TEST is for data without consideration of controls while T TEST 2 takes control runs into account. Both programs are written in the conversational language "FOCAL."

The error variance is read in as calculated by ANVAR and the value of t required is read in from a table of such values. A significant difference between means exists if

$$\frac{\text{mean A} - \text{mean B}}{\text{error variance}} - t > 0 \qquad \text{(E.1)}$$

The programs test all possible combinations of corresponding means and print out those which differ significantly together with the actual t value for the comparison.

Listings of T TEST and T TEST 2 follow.

```
C-FOCAL,1969

01.10 E
01.20 A "A"A;A "T"T;F I=1,36;A U(I)
01.40 F I=1,6;D 4
01.45 T "                      T TEST"
01.46 T %4.02,!!,"          ERROR VARIANCE",A,"  T(P=0.05)",T
01.50 T !!,"                         M0DES            INTENSITIES",!
01.60 F I=1,6;D 3
01.65 T !!
01.70 F I=1,5;F J=I+1,6;D 7
01.80 F I=1,5;F J=I+1,6;D 8
01.90 Q

03.10 T %5.01,!,"            ",I,"  ",M(I)/6,"          ",S(I)/6

04.10 F J=<(I-1)*6+1>,<(I-1)*6+6>;S S(I)=S(I)+U(J)
04.20 F J=0,5;S M(I)=M(I)+U(I+J*6)

07.10 S B=FABS(M(I)-M(J))/6*A-T;I (B)7.3;
07.20 T %1,!,"            M",I," M",J," T";T %5.02,B+T
07.30 R

08.10 S B=FABS(S(I)-S(J))/6*A-T;I (B)8.3;
08.20 T %1,!,"            S",I," S",J," T";T %5.02,B+T
08.30 R
```

TTEST, Program to perform Student "t" test on means of parameters found significant in analysis of variance-no control runs

```
C-FOCAL,1969

01.10 E
01.20 A "A"A;A "T"T;F I=1,48;A U(I)
01.40 F I=1,6;D 4
01.45 T "                      T TEST"
01.46 T %4.02,!!,"          ERROR VARIANCE",A,"  T(P=0.05)",T
01.50 T !!,"                          M0DES           INTENSITIES",!
01.60 F I=0,7;D 3
01.65 T !!
01.70 F I=0,6;F J=I+1,7;D 7
01.80 F I=1,5;F J=I+1,6;D 8
01.90 Q

03.10 T %5.01,!,"             ",I,"  ",M(I)/6,"         ",S(I)/6

04.10 F J=<(I-1)*8+2>,<(I-1)*8+7>;S S(I)=S(I)+U(J)
04.20 F J=0,7;S M(J)=M(J)+U(J+1+(I-1)*8)

07.10 S B=FABS(M(I)-M(J))/6*A-T;I (B)7.3;
07.20 T %1,!,"            M",I," M",J," T";T %5.02,B+T
07.30 R

08.10 S B=FABS(S(I)-S(J))/6*A-T;I (B)8.3;
08.20 T %1,!,"            S",I," S",J," T";T %5.02,B+T
08.30 R
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TTEST2, Program to perform Student "t" test
on means of parameters found significant in
analysis of variance-control runs included

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