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META Meta + Hodos
by
James Tenney

Preface

META Meta + Hodos represents an attempt to organize certain ideas first presented in *Meta + Hodos* in 1961, incorporating insights and revisions that have emerged since then. The writing was initially motivated by the desire to provide an outline of my ideas and terminology for use by students in a class in Formal Perception and Analysis at the California Institute of the Arts. The intent was therefore to make it as *concise* as possible, even if at the expense of comprehensibility, and I am aware that the result is probably not easily penetrated by someone not already familiar with *Meta + Hodos*. Nevertheless, I am pleased with the form it has taken, and hope that others may find it of interest in spite of its difficulties.

James Tenney
November, 1975

A. On Perceptual Organization.

PROPOSITION I: In the process of musical perception, *temporal gestalt-units* (TG's) are formed, at several different *hierarchical levels*.

COMMENT I.1: The number of hierarchical levels in a given piece, and the relative durations of the TG's at adjacent hierarchical levels varies, depending on such things as style, texture, tempo, the duration of the piece, etc.

COMMENT I.2: TG's at a given hierarchical level are not always or necessarily disjunct — i.e., there are frequent intersections and ambiguities in their perceptual formation.

Definition 1: A TG at the lowest (or first) hierarchical level will be called an *element*.

COMMENT 1.1: An element is a TG which is perceived as (temporally) *singular* — i.e., not divisible into lower-level (shorter) TG's. (See Comment IV.1.3, below, for a further description of element characteristics).

Definition 2: A TG at the next higher (2nd) hierarchical level will be called a *clang*.

COMMENT 2.1: A clang is a TG at the lowest hierarchical level within which still-lower-level TG's are perceived.

Definition 3: A TG at the next higher (3rd) hierarchical level will be called a *sequence*.

COMMENT 3.1: A clang thus consists of a temporal succession of two-or-more elements; a sequence consists of a temporal succession of two-or-more clangs. Note that a combination of two-or-more elements occuring simultaneously does not necessarily constitute a clang. (for the case of simultaneous TG's see Definitions 5 through 8, below.)

Definition 4: The TG at the highest hierarchical level is the *piece* as-a-whole (but see Proposition V and Comment V.1, below).

COMMENT 4.1: The number of intermediate hierarchical levels (between those of the sequence and the piece) is variable (cf. Comment I.1, above).

Definition 5: A TG whose component, next-lower-level TG's are perceived one-at-a-time will be called *monophonic*.

Definition 6: A TG whose component, next-lower-level TG's are perceived two-or-more-at-a-time will be called *polyphonic*.

Definition 7: A TG whose component TG's at all lower levels are monophonic will be called *simple*.

Definition 8: A TG whose component TG's at any lower level are polyphonic will be called *compound*.

COMMENT 8.1: These terms will frequently be combined to describe four types of "vertical" construction or texture:

(1) a *simple-monophonic* TG (at a given hierarchical level) is one whose component TG's are monophonic (at all lower levels) and are perceived one-at-a-time (at the given level);

(2) a *simple-polyphonic* TG (at a given hierarchical level) is one whose component TG's are monophonic (at all lower levels) but are perceived two-or-more-at-a-time (at the given level);

(3) a *compound-monophonic* TG (at a given hierarchical level) is one whose component TG's are polyphonic (at any lower level) but are perceived one-at-a-time (at the given level);

(4) a *compound-polyphonic* TG (at a given hierarchical level) is one whose component TG's are polyphonic (at any lower level) and are perceived two-or-more-at-a-time (at the given level).

COMMENT 8.2: The relationships between these four types of texture at three adjacent hierarchical levels is shown schematically in Figure 1.

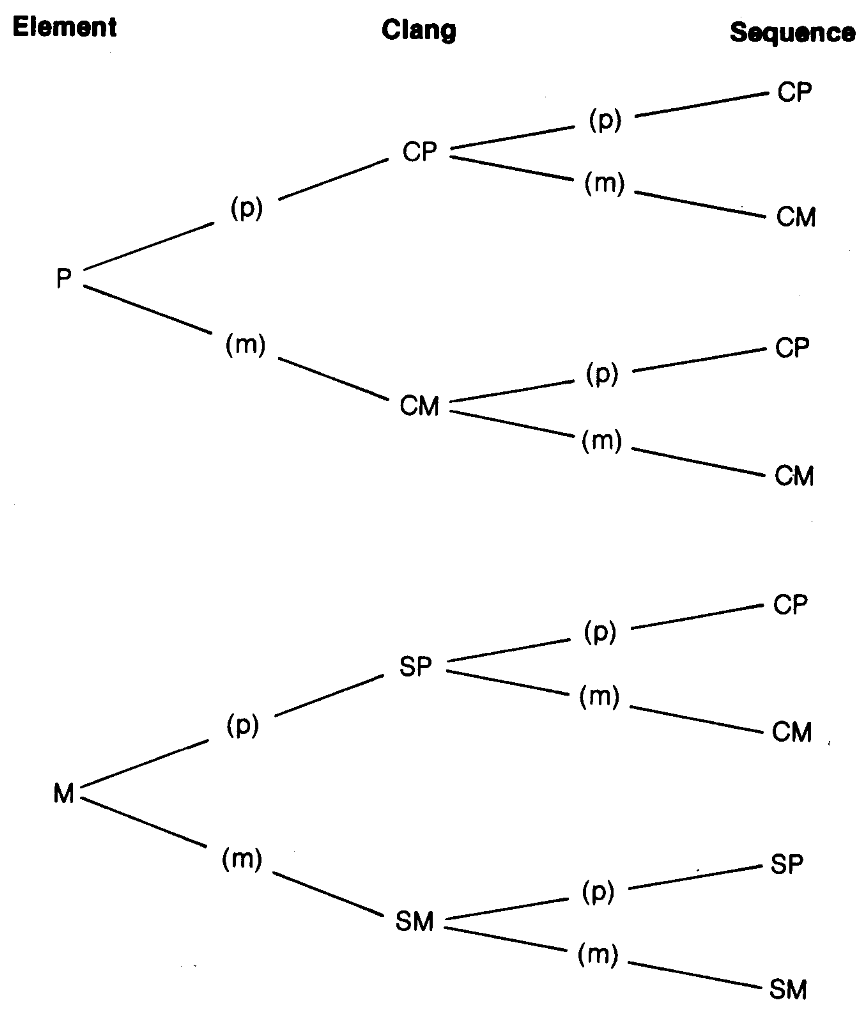


Figure 1: Relationships between simple, compound, monophonic and polyphonic TG's at three HL'S (M = monophonic, P = polyphonic, S = simple, C = compound, (m) = perceived one-at-a-time, (p) = perceived two-or-more-at-a-time).

PROPOSITION II: The perceptual formation of TG's at any hierarchical level is determined by a number of factors of cohesion and segregation, the most important of which are *proximity* and *similarity;* their effects may be described as follows:

PROPOSITION II.1: Relative temporal *proximity* of TG's at a given hierarchical level will tend to group them, perceptually, into a TG at the next higher level.

PROPOSITION II.2: Relative *similarities* of TG's at a given hierarchical level will tend to group them, perceptually, into a TG at the next higher level.

PROPOSITION II.3: Conversely, relative temporal *separation* and /or *differences* between TG's at a given hierarchical level will tend to segregate them into separate TG's at the next higher level.

COMMENT II.3.1: The perceptual formation of *lower-level* TG's is also affected by several secondary factors of cohesion and segregation, including *accent, repetition, "objective set",* and *"subjective set"* (see *Meta + Hodos,* 1961), but these will not be dealt with here.

B. On Musical Parameters.

Definition 9: A *parameter* will be defined here as any distinctive attribute of sound in terms of which one sound may be perceived as different from another, or a sound may be perceived to change in time.

COMMENT 9.1: This definition refers to "subjective" or *musical* parameters (e.g., pitch, loudness, etc.), as distinct from "objective" or *acoustical* parameters (frequency, amplitude, etc.).

COMMENT 9.2: There is not, in general, a one-to-one correspondence between musical and acoustical parameters. Where there *is* such a correspondence, the relation is more nearly logarithmic than linear.

PROPOSITION III: Pitch, timbre, and (musical) time are not simply one-dimensional parameters, because each includes at least two relatively independent "sub-parameters".

COMMENT III.1: Similarities and differences between any two pitch *intervals* are perceived in two different ways, depending on their relative magnitudes and their interval qualities. These, in turn, result from differences in what will be called (1) *pitch-height,* and (2) *pitch-chroma.*

Definition 10: *Pitch-height* refers to that aspect of pitch-perception which depends on the existence of continuous range of pitches, from low to high.

Definition 11: *Pitch-chroma* refers to that aspect of pitch-perception which depends on the phenomenon of "octave equivalence", and the fact that the continuous range of pitches is also *cyclic,* virtually returning to its starting point in each transition from one octave to the next.

COMMENT 11.1: These two sub-parameters may be related to the fact that there are two distinct mechanisms of pitch-perception involved in hearing — a "place" mechanism (determining pitch-height) and a "time" mechanism (determining pitch-chroma). The place mechanism is most effective for high frequencies, the time mechanism for lower ones, but the two overlap over a fairly broad range in the middle register, and it is here that our pitch-perception is the most acute (and the most bi-dimensional).

COMMENT 11.2: The multi-dimensionality of *timbre* is due to the fact that it is determined in a complex way by our perception of a large number of acoustical features, which may be subsumed under three categories:

(1) the steady-state *spectrum,*
(2) various kinds of steady-state *modulations,* and
(3) transient modulations or *envelopes.*

COMMENT 11.3: The sub-parameters of (musical) *time* will be called (1) *epoch,* (2) *duration,* and (3) *temporal density.*

Definition 12: *Epoch* refers to the moment of occurence — in the ongoing flow of experienced time — of any musical "event", compared to some reference moment such as the beginning of the piece.

Definition 13: The *temporal density* of a TG is the number of its component, next-lower-level TG's per unit time; ("*duration*" will be used in its usual sense).

COMMENT 13.1: The average temporal density of a TG at a given hierarchical level will thus be equal to the reciprocal of the average duration of its component TG's at the next lower level.

COMMENT 13.2: "Tempo" is a special case of temporal density, referring to an expressed or implied pulse or "beat", rather than to actual durations, and it is only relevant to *lower-level* TG's.

Definition 14: Pitch-height and epoch (which correspond most closely to the acoustical parameters, log-frequency and "real" time) will be called *distributive* parameters, because a difference in at least one of these is necessary for two sounds to be perceived as *separate.*

Definition 15: All other parameters (including loudness, pitch-chroma, duration, temporal density, and the several sub-parameters of timbre) will be called *attributive* parameters. Note that a difference in any of these is insufficient, by itself, for two sounds to be perceived as separate — there must *also* be a difference in one of the distributive parameters.

C. On Formal Perception and Description.

PROPOSITION IV: The perception of form at any hierarchical level involves the apprehension of three distinct *aspects of form,* at that and all lower levels. These three aspects of form will be called *state, shape,* and *structure.*

Definition 16: *State* refers to the statistical and other "global" properties of a TG, including the *mean values* and *ranges* in each parameter, and its *duration.*

Definition 17: *Shape* refers to the "profile" of a TG in some parameter, determined by *changes* in that parameter with respect to either of the distributive parameters, epoch and pitch-height (or their acoustical correlates, "real" time and log-frequency).

Definition 18: *Structure* refers to *relations between subordinate parts* of a TG — i.e., relations between its component TG's at the next (or several) lower level(s). (See also Definition 19 and its Comments, below.)

PROPOSITION IV.1: A complete description of a monophonic TG at any hierarchical level requires descriptions of state, shape, and structure, for every parameter with respect to *time.*

COMMENT IV.1.1: In this context (i.e., that of monophonic TG's), shape is time-dependent, while state and structure are "out-of-time" characteristics (but see Comment IV.2.1, below).

COMMENT IV.1.2: The state of a monophonic TG simply depends on lower-level *states;* shape is determined by *changes of state* at the next lower level; structure depends on *relations between states,* shapes and structures at the next (or several) lower level(s) (see Figure 2).

COMMENT IV.1.3: Since, by Definition 1, Comment 1.1, an element is not perceived as "divisible" into lower-level TG's", the structure of an element is not perceived directly — i.e., element-"structure" is located in the "infra-formal" area of Figure 2, below the "threshold of formal perception". Element-"shape" is sometimes above, sometimes below this threshold.

COMMENT IV.1.4: The various state-descriptions of an element are equivalent to the set of parametric values needed to describe the element (except when aspects of element-shape are also reduced to parameters — e.g., amplitude-envelope shape).

COMMENT IV.1.5: The "similarities" and "differences" of Propositions II.2 and II.3 may be of all three kinds — i.e., of state, shape, or structure.

Definition 19: There are three basic types of structure (corresponding to the three connecting lines to "structure" in Figure 2). These will be called

(1) *statistical structure* (i.e., relations between lower-level states),
(2) *morphological structure* (relations between lower-level shapes), and
(3) *cascaded structure* (relations between lower level structures).

COMMENT 19.1: Each of these three types of structure may be specified by showing the relations between each lower-level TG and *every other TG* at that level. For a given set of relations (limited in such a way that there is only one relation between each pair of TG's), this might be done by arranging them in a square array or matrix. In the case of statistical structure, such a matrix might show, for example, the set of *intervals* between the parametric mean values of each pair of TG's.

COMMENT 19.2: For morphological structure, the relations included in such a matrix might be as few as three (e.g., $=$, $\neq$ and T, for "identical to", "unrelated to", and "related via some transformation", respectively), or the "T" might be expanded into a longer list such as the following:

E / C (for expansion / contraction of intervals), X / L (extension / elision at the ends of a TG), I / D (interpolation / deletion into or from within a TG), I (inversion), R (retrogression), W ("warping" or distortion of shape, still preserving its essential topological features), P (permutation of the order of component TG's), etc.

COMMENT 19.3: For cascaded structure, the only relations needed for such a matrix might be $=$ and $\neq$.

Definition 20: In addition to the three basic types of structure listed in Definition 19, there is still another type which is relevant to musical perception, one involving relations between *relations,* rather than relations between (various aspects of) the TG's themselves. These will be called *relational structures,* and may be of three kinds: (1) *state-relational* structure, (2) *shape-relational* structure, and (3) *structure-relational* structure.

PROPOSITION IV.2: A complete description of a polyphonic (or compound-monophonic) TG at any hierarchical level requires descriptions (in addition to those listed in Proposition IV.1) of state, shape, and structure for each of the *attributive* parameters with respect to *log-frequency.*

COMMENT IV.2.1: In this context, although shape is not time-dependent, it still involves the sequential order of states in the frequency domain; state and structure do not.

COMMENT IV.2.2: For polyphonic TG's, the relationships between state, shape, and structure (with respect to frequency) — such as those described in Comment IV.1.2, above — are not yet known.

PROPOSITION V: Formal properties at a given hierarchical level determine the (non-semantic) "content" of the TG's at the next higher level; they also determine the "context" (or "function" or "environment") of TG's at the next lower level.

COMMENT V.1: What we do finally *call* (non-semantic) "content" is the result of "forms" at a level below the first one we are able to perceive "formally"; what we call "context" (or "function" or "environment") is determined by formal conditions at a level above the largest one we *choose to deal with* "formally".

PROPOSITION VI: As we move from the infra-formal area up into and through the first few specifically formal hierarchical levels, new parameters emerge.

COMMENT VI.1: Even *within* the infra-formal area, there is a similar "emergence" — e.g., the transition from the basic physical nature of the signal as (simply) amplitude vs. time, to the (acoustical) parameter, *frequency.* Examples above the threshold include the *timbre*-effects of rise-time and vibrato (at HL(1) in Figure 2), and *temporal density* (at HL(2)).

PROPOSITION VII: There is a close correlation between what may be called *parametric focus* and the relative *range of variation* of next-lower-level states within a TG; i.e., the greater the range in a given parameter, the more one's attention will be focussed on the changes in that parameter, and the more prominent will be the shape determined by those changes.

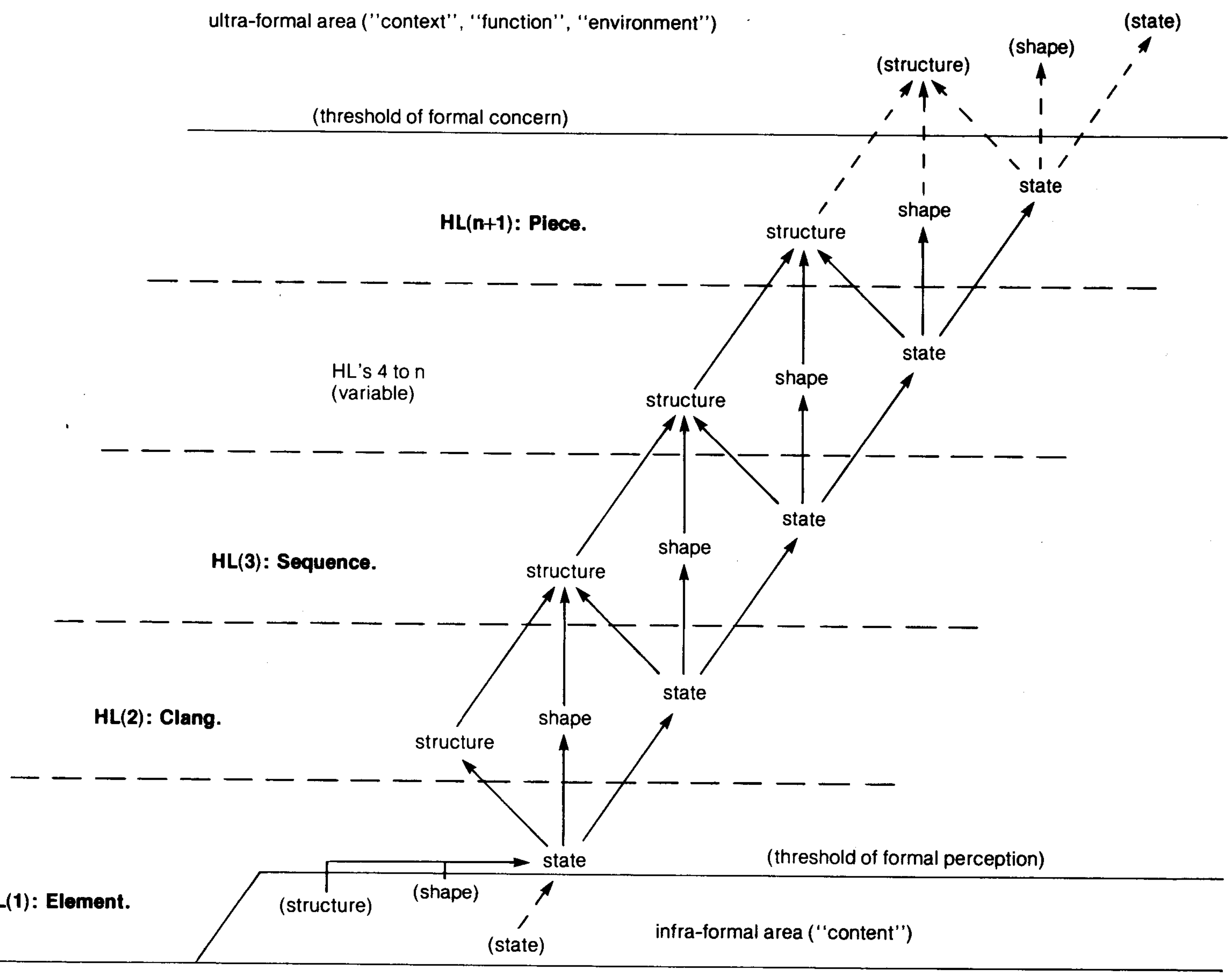


Figure 2: Relationships between the three aspects of form at several hierarchical levels (HL's).

Definition 21: A parameter whose variation (over a relatively wide range) at the next lower level thus focuses the attention on the shape of a TG in that parameter will be called a *formative* parameter.

Definition 22: A parameter whose relative constancy (or variation over a *narrow* range) at the next lower level is thus significantly responsible for its unity as a gestalt (via the similarity-factor of Proposition II.2) will be called a *cohesive* parameter.

PROPOSITION VIII: The formative parameters of a TG are generally different from the cohesive parameters of that same TG.

COMMENT VIII.1: This follows almost simply "by definition", but its implications are important enough to justify it as a separate Proposition.

PROPOSITION IX: The formative parameters of a TG at a given hierarchical level are generally different from the formative parameters of the next-higher-level TG which contains it.

COMMENT IX.1: One obvious exception to Propositions VIII and IX may occur when the formative parameter of a TG is pitch, but this is only possible because the number of distinguishable values in this parameter is very great — and it can only occur when the range of pitch-variation within the next-lower-level TG's is relatively limited. The more extensive the range covered within each lower-level TG, the less perceptible will be the changes of pitch-state from one TG to the next, and thus the less effective will pitch be as a formative parameter at the next higher level. This adjacent-level "trade-off" relation is made more explicit and precise in the following Proposition:

PROPOSITION X: For any parameter with respect to time, the greater the range of variation at a given hierarchical level, the smaller the range of variation possible at the next higher level, and vice versa.

COMMENT X.1: For a given parameter, and under the special condition that the ranges are identical for all TG's at a given hierarchical level, the following relations will hold:

For the first hierarchical level, considered by itself, the maximum range available is $N(1)_{max} = N_t$, where N_t is the total number of distinguishable values in that parameter. When two hierarchical levels are considered, the maximum range at the second level is

$$N(2)_{max} = N_t - (N(1) - 1).$$

For a third level, the maximum range will be

$$N(3)_{max} = N_t - (N(1) - 1) - (N(2) - 1).$$

More generally, the maximum range available at a given level (L) is

$$N(L)_{max} = N_t - (N(1) - 1) - (N(2) - 1) - \ldots (N(L-1) - 1), \text{ or}$$

$$N(L)_{max} = N_t - N_L + L - 1.$$

Finally, the total available range (N_t) may be distributed equally among some number of levels (L), so that

$N(1) = N(2) = \ldots N(L)$, and $N(L+1)_{max} = 0$, by setting each N at

$N = N_t / L+1$.

Definition 23: A TG whose component, next-lower-level TG's all have the *same state* in a given parameter will be called *ergodic* with respect to that parameter.

COMMENT 23.1: The shape of an ergodic TG is thus "flat" in that parameter.

COMMENT 23.2: An ergodic TG has the same parametric state as each of its component, next-lower-level TG's.

Definition 24; A TG whose component, next-lower-level TG's have *different states* in a given parameter will be called *non-ergodic* with respect to that parameter.

COMMENT 24.1: The *shape* of a TG may thus be either ergodic or non-ergodic, with respect to a given parameter.

Definition 25: A TG whose component, next-lower-level TG's all have the *same shape* in a given parameter will be called *isomorphic* with respect to that parameter.

Definition 26: A TG whose component, next-lower-level TG's all have *different* (or more precisely, *unrelated*) *shapes* in a given parameter will be called *heteromorphic* with respect to that parameter.

Definition 27: A TG whose component, next-lower-level TG's have shapes that are *related* to each other via some process of *transformation* will be called *metamorphic* with respect to that parameter.

COMMENT 27.1: The *morphological structure* of a TG may thus be either isomorphic, heteromorphic, or metamorphic, with respect to a given parameter.

D. On Entropy As A Measure Of Variation.

Definition 28: One of the most important aspects of musical experience is the perception of variation, and a useful measure of variation is *entropy*. In information theory, the entropy of a "message" consisting of a series of n discrete "symbols" drawn from an "alphabet" of N equally probable symbols is

$H = n \log_2 N$ (bits per message). The entropy of each symbol is

$H = \log_2 N$ (bits per symbol).

COMMENT 28.1: The most important variable here is N, the number of symbols available. In the special case where $N = 1$, $H = 0$.

COMMENT 28.2: When the available symbols are not equally probable — i.e., when they do not occur with the same relative frequencies (p_i) — then

$H = - \Sigma p_i \log_2 p_i$ (bits per message).

Definition 29: We may define as many different types of entropy as there are different types of structure. Thus, we may distinguish between *statistical, morphological,* and *structural entropies,* according to whether the "symbols" considered are lower-level *states, shapes,* or *structures.* In addition, there will be three *relational entropies* — those involving state-relations, shape-relations, and structure-relations.

Definition 30: The entropies of a TG at a given hierarchical level may be measured either in terms of component TG's at the lowest (i.e., element-) level, or in terms of component TG's at the next lower level. The first kind of measure (which has been the usual procedure in most applications of information theory) will be called an *additive* measure, the second (which will be used most often here) will be called an *adjacent-level* measure of entropy.

Definition 31: Since a TG at every hierarchical level except the lowest and highest (i.e., any except an element or the whole piece) may be considered *both* a message (containing lower-level symbols) *and* a symbol (contained within a higher-level message), the various entropies may be defined for a TG either as *message-entropies* or as *symbol-entropies.*

COMMENT 31.3: The following Propositions refer to adjacent-level message-entropies of a TG:

PROPOSITION XI: The statistical entropy of an ergodic TG is zero.

PROPOSITION XII: The state-relational entropy of an ergodic TG is zero.

PROPOSITION XIII: The statistical entropy of a non-ergodic TG at a given hierarchical level depends on

(1) the number of its component, next-lower-level TG's,
(2) the number of their distinguishable states, and
(3) the relative frequencies of these states.

PROPOSITION XIV: The state-relational entropy of a non-ergodic TG at a given hierarchical level depends on

(1) the number of its component, next-lower-level TG's,
(2) the number of the distinguishable differences between their states, and
(3) the relative frequencies of these differences.

PROPOSITION XV: The maximum statistical entropy attainable in a TG at a given hierarchical level is *inversely related* to the statistical entropy of its component TG's at the next lower level. (This is a consequence of Proposition X.)

PROPOSITION XVI: The morphological entropy of an isomorphic TG is zero.

PROPOSITION XVII: The shape-relational entropy of an isomorphic TG is zero.

PROPOSITION XVII: The morphological entropy of a heteromorphic TG is maximal (for a given number of next-lower-level TG's).

PROPOSITION XIX: The shape-relational entropy of a heteromorphic TG is zero.

COMMENT XIX.1: There must be a meaningful way to define the morphological entropy of a metamorphic TG, but this has not yet been found.

COMMENT XIX.2: Nothing is yet known about structural entropies.

Biofeedback With Cerebral Evoked Potentials And Perceptual Fine-Tuning In Humans

by
Christopher Mark Nunn*

ABSTRACT

This paper reviews the design of experiments to study a new application of *brainwave biofeedback.*

Typically, brainwave biofeedback consists of informing a person as gross patterns appear in recordings of his brainwaves, such as the presence or absence of waves in a certain range of frequencies. By training with this feedback, some people have learned to control the patterns. However, the psychological implications of this control that are reported by different individuals vary and often conflict. Therefore, as one might have expected, the control of gross patterns of brainwaves gives ambiguous results.

Now it is proposed that indices in brainwaves of specific psychological factors should be used in biofeedback training. Such indices are found in cerebral evoked potentials — responses in brainwave recordings to the perception of stimuli. A result of training a person to modify his cerebral evoked potentials may be to change his perception of the stimuli which evoke these responses.

This paper illustrates this proposition with an experimental design to modify an index in cerebral evoked potentials of the "significance" of a stimulus, labeled P_{300}. The goal of such experiments would be to train a person to recognize and attend to any given stimulus as reliably as a person recognizes and attends to his own name.

The *applications* of such training in perceptual judgement might include (1) teaching absolute pitch, (2) training autistic individuals to respond more consistently than usual to a given stimulus, (3) teaching athletes to have unusually accurate sense of limb and body position for more reproducible performances and (4) training professionals, such as airline pilots, to be as reliably aroused by emergency indicators as they are to the sounds of their own names.

* B.Sc., McMaster University, 1972; B.A., York University, 1974; M.A., York University, 1976.

CONTENTS

LIST OF ILLUSTRATIONS

PREFACE

This paper is a review of the design of experiments on human learning involving feedback from cerebral evoked potentials. The plan was that this thesis would also contain some well-analyzed data from preliminary experiments. However, the available facilities were not adequate, so this thesis has become a report on experimental design.

The INTRODUCTION explains the central idea of this thesis in plain language. Sections which follow the introduction provide the details which should be considered in designing a new class of biofeedback experiments. BIOFEEDBACK is the title of a section which explains the term. It discusses a model of human perception based on the principles of biofeedback. This section also reviews most of the experiments that have been published concerning the modification of cerebral evoked potentials with feedback. CEREBRAL EVOKED POTENTIALS are discussed in a separate section which reviews the ways to record cerebral evoked potentials by averaging and sorting, and the aspects of experimental manipulations which they encode. A final section outlines experimental designs for testing the thesis that an experiment with evoked potential feedback may be devised to improve the reliability of perceptual judgement.

Acknowledgement is due to the Graduate Studies Program at York University for conferring the honour and the funds of a graduate scholarship for my project. It helped me to complete this work.

My appreciation and admiration is most deserved by Professor Ian P. Howard, who served as my major advisor while I prepared this paper. I am grateful to Associate Professor David Rosenboom for sowing the ideas which inspired this project. For enabling and sustaining this study with their support, encouragement and guidance, I thank Associate Professor Christopher Innes and my family. Thanks for advice and thoughtful criticism are due to Professor Robert H. Haynes, Assistant Professor James A. Gabura, Professor Neil I. Wiener and Dr. Ted Coons.

1.0 INTRODUCTION

This paper contains a proposal for a new application of the technique of brainwave biofeedback.

In typical biofeedback experiments a subject is trained to become aware of, or gain control over some internal state of his body by having displayed to him the monitored electrophysiological activity which accompanies that internal state. For instance, one might attempt to train a person to control his heartbeat by displaying to him a picture of the electrical signals from his heart as it is beating. Such electrical signals are easily monitored and are reliable indicators of electrophysiological activity.

The internal state that I propose for investigation is associated with the arousal that is caused by a significant stimulus, for instance one's own name. Therefore, I need a reliable electrophysiological indicator of the state of arousal in a person that is caused by a significant stimulus. This is a much more difficult problem than is found in typical biofeedback experiments, because sophisticated and some as yet unproven techniques are required to monitor and to interpret brainwave responses that are evoked by a single sensory event. These techniques will be discussed later.

Research has shown that there is an increase in the amplitude of a particular segment of a person's brainwave recordings when he perceives a stimulus that is especially significant to him. For example, a person's own name generally elicits a marked brainwave response if it is heard when it is not expected, but another name does not. This suggests that there is a relationship between brainwaves and perception. The link between brainwave recordings and sophisticated perceptual behaviour such as the identification of a name is not yet understood. However, it is known that primitive perceptual behaviour such as arousal to a name is typically accompanied by a few brief spurts of synchronous neural activity in many brain cells. Generally, when a person detects and recognizes a significant stimulus such as his own name, many brain cells fire at the same time causing a particular segment of the brainwave recording to have a large amplitude.

Conversely, when a person detects and recognizes a stimulus that is insignificant to him, relatively fewer brain cells would respond synchronously giving a smaller amplitude in a segment of the person's brainwave recording. Experimental evidence suggests that such brainwave responses, called evoked potentials, are reliable indicators of the states of arousal that are elicited by various stimuli when a person is trying to detect a particular stimulus. This evidence will be reviewed later.

Since biofeedback is known to have trained people to become newly aware of internal states and also to control internal states, it might be valuable to investigate whether feedback of the evoked potentials improves a person's consistency in detecting a particular stimulus. To investigate this idea, research could proceed in two ways.

On one hand biofeedback has been used to train a person to become newly aware of existing internal states. Therefore, feedback to a person of evoked potentials while he is trying to detect a significant stimulus might help him to feel his initial internal response to that stimulus more reliably. A consequence of this training would be that a person would make fewer mistakes in identifying that stimulus than is common in a signal-detection task, because his attention would become more reliably aroused to that stimulus as training encourages him to associate paying attention to that stimulus with his initial internal response to that stimulus. In this way a person could be trained with feedback of his evoked potentials to detect a significant stimulus more reliably than before training.

On the other hand biofeedback has been used to train people to control internal states. Therefore, feedback to a person of his evoked potentials may be used to train him to give evoked potentials of an unusually high amplitude in response to a given stimulus. Such an increase in amplitude, indicating an increase in the number of synchronously active brain cells, might be accompanied by an increase in the person's arousal to the stimulus. An increased arousal to a given stimulus would give that stimulus special significance. In this way a person might learn to recognize any given stimulus more reliably than before training.

2.0 BIOFEEDBACK

This chapter is a review of a topic in learning theory called biofeedback. The chapter is composed of three main parts. It begins with definitions of terms, then develops a biofeedback model of perception and concludes with a summary of evidence which supports the thesis that biofeedback with cerebral evoked potentials might be used to train people to "improve" their perception of particular sensory events.

2.1 Introduction to Biofeedback

Learning requires effort. People who like to learn tolerate the effort. Others dislike the effort, so they scorn learning. Everyone faces a growing body of knowledge that is much too large to be assimilated in a single lifetime. The increasing volume of information and the effort that is required to learn what amounts to an ever smaller portion of it frustrate reluctant learners and eager learners alike. Therefore, many accomplished learners are working to reduce the amount of information with which a person must become familiar to be educated by evolving a general systems theory which incorporates universal strategies for dealing with varieties of isolated facts. What, then, is being done to reduce the effort of learning?

2.11 Programmed Learning

Some researchers are working to improve poor communication which hinders learning. Others hope to reduce the effort of learning by designing new teaching methods which require shorter and shorter periods of instruction. One approach that has proven to reduce the effort of learning through improved communication and reduced time for acquisition is *programmed learning.*

Programmed learning is best known in association with teaching machines, because it is an easy technique to mechanize. Programmed learning is a general method for providing a learning experience by drawing a person's attention to a logical sequence of activities to build, step-by-step, in small increments, toward a new behaviour or concept. Learning experiences are programmed in linear and often branching sequences of steps. Users of such programs may proceed at their own rates through successive, somewhat repetitive steps: each step being presented at the completion of the preceeding step, until the whole sequence is completed.

2.12 Operant Learning

The type of programmed learning that is important in this thesis is *operant learning*. This is a process in which the behaviour of an organism creates a situation for learning to occur. Specifically, after a learner spontaneously performs a behaviour that the experimenter has chosen for a goal, the experimenter may offer encouragement or discouragement to the learner for performing that behaviour. The hope is that the learner begins to associate the encouragement or discouragement with performance of the particular behaviour that is the goal of the experiment. Following several trails, learning occurs when a change can be found in the rate of appearance of the behaviour that is the goal of the experiment.

For example, the biting of fingernails is considered by some people to be an undesirable behaviour. Therefore, a goal of operant training might be the reduction in frequency of fingernail-biting. A simple method of achieving this goal is to paint the fingernails with a bad-tasting lacquer. Thereafter, an inadvertent bite would give a repulsive taste. After several bad-tasting results from fingernail-biting, a person would usually do it less frequently. This operant training can be continued until the fingernail-biting is eliminated.

Operant training can be performed when four basic functions are programmed. First, one behaviour must be chosen by the experimenter as a well-defined goal. Also, a means of recognizing when the behaviour happens must be arranged. Third, a reinforcer must be chosen to encourage or to discourage the learner to perform the behaviour. Some means of mechanically administering the reinforcer must be found. The fourth function to be programmed is the reinforcement schedule, that is, whether to administer the stimulus once for each performance of the behaviour, intermittently, randomly, or after an interval of time.

In summary, operant learning proceeds when a learner is allowed to explore a free range of behaviours, some of which are followed by positive or negative reinforcers which the experimenter presents to the learner and which either encourages or discourages the learner in performing particular behaviours. Such training is suited to promoting and eventually stabilizing a given behaviour, or on the contrary, to repressing and eventually eliminating a given behaviour.

2.13 Feedback

Biofeedback describes a class of operant techniques which have physiological states for goals. Before discussing the concept of biofeedback as a whole, the concept of *feedback* will be reviewed.

Feedback means that a portion of the output of a system is returned to the input of the same system. A familiar effect of feedback is the undesirable howl of a public address system which goes into oscillation if the microphone picks up sound from the speakers. This return of sound,an output, to the microphone, an input, creates a circular path in which a signal is cycled through an amplifier. With successive cycles the sound grows louder and louder until the amplifier is saturated, so the howl stays at maximum volume. To stop this howl one must interrupt the circular path, for instance by covering the microphone. To prevent further howling one must reduce the feedback, for instance by lowering the volume of the amplifier.

Feedback can have one of two effects: positive and negative. This idea is a parallel of one that was introduced earlier: operant training can either promote or repress a given behaviour. For a familiar example of feedback, consider the following elementary concept of business.

Large businesses tend to get larger. The more money a business has, the more advertising it can afford. Advertising leads to more business, so businesses that can afford plenty of good advertising make large profits and get larger.

Making profits gives an incentive to expand business. Therefore, businesses which receive large profits tend to grow. A change in state, such as growth of a business, is a product of positive feedback from receipt of profits.

A decline in business is also an effect of positive feedback. For instance, given less money to spend on advertising, small businesses incur a loss of profits. A drop in the quality or quantity of advertising leads to a drop in business, so small businesses tend to get smaller. Therefore, a change in state such as depletion of business, is a product of positive feedback from loss of profits. In other words, *positive feedback fosters a change in state*.

On the contrary, *negative feedback inhibits change.* For example, as a business matures, it tends toward an optimal size. Operating on a scale which is either larger or smaller than the optimal size decrease profits. Consequently, to receive the most profit, businesses must maintain their optimal scale of business.

In summary, feedback denotes the return of outputs to inputs in a single system. This mechanism operates on information about the difference between the actual states of a system and a model state for that system. Positive feedback drives the system to increase the differences between the states; negative feedback drives the system to decrease the differences between the states.

Negative feedback provides control. It drives systems to stabilize at or near a model state. The intensity of the drive in many systems varies directly with the size of the system and model states. Positive feedback provides a loss of control by fostering accelerating changes in state. These are the effects of feedback.

2. 14 Biofeedback

Adding the prefix 'bio' to the term feedback restricts the use of the term to biological systems. Therefore, in a mechanical sense biofeedback means that a portion of the output of a biological system is returned to the input of the same biological system. Operationally, biofeedback involves the use of information about the differences between the actual states of a biological system and a model state for that system, such that the differences are increased (positive feedback) or decreased (negative feedback).

Biological systems have "naturally built-in circuits" which exert feedback control. However, it is also possible, through science and technology, to create novel circuits. Such contrived circuits allow additional biofeedback to occur. The use of these circuits gives people an opportunity to see, hear or feel latent aspects of their own physiology. This additional biofeedback provides an opportunity for people to control aspects of their own physiology. The use of biofeedback to gain control is called *biofeedback training.* In general, biofeedback training refers to the use of both natural and contrived biofeedback.

A less general definition of biofeedback is the name of a signal, a biofeedback signal, which travels in a circular path from a person's biological output back to the person's perceptual input.

The circular path of a biofeedback signal includes four parts: a biological process; a monitor which records an output of the biological process; a comparator which compares the monitored signal with a reference signal; a process which controls the biological process and is itself controlled by the output of the comparator. This is a mechanical unit of biofeedback showing how biofeedback is engineered. It is shown in figure 2.1 which illustrates the development of biofeedback from basic feedback as a summary of discussion to this point.

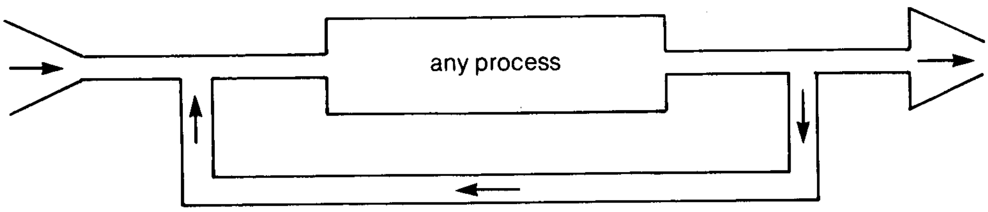
An example of a biofeedback signal is the neural message that goes to a person's brain from sensors that detect the stretch of muscles in the wall of his abdomen. Distention of the abdomen indicates that the stomach is full. The sensory message which is initiated by stretching these muscles inhibits the mechanism which makes a person feel hungry. The mechanism is probably based on a simple decision-making process like the following: in the brain the biofeedback signal is compared with a signal in memory which represents the abdominal distention when a person needs food. If they match, then the person feels hungry, so he eats, distends his abdomen and satiates his hunger. Without a match, the person is not hungry. (see figure 2.1(b) ii).

The biological significance of feedback-control is apparent from its mechanism in biochemistry. Generally, a product of a metabolic pathway inhibits a stage in its own production. This serves to conserve energy and raw materials by limiting the productivity of processes which build-up or break-down metabolites to exactly meet the needs of the organism; there is neither surplus nor deficit. Therefore, feedback-control is economical.

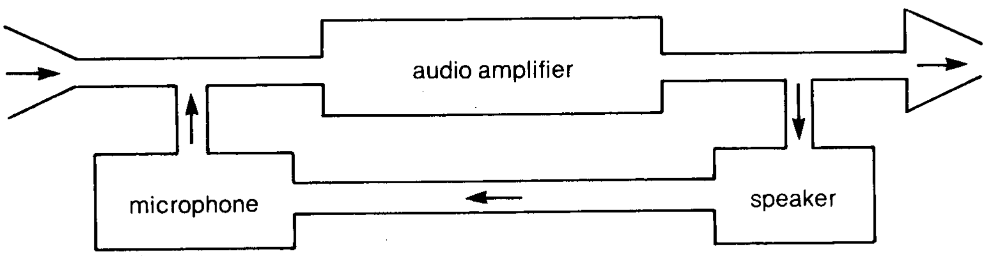
The point of control in biochemical feedback-control is the enzyme (a biological catalyst) rather than the processes which consume the end-product. This is efficient, because controlling the rate of consumption is linear, thus slow compared with controlling the rate of enzymatic action which is exponential.

figure 2.1 (a) ILLUSTRATIONS OF FEEDBACK

i FEEDBACK: a general case



ii FEEDBACK: an oscillating public address system



iii FEEDBACK: eliminating fingernail-biting

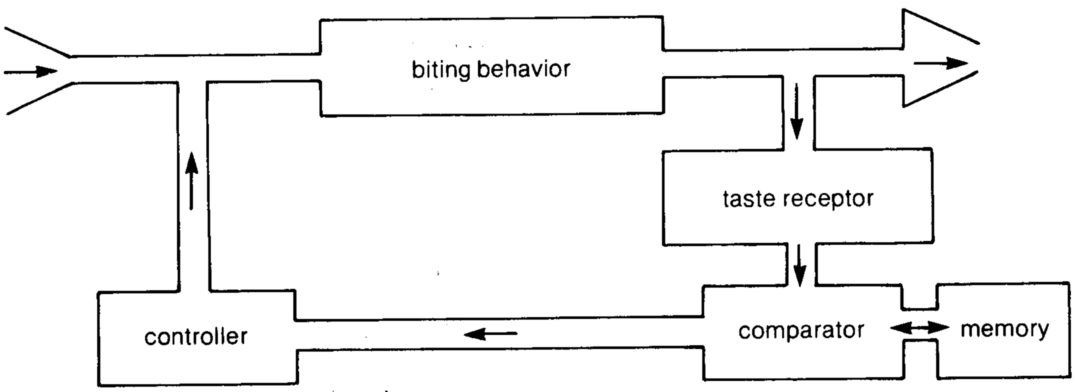
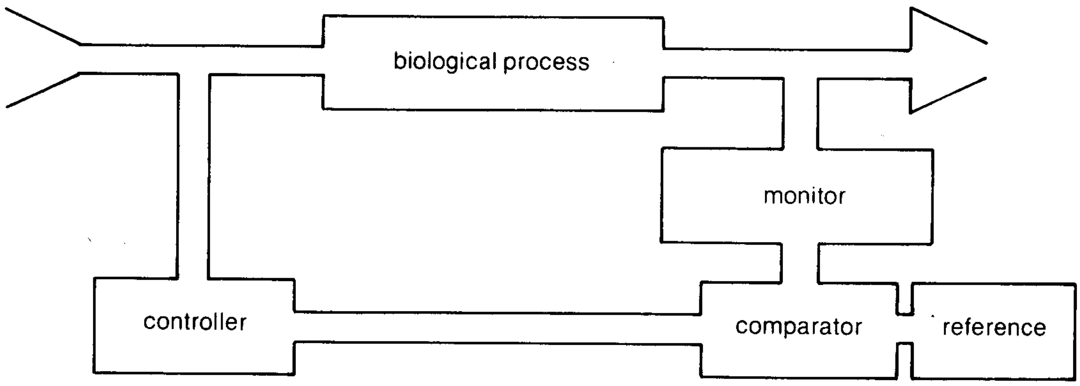
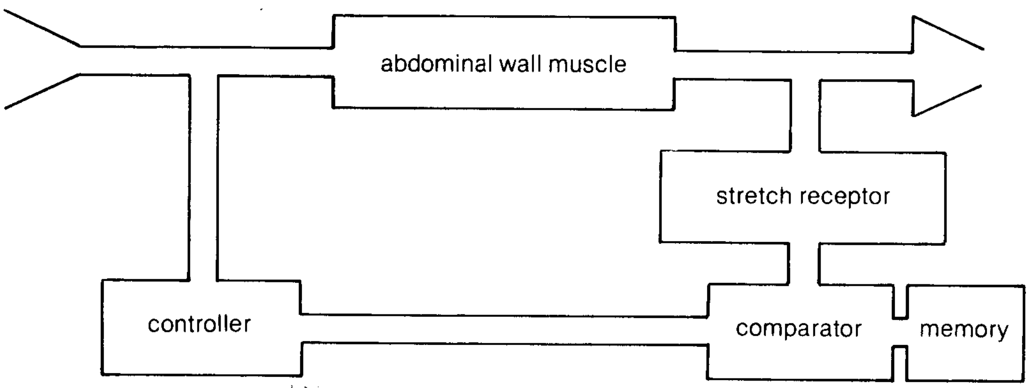


figure 2.1 (b) ILLUSTRATIONS OF BIOFEEDBACK

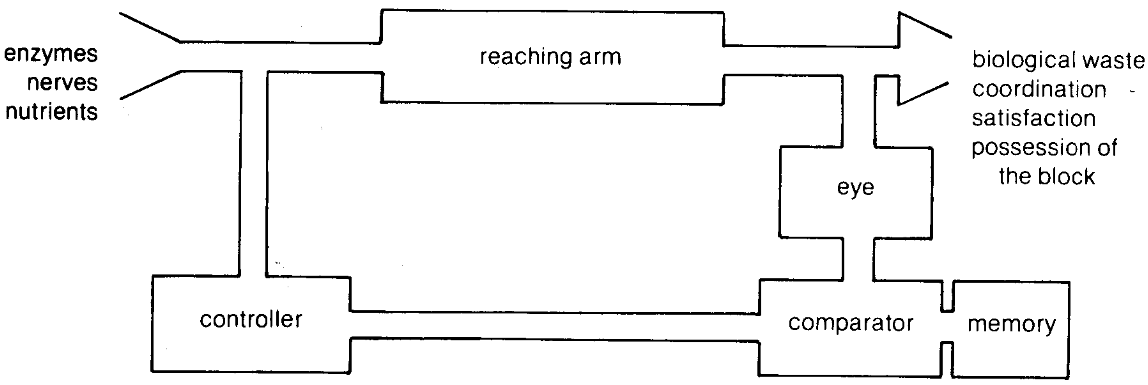
i BIOFEEDBACK: a mechanical model



ii BIOFEEDBACK: a mechanism of hunger



iii BIOFEEDBACK: reaching and grasping behavior



Enzymes do not undergo permanent changes. They merely facilitate metabolic processes. Generally, feedback-control is like that. Adjustment is made by processes which are external to the one being controlled. Sometimes the "controlling" and the "controlled" processes can not be directly connected, so monitors are used to interpret their activities for them. Therefore, a general description of biofeedback must include (1) a tissue which generates a signal (the product), (2) a monitor of the signal and (3) a process which controls the amount and the type of signal that the tissue generates, in accordance with (4) a reference.

The mechanism of the menstrual cycle is an example of a biofeedback-controlled system which is totally internal to an organism. For an example in which the path of the biofeedback signal is partially external to an organism, imagine the following events in the reaching and grasping behaviour of an infant:

> Suppose the object to be reached and grasped is a block of wood. The infant decides on the goal, looks at it and then extends an arm toward the block. This behaviour of reaching creates a situation for learning to occur.
>
> When the infant watches the motion of the arm in relation to the block, information about the arm and the block is compared in the infant's brain. If the arm strays from its intended course, then corrections in its motion can be made.

In other words, the behaviour of reaching is an externally directed activity which is perceived visually. What is perceived is compared in the brain with the goal of grasping the block of wood. Since the act of reaching is also perceived by a variety of receptors that respond to limb position, notably joint, muscle spindle and touch receptors, many repetitions of reaching and grasping activity result in the development of the proprioceptive sense (a sense of "touch" for the movement and the position of the body and limbs). With practise in perceiving the movement and position of the body and limbs visually and with proprioception, the child can eventually succeed in reaching and grasping an object even after diverting his gaze from the object.

Thus, eye-hand coordination and depth perception are developed by reaching and grasping. When the proprioceptive sense and the visual sense work in harmony, fewer errors are made in reaching and grasping. Errors that are made help in the development of concepts about what is seen, so that, for example, the most complete objects represented in overlapping images are assumed to be closer to the viewer than less complete objects. Therefore, the reaching and grasping behaviour of an infant provides comprehensive biofeedback training (see figure 2.1 (b) iii).

Strictly defined, biofeedback is a feature of any biological system that uses feedback. Therefore, the reaching and grasping activity of chimpanzees is biofeedback. However, two prevalent connotations of biofeedback make it difficult to accept his example. The first is that biofeedback refers only to humans and the second is that biofeedback refers only to cases in which the feedback is artificially contrived. These restricting connotations are not necessary, but the reasons for their emergence are worth considering.

The first reason is that a much greater variety of experiments can be performed on humans than on other organisms. The advantage of working with humans is that they can be trained with intellectual feedback, such as a sense of accomplishment. Some other organisms have been trained with electrical stimulation of a region of the brain called the "pleasure center", but there is no evidence from this research to suggest that such stimulation serves as intellectual feedback from them. Predominantly, therefore, training organisms other than humans to display control of physiological states is limited, because they respond only to feedback which satisfies a physiological need, such as food, water, heat or light (Wyricka, 1975). Therefore, biofeedback has the connotation of referring particularly to the training of people to control aspects of their own physiology. To repeat, however, it is not necessary to adopt this limited definition of feedback.

The second reason for the development of a new connotation of biofeedback deals with the contrivance of biofeedback training. This is a result of the development of biofeedback technology. This is a response to the need for instruments to analyze and to display to the learner interpretations of his own physiological activity. Because of advertising, mention of the term biofeedback conjures up the image of a person who concentrates on a light, a meter or a sound in an instrument that is connected to him with wires. However, learning to speak involves biofeedback, that is, hearing oneself make sounds, without such contrivance. Again, it is not necessary to restrict the meaning of biofeedback to artificially contrived mechanisms for learning physiological control.

In summary, biofeedback involves instructing a person about the immediate state of his own physiological activity. This enables the person to correlate his physiological recordings with some other signals such as his feelings and his attempts to change the recordings. This way, with practise, a person may learn to control his physiological activity. Once having gained such control, a person would not require further biofeedback, except perhaps for occasional retraining, provided he has been able to identify his physiological activity with some other signal that he normally produces and is normally aware of. By learning to associate that signal with the physiological activity, and by learning to control the signal, a person can come to control the physiological activity in the absence of further feedback.

2.15 Distinctions of Biofeedback

Among teaching methods, biofeedback training has two main distinctions. First, it has helped people to bring under voluntary control some internal biological processes that were traditionally thought to be involuntary autonomic processes. Second, whereas a few individuals have learned to control involuntary autonomic processes through years of meditative discipline, many people have achieved the same control in considerably less time with biofeedback training. Many of the original papers on these subjects are collected in the Aldine Atherton Annual, *Biofeedback and Self-Control.*

One feature of autonomic processes that has been examined by many researchers is brainwaves. Early biofeedback experiments demonstrated that a person could learn to control gross characteristics of brainwaves with biofeedback training. Barbara Brown, a medical doctor and a pioneer in this research, summarizes in simple language, much of the early research on the feedback of brainwaves in her book, *New Mind, New Body* (1974). Similar books are *Visceral Learning* by J. Jones (1973) and *Alpha Brainwaves* by J. Lawrence (1972).

The most excitement about biofeedback has been caused by its potential for influencing brainwaves, consciousness and thinking. The inspiration for writing this paper grew out of that excitement. Hopefully this paper about a new application of biofeedback will heighten that excitement. More research is needed to establish what is known and as this paper demonstrates, there is potential for more applications of biofeedback to be invented and studied.

2.16 Biofeedback Instruments

In general, instruments used for biofeedback training measure and interpret audio, electrical mechanical, thermal and video aspects of biological activity. A few of the electrophysiological signals that biofeedback instruments monitor are:

name	symbol	source
electrocardiac	ECG	heart
electrodermal	GSR	skin
electroencephalic	EEG	brain
electromyogenic	EMG	muscle
electro-ocular	EOG	eye muscle
electroretinal	ERG	retina

This thesis discusses a new application of biofeedback using EEG signals. Some considerations that should be involved in the design of biofeedback instruments are discussed in appended articles.

The previous section (2.1) introduced biofeedback which is both a natural and vital biological function and a new and versatile technique for experimentally modifying biological activity. The next section attempts to bridge the gap between theories of biological activity and human perception. In particular, it reviews a biofeedback model of perception. This model is consistent with the modern concept of the human brain as

> "*a complete functional system* . . . [of] complex composition . . . [with] a constant (invariant) task, performed by variable (variative) mechanisms, bringing the process to a constant (invariant) result" (Luria, 1973, page 28; square brackets added).

In a similar vein,

> ". . . there are few areas of the brain that are concerned with the regulation of one and only one behaviour and there is no single area in the brain that has complete control over any behaviour" (Valenstein, 1973, page 122).

The model stresses that natural biofeedback mechanisms play fundamental roles in perception. On the basis of this model the last section in this chapter presents reasons for thinking that an experiment using biofeedback might be designed to train people to recognize any given stimulus more reliably than without training.

2.2 A Biofeedback Model of Perception

This section discusses a theoretical model of perception based on the concept of biofeedback. First, a simple biofeedback system is described. Then, it is proposed that a perceiving, imagining and self-aware system is essentially a complex system of interrelated biofeedback units.

2.21 A Mechanical Unit of Biofeedback

A model of the mechanism of biofeedback is introduced earlier in the subsection entitled *Biofeedback*. The model consists of four stages arranged in a circular pattern: a biological process; a monitor; a comparator; a control process. A fifth stage, a memory, provides a reference signal that is compared with another signal in the comparator. This arrangement of five stages is a simple decision-making system.

The decision that this system makes is whether to maintain or to adjust the activity of the biological process in the system. To do this, the activity of the biological process is sampled by a monitor. The monitor interprets this activity for a comparator which compares the monitored activity with a reference signal from a memory. The reference signal represents what the monitored activity should be. The result of the comparison directs a control process either to maintain or to adjust its control of the activity in the biological process.

This decision-making system is a *feedback-controlled system*. The monitored activity is a feedback signal which is compared with a reference signal. If the signals match, then control is maintained and the activity of the system is stabilized. However, if a disturbance causes the signals to differ, then the control is adjusted and the activity of the system is changed to reduce the difference between the signals.

Reducing the effect of a disturbance is a result of negative feedback. A biological effect of negative feedback is homeostasis, the maintenance of biological equilibria.

Some biological equilibria physically exist within other biological equilibria. For instance, most enzymes within a single cell regulate activity and are inhibited by the end-product of that activity. On a more complex biological level the outputs of tissues often serve as negative feedback for the production of hormones that control the activity in the same tissues. On a more complex biological level the verbal output of vocal organs serves as negative feedback when the speaker listens to himself and corrects his speech.

From this biological suggestion it might be reasonable to consider perception in terms of a hierarchical structure of units of biofeedback. However, one fundamental obstacle prevents the development of such a model at this point. Because of the variability of brain mechanisms for performing identical tasks, no stationary structures such as a particular biological tissue, a monitor, a comparator and a control can be identified. Even the clue that the configurations of DNA and RNA (deoxyribonucleic acid and ribonucleic acid, the substances of genetic material) are involved in memory, does not help. No fixed group of neurons always performs the same function in perception. Therefore, a description of the perceiving brain is needed which ignores the identity of mechanisms, but describes the function of mechanisms that are involved in perception.

A way to do this is to reconsider the basic unit of biofeedback in a different way. The revised unit is called an operational unit of biofeedback.

2.22 An Operational Unit of Biofeedback

The operational unit (adaped from Powers et al, 1960) of biofeedback is derived from the mechanical unit of biofeedback as shown in figure 2.2. It is a feedback-controlled system that consists of a comparator function, an output function and a biofeedback function. An environment function accounts for external influences on this model.

The *biofeedback function* represents all operations at the input of a biological system. Other inputs such as nutrients are ignored.

The *output function* represents the effects of biological activity which influence that activity. Other outputs such as wastes are ignored.

The *comparator function* represents an operation that brings the output function into alignment with reference signals in the environment.

The *environment function* represents the influence of other units of biofeedback and the generation of noise in the biological system.

The operational unit of biofeedback works to resist change. Therefore, the unit compensates for disturbances by establishing new equilibria.

2.23 Interacting Biofeedback Units

Consider several operational units of biofeedback which interact in a hierarchical structure. At the base of the hierarchy are all units whose environment functions include signals from outside the organism. These first order systems serve as an interface between the organism and its environment.

Disturbances in the environment cause disturbances in some first order systems. These disturbed systems would disturb adjacent systems by direct interaction or by induction. Therefore, a single disturbance from outside the organism or noise in a first order system would trigger chaotic chain reactions if the activity of first order systems was not controlled.

Second order systems impose this control on first order systems. Second order and higher orders of biofeedback units respond to signals that are entirely within the organism. The feedback signals in the internal environment are the only points of connection between biofeedback units, so changing mechanisms of perception means changing these signals. It is more economical for connections to be feedback signals than inputs or outputs, since they are functions of change rather than on-going activity. Besides, self-destructive conflict can result in feedback-controlled systems from connecting inputs and outputs.

The output functions of second order systems which contain second order feedback signals, become the reference signals for first order systems. Therefore, second order systems specify the goals of first order systems. Whereas first order systems sense disturbances in the environment of an organism, second order systems specify how the first order systems will respond to the disturbances. In this way, successive orders of biofeedback units control preceding orders and chaotic chain reactions are prevented.

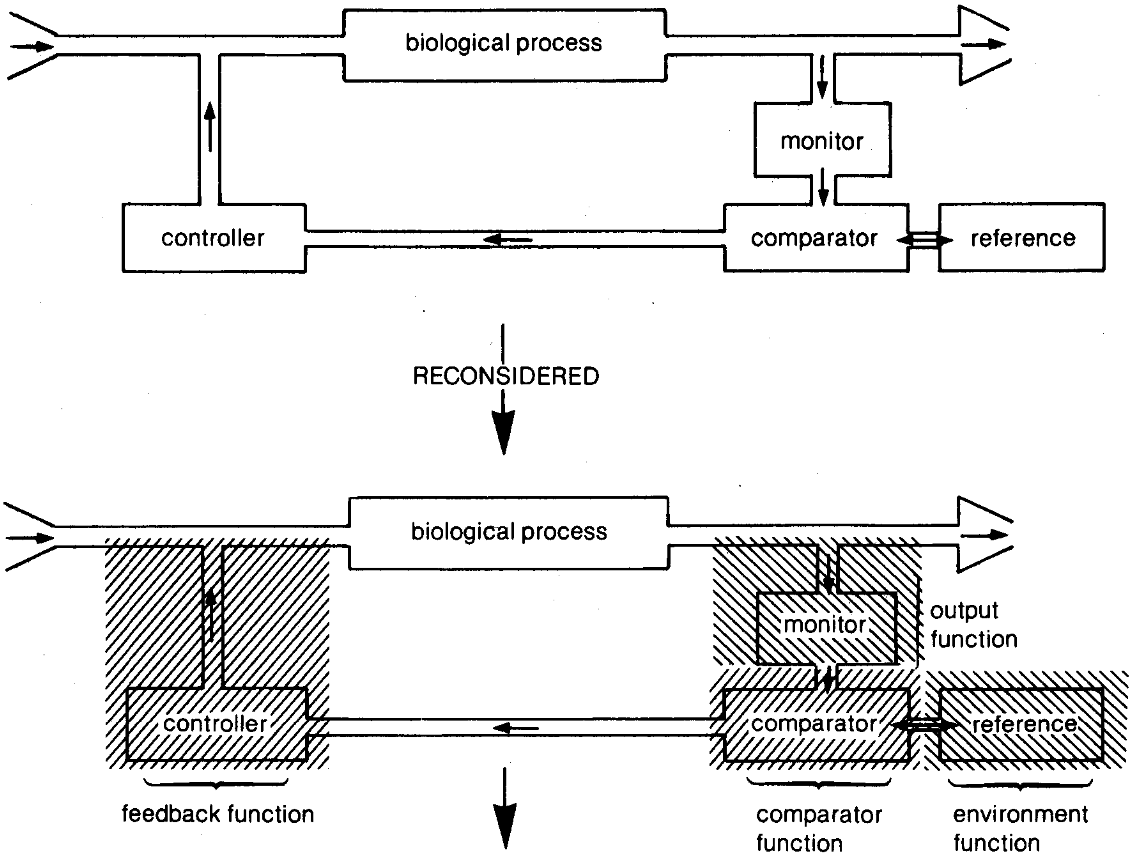
For instance, first order systems in the auditory system respond to the frequencies and the intensities of sounds. This is the first stage in auditory perception. When a sound consists of only a few frequencies, then some first order systems are activated while others are not. If a sound is excessively loud, then a first order system would initiate the tympanic reflex, tightening the tympanic membrane (eardrum) and preventing injury.

Second order auditory systems would set the thresholds (sensory magnitudes) for first order functions. Also second order systems would specify the signals (sensory identities) to which first order systems are sensitive. Each successive order works in the same way: specifying both magnitudes and identities of internal environmental disturbances to which preceding orders of biofeedback units will respond.

Clearly a complex system could consist of many orders of biofeedback units arranged in a hierarchy (see figure 2.3). Each order tracks signals from the units in adjacent orders. At the

FIGURE 2.2 BIOFEEDBACK UNITS

i A Mechanical Unit of Biofeedback



ii An Operational Unit of Biofeedback

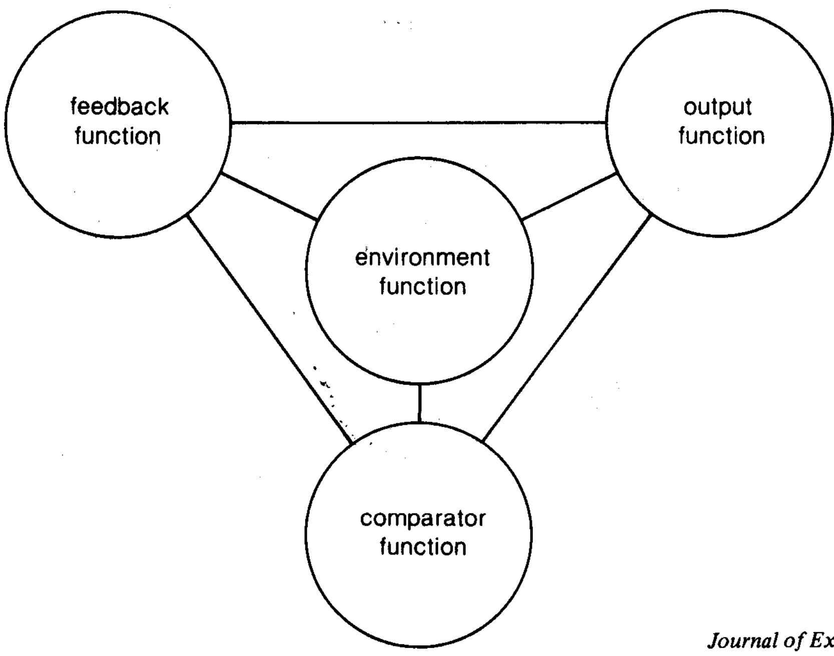
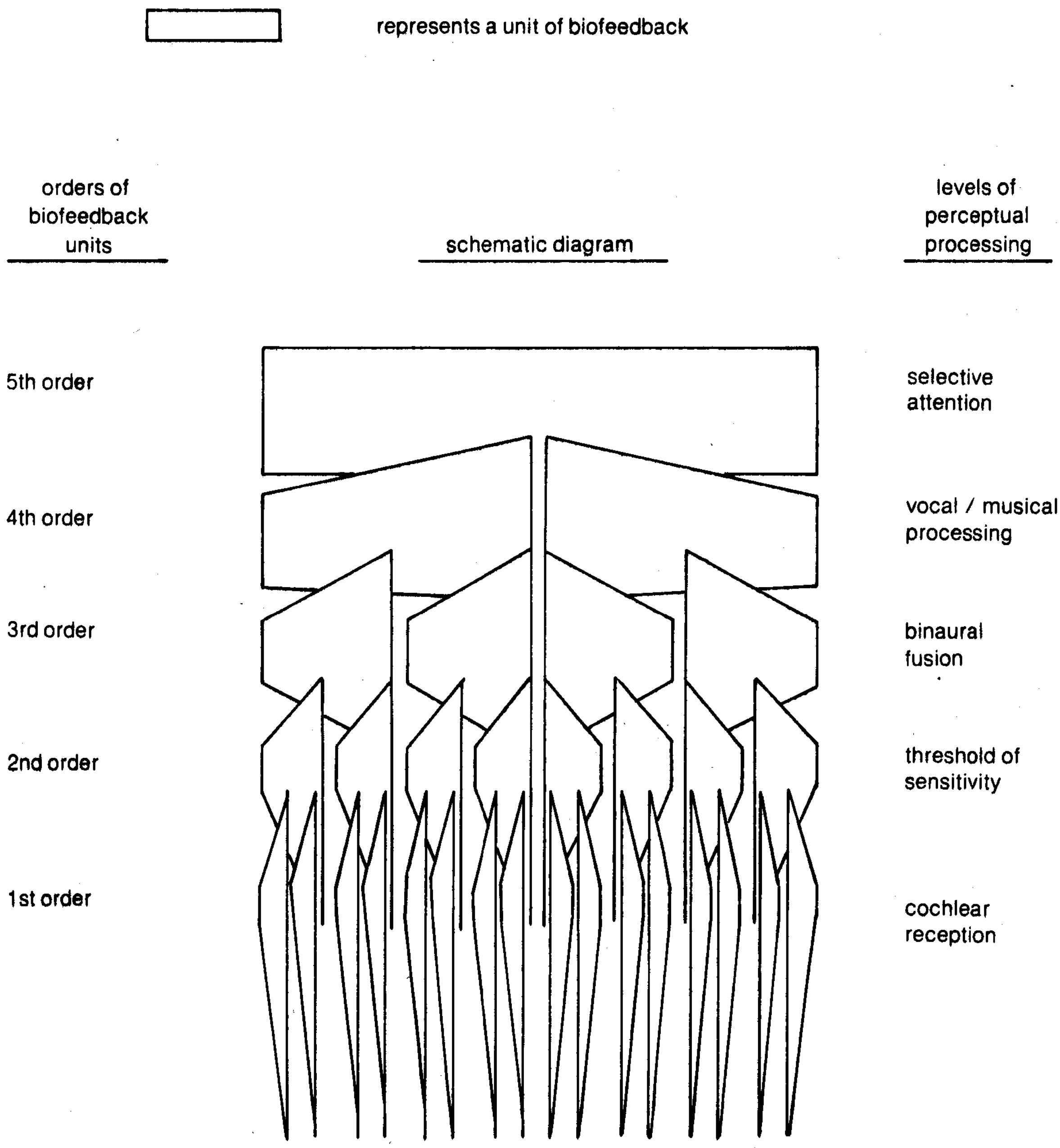


figure 2.3 A HIERARCHY IN AUDITORY PERCEPTION



bottom of this hierarchy are factors in the environment of the organism which initiate ascending disturbances. At the top of the hierarchy are factors which determine consciousness, a process that is capable of initiating descending disturbances. Ascending and descending disturbances represent afferent and efferent signals in the nervous system.

This hierarchical system of biofeedback units is capable of homeostasis, responds to changing rather than stationary states, contains short and long term memories as reference signals and adapts to a wide variety of environments. Therefore, this model is already a sophisticated perceptual system. To account for learning it is assumed that repeated use of a sequence of biofeedback units of different orders would facilitate this organization, by determining a higher order reference signal to recall this organization.

One could account for imagination in the following way. Any unit in the system functions only by bringing feedback signals to some reference level. Therefore, high-order systems cannot distinguish between reference signals that originate from within the organism and outside the organism. Signals from either source disturb low-order systems. Therefore, ascending signals might as easily conjure imaginary sensations as real sensations.

What must remain incomplete in this model is an explanation of how to make it self-determining and deliberate. So far it only reacts to internal environmental disturbances or internal noise. It is not apparent how high-order systems go about selecting and directing perceptual behaviour. However, for purposes in this paper, this model adequately represents perceptual behaviour if one keeps in mind that both ascending and descending signals exist.

2.24 A PERCEPTUAL HIERARCHY

Making a model of perception from basic units of biofeedback produces a system which is biologically active and functionally passive like human perceptual systems. For instance, the metabolic processes of the retina are actively engaged in maintaining the sensitivity of the eye to light whether or not light is present. When light is present, depending on intensity, colour, shape and movement, it stimulates the retina in different ways according to the sensitivities of parts of the retina. Therefore, the visual system functions passively in the sense that visual information sorts itself according to the composition of the visual system.

Active functioning in perception happens in high-level processes such as dreams, imagination and selective attention. Active functioning can be described by the biofeedback model of perception. For example, section 2.25 presents a description of selective attention using the model. However, the model cannot explain how selective attention is controlled. It is not presently known how to account for the unprovoked assertiveness that is characteristic of humans and other organisms that display determination and deliberate behaviour.

The inability to account for active functioning is a limitation of the biofeedback model of perception, but the model is still very useful. The system made of a hierarchy of biofeedback units is passive like the perceptual system. Higher orders facilitate the sorting of information by lower orders. For example, spinal reflexes are considered *first order systems* that respond to disturbances in other first order systems by adjusting efferent signals to muscles according to afferent signals from the same muscles.

Second order systems set the reference levels for the reflex mechanisms. They also respond to disturbances in first order systems by conveying signals to higher orders, perhaps to arouse conscious awareness of reflex activity. Second order feedback signals represent the elementary sensations of characteristic patterns of stimuli.

Third order systems specify patterns of elementary sensations that form simple concepts which second order disturbances represent. For instance, intermittent touching and scraping of the skin might give rise to elementary sensations of itching. If such isolated stimuli occurred in a spatial or a temporal pattern, however, third order systems might be activated to distingujish an isolated itch from an insect landing on the skin. Therefore, third order systems detect patterns of patterns, that is, simple concepts.

Fourth order systems represent sequential concepts. For instance, if an insect were crawling on the skin, then a fourth order system might integrate a succession of itches into a unified experience. It might be sufficient to brush the skin to eliminate the disturbance. Such actions, though more sophisticated than reflexes, are performed regularly without being noticed by the performer.

Fifth order systems select fourth order disturbances that will receive high-level processing. For instance, if sensations of crawling insects were received more than once in a short period of time, then a memory of insect colonies might be recalled. A strong correlation between the experience and the memory would suggest that further attention is warranted. Attention might be given to fifth order disturbances due to "crawling" sensations if other disturbances do not take priority.

Sixth order systems determine the goals of an organism. The decision to conduct a visual search to determine whether to move away if a swarm of insects is found, would depend on the interactions between sixth order goals and fifth order alarms. Descending disturbances would assert goals and ascending disturbances would contribute to the formation of goals.

Other orders of biofeedback units may go beyond or go between the six that are mentioned above. Active functioning is not explained by the model, but can be illustrated with it. Nevertheless, the hierarchy of biofeedback units describes some very sophisticated perceptual behaviour. The hierarchy is illustrated in figure 2.3 and parallels in auditory perception are identified in the diagram.

2.25 Selective Attention

If every sensory event aroused a person's attention, then a flood of information would overwhelm him. Fortunately, a sophisticated perceptual behaviour prevents this. It selects from among many simultaneous sensations within and across sensory modalities, a small number of sensations that receive conscious attention. This behaviour is selective attention.

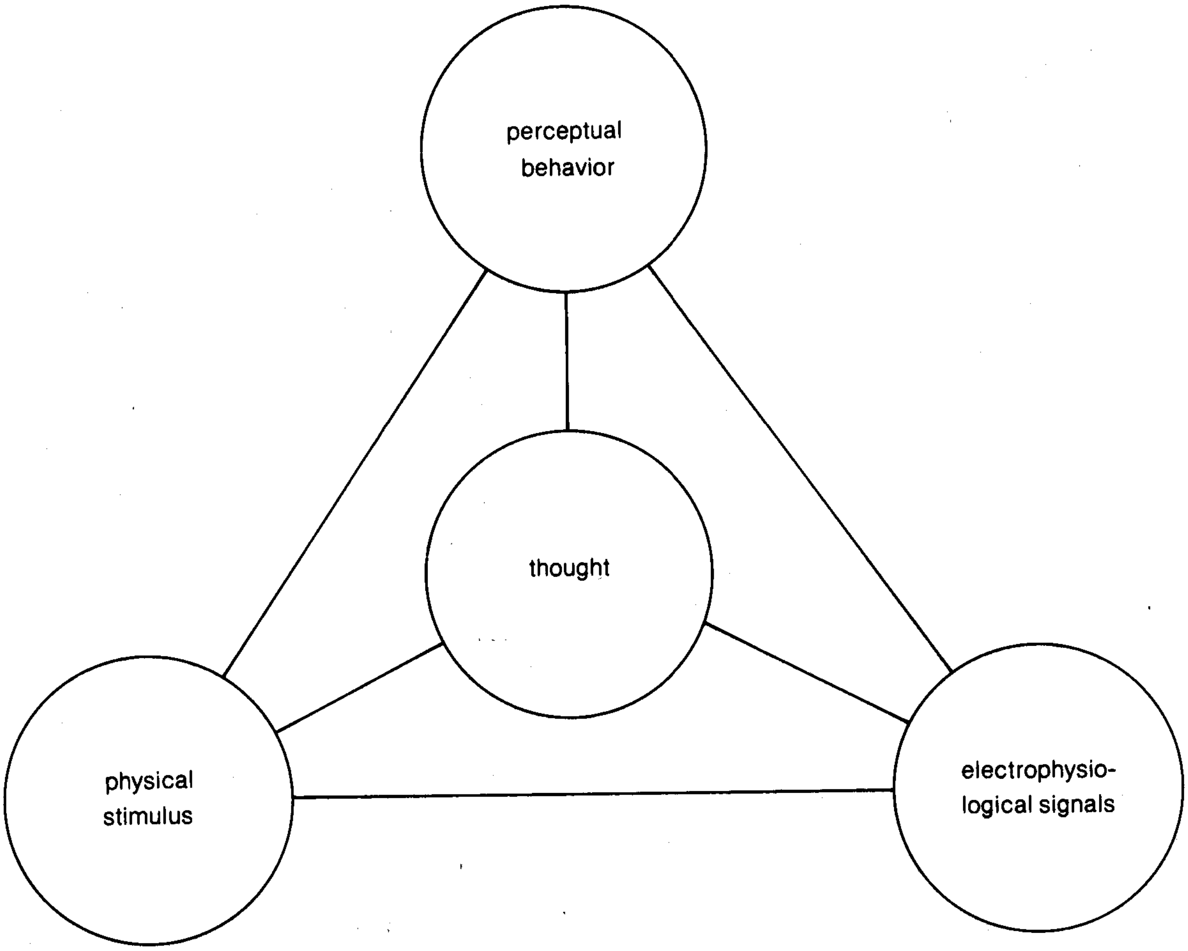
Selective attention is particularly interesting because it is a sophisticated behaviour which can be studied under well-controlled conditions. Electrophysiological signals that accompany selective attending are virtually free of contamination from EMG signals because movement is not required for selective attention. Instructing a person to be selectively attentive is simple because the instruction is easy to express, easy to understand and easy to follow. Therefore, selective attention is a good topic for comprehensive study since it is a voluntary, well-defined behaviour that is simply described, depends on easily specified physical events and is accompanied by relatively "clean" electrophysiological signals (particularly EEG). This makes selective attention a particularly good topic for studying the interrelationships between physical events, perceptual behaviour and electrophysiological concomitants of thought. Figure 2.4 depicts these four factors as interrelated and interdependent functions.

In the biofeedback model of perception the selection of perceptions for conscious processing can be directed by signals sent down the hierarchy. Such descending messages control the flow of ascending messages because each order of biofeedback units specifies with reference signals the goals of the next lowest order.

Repeated patterns of ascending signals tend to facilitate organizations of biofeedback units. This can have two effects: habituation and learning (perceptual). Habituation is desensitization to repeated patterns of ascending messages which are neither threatening nor important. The effect of these unimportant events is a shift in reference signals for biofeedback units. This increases their threshold of sensitivity to the events. Learning involves establishing new goals for biofeedback units due to repeated occurrences of important events. Electrophysiological evidence of habituation is reviewed in section 3.23 and evidence of learning is reviewed in section 2.3.

As a way of thinking about selecting perceptions in the biofeedback model of perception, consider units of biofeedback to be adaptive filters. Descending messages assign the patterns of lower order disturbances to which a given order will respond. However, repeated patterns of lower order disturbances are ascending messages that tend to change the organism's sensitivity to them. Therefore, biofeedback units "filter" ascending patterns of disturbances by passing the ones that are specified by descending reference signals and by rejecting others. Also,

FIGURE 2.4 INTERDEPENDENCE OF PSYCHOPHYSICAL FUNCTIONS



biofeedback units "adapt" to ascending patterns which are not specified, but are recurring, so that new goals become formed. Consequently, sensations are selected by rejecting others. This concept is supported by electrophysiological evidence that is reviewed in section 3.23.

The two operations, adaptation and filtration, appear to be working in opposition. To eliminate this difficulty, consider that parallel, unidirectional and interactive pathways of biofeedback units exist to handle ascending and descending messages. This is analogous to the parallel afferent and efferent innervation of the human body.

Ascending and descending messages are involved when people learn to respond to their own names. A person's name is a signal which is frequently repeated at irregular intervals in a person's early experience. It is usually spoken for a good reason, generally to attract attention. Therefore, people learn when they are very young that the sounds of their names are signals that should immediately arouse attention. Ascending messages from a name consequently promote the formation of the goal (set by descending messages) of paying attention when the name is heard.

For a name like "Mark" there is ample opportunity for confusion. Aurally, it is indistinguishable from "Marc". That is an unavoidable problem in audition. However, being similarly aroused by the word "mark" would be frustrating. Fortunately, it is rarely a source of confusion. The rarity of confusion makes the learning of a name and the accurate recognition of it an admirable demonstration of a complex perceptual behaviour.

As a name is being learned, its components must be sorted and stored in memory according to the way it sorts itself in the auditory system. With experience, the memory of the name must be refined so that the incidence of being falsely aroused by inappropriate stimuli is minimized. Furthermore, arousal to the name becomes dependent upon the context in which it is heard. Therefore, a person would tend to be aroused more by hearing a name when it is not expected than if it was heard in the lyrics of a familiar song. Consequently, people become "tuned" to hearing their own names.

There are more or less automatic forms of selective attention. One form allows people to concentrate. Another allows people to search for particular patterns of stimuli in complex sensory fields. Still another causes people to be startled by sudden, intense stimuli. Yet another, deals with stimuli, such as a name, which might only be important to one person.

The overt manifestations of the more automatic forms of selective attention, such as turning the head and eyes toward the source of a stimulus, resemble the responses in a reflex. Although they are not part of reflexes, unfortunately they have been named "orienting reflexes". "Orienting responses" is preferable. Some signs of the orienting response occur in EEG recordings shortly after the presentation of a stimulus. These signs are discussed in the next chapter.

The next section of this chapter reviews experimental evidence that shows that operant training can be used to modify the orienting response in EEG recordings. Before leaving this section on the Biofeedback Model of Perception, the main points of this section will be summarized.

To summarize, processes which happen between the presentation of a stimulus and the elicitation of a response are considered to be hierarchical and modifiable.

When a sensory event is received, it triggers a sequence of operations. A sensory receptor sends a message to the brain that an event is occurring. The importance of the message is assessed in relation to other activities. If the message is judged to be unimportant, then the processing of it stops. If it is judged to be important, then processing continues.

At an intermediate level of processing, a reflex action might be triggered. If this response adequately resolves the situation that is presented by the stimulus, then processing of the sensation stops. If not, then processing continues.

With further processing the sensory event qualifies as a more or less salient event. A few of the most important salient events to a person at a given time receive the highest level of processing, conscious attention.

Some salient events, like a person's name, are passively sought by pre-programmed mechanisms which act like filters. These programs are developed to cope with salient events that tend to recur. As the programs become learned, a person tends to be alerted to such events with increasing regularity. In the course of learning these events and programming the mechanisms for arousal which they trigger, a person fine-tunes his perceptual judgment so that he is not aroused unnecessarily by false alarms.

Gross differences in the processing of sensory events are reflected in neural activity. Salient events which receive conscious attention are accompanied by high amplitude neural discharges in a volley (labelled P_{300}) that appears in brainwave recordings at approximately 300 milliseconds after the presentation of each stimulus. Less salient events do not elicit as high amplitudes. This follows from the assumption that top priority events elicit activity in larger neural ensembles than lower priority events, because they require a greater quantity and a higher quality of processing. Therefore, brainwaves can be used to assess the gross significance that various stimuli have for a perceiver. The next section of this paper summarizes evidence from experiments which pertain to the idea that brainwave biofeedback might train a person to fine-tune his perceptual judgment.

2.3 Fine Control of Brainwaves After Training

Extensive research using operant and classical methods has proven that some individuals can be trained to control their brainwaves. Such training has been used mainly to teach individuals to control gross features of brainwaves, such as frequency content. However, a few researchers have investigated control of more specific features of brainwaves. A selection of articles from this small body of research is reviewed in the following section.

2.31 A Summary of Results from Eleven Experiments

Many changes in cerebral evoked potentials due to behavioural conditioning have been demonstrated (Morrell, 1961; John, 1961; Gerken and Neff, 1963; John et al, 1964; Mark, 1966). However, a major change in the direction of research occurred after Fox and Rudell in 1968 proposed a new strategy: to make changes in evoked potentials the objective of training instead of changes in behaviours with which changes in evoked potentials are associated.

Fox and Rudell (1968) reported an experiment to investigate the relevance of evoked potentials to behaviour. With the objective of changing visual evoked potentials, they trained cats to increase and to decrease the amplitudes of evoked potentials from identical stimuli. Changes in amplitude only occurred in the segment of the evoked potential waveform that was used as a reference for reinforcement. These were the only consistent effects of training. No changes were found in the cats' overt behaviours.

In 1969 Rosenfeld et al reported a modification to the earlier experiment. They trained humans instead of cats and examined auditory instead of visual evoked potentials. The human subjects did not perform as well as the cats. After training the cats' evoked potentials changed by as much as thirty-two percent; the humans', only fifteen percent. Despite this difference, the operant control of neural events was proven by these results to be sufficiently general to work in different species.

Later in 1969, Begleiter and Platz reported success in modifying visual evoked potentials in humans by classical training. Before training, the evoked potentials to conditioned stimuli were similar. During training, one conditioned stimulus gave an enhancement and another, no change, in a negative peak at an interval of 155 to 166 milliseconds after stimulation. The experimenters concluded that the components of evoked potentials "reflect the release of patterns of neuronal activity which relate to the perception of the stimulus and to the previous relevant experience of the organism." (Science, volume 166, page 771, 1969). The results also show that control of evoked potential amplitudes can be achieved with classical training in the visual modality as well as with operant training in the auditory modality (mentioned earlier in Rosenfeld, 1969).

To verify earlier results, Fox and Rudell repeated their experiments in 1970. Again, they reported success in training cats to change the amplitudes of their evoked potentials. This time Fox and Rudell noted that each cat's evoked potentials are unique. Also, when Fox and Rudell did not reinforce the cats, only 26 percent of their evoked potentials met the criterion for reinforcement, compared with 68 percent when they did reinforce them. This proves that the reinforcer caused the changes in amplitude that were found.

In 1971 Fetz and Finocchio reported a study of the electrical activity in an entire neural pathway. The pathway includes brain cells in the motor cortex, arm muscles and elbow proprioceptors. In this experiment, patterns of motor activity were operantly trained in a monkey. Fetz and Finnochio found that in the remarkably short training period of fifteen minutes the monkey learned to dissociate the activity of a brain cell and the muscle which normally contracted seventy milliseconds after peak activity in the brain cell. In one experiment the monkey was trained to suppress the activity of the brain cell while the muscle contracted on cue. This is further evidence that operant training can be used to change functional relationships in brain mechanisms.

In 1972, while discussing the significance of operant control of evoked potentials, Rudell expressed an important conclusion: ". . . if an animal can, under reinforcement control, come to manipulate aspects of the wave (evoked potential), these aspects must functionally participate in or be the consequence of some behaviour or state of the animal." (*Journal of Neurophysiology,* volume 35, page 892, 1972, parentheses added). By inference, biofeedback training to modify cerebral evoked potentials might influence functions which are part of the perception of the stimuli that elicit evoked potentials.

The same paper reports results of three experiments. Rudell and Fox tried to operantly train cats to change their visual evoked potentials at intervals of time after stimulation that were shorter than those found in previous experiments. They were successful. Rudell and Fox also systematically changed the intensity of the stimuli in order to examine the sensitivity of various components of evoked potentials to the properties of the stimulus. They found the size of each component to be a function of intensity. They concluded that an evoked potential represents several independent factors of perception and some of these factors can be controlled with operant training. Also, this control is independent of uniform changes in the whole evoked potential that are a function of properties of the stimulus.

Later in 1972, Rosenfeld and Owen reported another experiment on operant training of visual evoked potentials. They proposed that the cats probably learn to generate a state of tension in the brain before being presented with a stimulus. They postulate that this "tension" might be the result of presetting the excitabilities of sets of synapses. According to the biofeedback model of perception (recall section 2.24) this would mean lowering the thresholds of first order systems by second order systems. Consequently, any stimulus might trigger an "avalanching" release of the tension. This is one theory to explain gradual building of potential in the brainwave preceding an expected event ("contingent negative variation") and specially large deflections in the brainwave following the occurrence of such events.

Rosenfeld and Hetzler (1973) tested the ability of rats to discriminate between different operantly trained evoked potentials. The study was only partially successful. Rosenfeld and Hetzler concluded that some states which are obtained in individuals after conditioning neural events do not correspond to states which normally exist in untrained animals. By inference, evoked potential feedback might train a person to be aroused by any given stimulus without him knowing exactly how. Being conditioned without being aware of it is a topic of current research (Brandeis and Lubow, 1975).

Lelord et al (1973) reported a potentially valuable experiment. The subjects in their study were perceptually normal children and autistic children who display perceptual inconstancy by alternately over-reacting and under-reacting to sensory events. Training to modify auditory and visual evoked potentials was successful in both groups of subjects. The authors did not report any behavioural effects of this training. Perhaps their experimental design was not suited to detecting any. With their evidence that evoked potentials can be modified with training, a more comprehensive experimental design that is suggested in this thesis could be used to assess the effects of such training on the perceptual behaviour of autistic children. Such a study might support the theory that brainwave biofeedback can be used for perceptual fine-tuning. Such a study might also provide a model for the training of perceptually handicapped people to perceive "better".

In 1974 Shinkman et al reported a study of the direct operant modification of activity in a brain cell that is elicited by a stimulus. He recorded visual evoked potentials in cats. Twenty of twenty-one cells that he studied reached or exceeded a thirty percent change in the rate of firing. Shinkman concluded that his results provide a cellular basis for operant training of stimulus-evoked neural activity.

A study of a promising application of brainwave biofeedback was reported by Finley et al (1975). They investigated a dual strategy for reducing the occurrence of seizures suffered by a severe epileptic. One strategy was to train the subject to suppress the pattern of brainwaves which accompanies the seizures. The other strategy was to train the subject to generate a pattern of brainwaves that defeats the pattern which accompanies seizures. Bogus feedback was scattered among genuine feedback. Whereas the bogus feedback caused no change or worsened the subject's condition, genuine feedback improved it. The result of genuine feedback was a reduction in the incidence and the severity of epileptic seizures and this improved condition persisted after the training was discontinued.

The results of the reports that are summarized in this section represent most of what is known about the operant training of neural activity which accompanies well-defined behaviour. More of this research is needed because brainwave recordings and broadly-defined behaviours are poorly correlated. Better correlations are needed to improve scientific understanding and to indicate more applications of this knowledge. "To understand nervous function one needs to look at interactions at a cellular level, rather than either a more macroscopic or microscopic level, because behaviour depends on the organized pattern of these intercellular interactions." (Barlow, 1972 in *Perception,* volume 1, page 371) To understand the relationships between nervous function and psychological function it is necessary to examine the activity in small aggregates of brain cells which accompanies focused human performance in well-specified psychological tasks.

The following chapters discuss how this can be done.

3.0 CEREBRAL EVOKED POTENTIALS

This chapter is a review of phenomena studied in experimental psychology called *cerebral evoked potentials.* First, these "reflections in brainwaves of mental events" are identified and the means of recording them are briefly summarized. Next, the effects of physical properties of stimuli on cerebral evoked potentials are reviewed. Finally, the effects of psychological variables on cerebral evoked potentials are reviewed.

The purpose of this chapter is to familiarize the reader with the breadth and the depth of knowledge from which the goals of this thesis emerged. In particular, this chapter gives the sources of many elements of the experimental designs that are discussed in chapter 4.0. Although this review is comprehensive, it is not exhaustive. Therefore, numerous references are included to assist the reader in exploring any topic in more depth.

3.1 Introduction to Cerebral Evoked Potentials

The tissue of the brain is basically composed of two types of cells, neurons and glial cells. Neurons are excited to generate an action potential which is an electro-chemical impulse. This is a very fast response in three respects: speed, latency and recovery. Glia are postulated (Luria, 1973, *The Working Brain,* pages 281 to 282) to produce and to modify special RNA (riboxynucleic acid) and DNA (deoxyribonucleic acid) molecules which carry memories. This response is several hundred times slower than the response in neurons. Therefore, it might be that the very fast operations of the brain are to receive, to organize and to transmit information and the moderately fast operations are to record, to correlate and to playback information.

The operations in the brain result from a mixture of electrical and chemical processes. Consequently, it is possible to monitor some of the activity in the brain by recording electrical signals. This gives brainwave recordings. Brainwaves which are recorded from the scalp are considered to reflect the collective activity of many neurons.

When a brainwave recording shows an electrical event which has a large amplitude, it is considered to reflect extensive synchrony in the activity of brain cells. Lower amplitudes would imply less extensive synchrony.

In order to determine whether there are perceptual implications to changes in the amplitude of brainwaves, the basic technique for studying an unknown or "black box" process has been used. This technique involves introducing various signals at the input and examining what happens at the output. In other words, researchers design experiments to stimulate subjects and to examine the brainwave recordings to determine the effects of stimulation. This technique has evolved into a sophisticated analytical technique which is reviewed in chapter 4.0 under *Signal Detection Format*.

A detailed account of the techniques and the equipment for recording brainwaves is not necessary for a basic understanding of the issues that are discussed in this paper. It is sufficient to know that brainwaves are very small signals which must be amplified to almost one million times their original size to be seen clearly on a display. They can be recorded with small metal electrodes placed on the surface of the scalp and the application of these electrodes is painless and harmless. At no time during the recording of brainwaves is a subject in danger of receiving an electric shock. Electrical isolation ensures the safety of the subject. Details of typical experimental set-ups can be found in Thompson and Patterson (1974), *Bioelectric Recording Techniques*. Some details of a particular experimental design will be summarized in chapter 4.0.

3.11 Single Evoked Potentials

The segment of a brainwave recording which begins at the time of the onset of a stimulus and ends after an interval of time that is chosen by the experimenter contains a response to the stimulus that is called an *evoked potential*. It is "evoked" because it reflects a response in the brain to the stimulus. It is a "potential" because brainwaves are electrical and are characterized by variations in voltage, a synonym of potential. There are also evoked potentials in other tissues, but this paper only discusses evoked potentials in the brain.

Auditory evoked potentials recorded from a person's scalp contain a sequence of fifteen separate waves (Picton et al, 1974). Each wave is believed to represent the activation of groups of brain cells in the auditory pathway as a person's response to a stimulus develops in the brainstem and travels to the cortex of his brain.

The evoked potential waveform is a distribution in time of the probabilities of firing in single brain cells which are activated during the perception of a stimulus (Fox and O'Brien, 1965). Presumably, a detailed picture of evoked potentials would show waveforms of evoked potentials to be stepped functions (Stevens, 1972) which represent a distribution of the sums of impulses from individual brain cells which fire at different rates at different times after a stimulus is received. Since there are several conceivable stages in the perception of a stimulus, such as:

receiving the sensation by sensory receptors,
noticing that something is happening,
determining which sensory modality is excited,
doing something about it with a reflex,
assessing its priority,
directing attention to it, if necessary,
deciding to do something about it and
doing something about it with an appropriate action,

it is assumed that late components of an evoked potential reflect aspects of the cognitive end of perceptual processing and early components, the sensory end of perceptual processing. This assumption is confirmed by experiments that are discussed in sections 3.22 and 3.23.

While a segment of a brainwave recording reflects a response to a stimulus, being recorded from the scalp, it probably also reflects activity in the brain that is not related to the presentation of the stimulus. Although the unrelated activity could be very important to the organism, it is unwanted by an experimenter who is examining evoked potentials. Therefore, when evoked potentials are the signals under examination, brainwaves which are not related to a stimulus are considered to be "noise".

The great irregularity of noise and its large amplitude make each recording of an evoked potential unique. Even when several are recorded under identical conditions, but at different times, they have substantial differences. This makes it extremely difficult to correlate psychological or behavioural measures with single evoked potentials. However, recently a statistical method has been developed to sort various kinds of single evoked potentials (Bartlett et al, 1975). Despite this isolated endeavour, most studies on evoked potentials use averaged evoked potentials. They will be discussed later along with a new method of averaging.

Analyses of evoked potentials almost exclusively involve amplitude and latency. This approach might be over-simplified. There are many ways that evoked potentials might encode stages in perceptual processing. Granted, an evoked potential can be considered as a distribution of amplitudes in time, but other general properties of signals apply to evoked potentials as well. In addition to amplitude spectra, evoked potentials have frequency and phase spectra. These derive from the supposition that evoked potentials can somehow be represented by a collection of sinusoidal or exponential components. All three spectra have limits and ranges, central tendencies, energy and power distributions and characteristic spreads which are statistical measures that might parallel behavioural measures in perception.

Consider the following diagram: Figure 3.1 ⟶

This diagram illustrates typical waveforms. The difference between the brainwave recording and the evoked potential that it contains is due to noise. Differences between this evoked potential and other evoked potentials might include any of the following visible features:

a change, positive or negative, in the direct-current voltage of the whole waveform;
a change, positive or negative, in the amplitude of an existing volley;
the generation of a new volley, positive or negative, between two volleys;
the telescoping of two volleys into one;
a shift in the latency of a volley;
a shift in the spread of a volley;
a change in the smoothness of the waveform;
a change in the source of the waveform which can be shown by analyzing simultaneous brainwave recordings from an array of recording sites (Clynes, 1965; Clynes and Milsum, 1970; Squires et al, 1975b — P_{300}).

Therefore, single evoked potentials might contain a lot of information. Unfortunately, most of this information must be sacrificed when standard methods are used to extract evoked potentials from noise.

3.12 Averaged Evoked Potentials

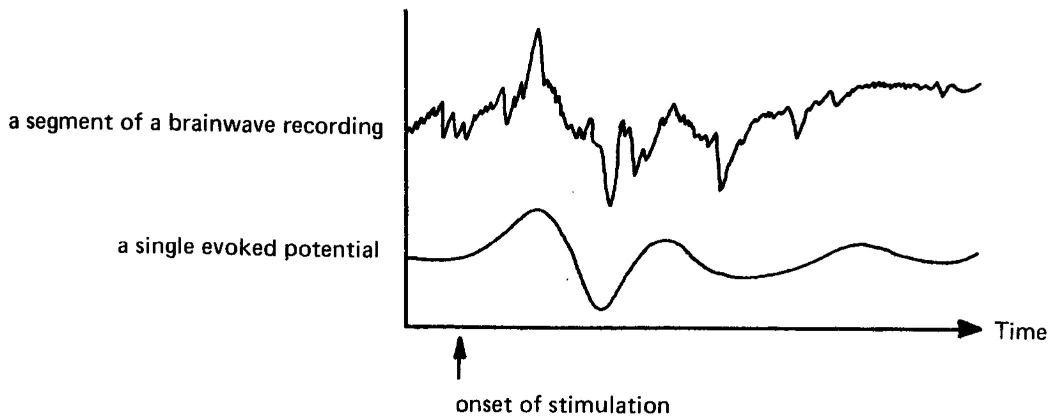
Single evoked potentials can be as much as 100 times smaller than biological "noise". Therefore, it would be useful to increase the ratio between the levels of the signal (evoked potential) and the noise to make the signal more visible.

Evoked potentials are usually defined as bioelectrical responses which begin at the onset of presentation of each stimulus. With this definition it is possible to extract representations of evoked potentials by adding together equal segments of brainwave recordings which start at the onsets of several presentations of a stimulus. Although this is basically a summation of waveforms, the representative waveform that results is called an *averaged evoked potential.* The reasons for this will become clear as "averaging" is discussed further.

The effect of summing several segments of brainwave recordings is to enhance features which are common to all samples and to repress transient features. The sum of randomly chosen segments of a non-periodic process tends toward zero, so the sum of the biological noise which is defined as irregular bioelectrical activity that correlates little or not at all with the presentation of stimuli, tends toward zero. The sum of regularly chosen "in phase" (this describes cyclical processes which are in the same part of their cycles; antonym: "out of phase") segments of a periodic process tends toward infinity, so the sum of regular bioelectrical activity that correlates well with the presentation of stimuli, tends toward infinity. Therefore, as more samples are added together, the consistent features become more prominent and the inconsistent features become less prominent. In fact, the ratio of the consistent to the inconsistent features increases by a factor of $\sqrt{N}$, where N represents the number of samples that are summed.

Typical Evoked Potentials

figure 3.1



The result of the summation is to produce a single waveform which represents the most consistent features of many samples of brainwaves. Therefore, it is a statistically-derived result which represents the prominent contributions of many samples, so it is a form of average. The "average" does not necessarily represent "N" identical evoked potentials, because slight and irregular differences between individual evoked potentials would be "averaged out" by tending toward zero in the process of summation. The average does represent the general features of many evoked potentials and the more samples of brainwaves that contribute to a regular average, the less representative is the average of any individual sample.

3.13 Weighting Averaged Evoked Potentials

To increase the relevance of an averaged evoked potential to individual samples of brainwaves, one must augment the average by a method which limits the number and the distribution of samples of brainwaves. In other words, the idea is to accumulate a weighted average.

Limiting the number of samples in an average to the smallest number that permits an acceptable resolution of the averaged evoked potential in noise makes the average more representative of each sample than if a larger number of samples were averaged. The cost of this limitation is that the experimenter must accept a more complex ("noisy") waveform than if it was made by adding more samples. However, this cost can be justified by the appearance of short term changes in the evoked potentials that would otherwise have been lost in an average made from many more samples.

The limited number of samples per average could be considered as a window of fixed dimensions through which evoked potentials can be observed. Observations are more obscure with a smaller window. However, observations through a smaller window are focused more on a small space and lead to more detailed descriptions of the contents of that space. To compare one small space with other small spaces, a person could move the window.

In other words, by limiting the number of samples per average to a fixed number, averages are obtained which represent only a small part of a large distribution of samples.

Weighted averaging is actually what is done in special purpose computers which distribute successive inputs of waveforms across a single series of capacitors to form a sequence of voltages that represents an averaged waveform. This point will be reviewed in a section of chapter 4.0 entitled *Using a Special Purpose Computer-averager.*

Weighted averaging can be done on a general purpose computer. Since a valuable use for weighting averaged evoked potentials is to determine the trend of changes in the most recent samples of brainwaves, weighted "averaging" can be done by summing a fixed number of the most recent samples. Therefore, when each new input is received, the oldest sample in memory is discarded. Consequently, the weighted average reflects only the most recent inputs.

Another method of weighting an average is to multiply each new input that is added to an "average" by a given number β for $0 < \beta < 1$ and to multiply the existing "average" by the factor $(1 - \beta)$. This method is discussed in a section of Chapter 4.0 entitled *Using a General Purpose Computer.*

3.2 Cerebral Evoked Potentials and Sensory Perception

Brainwaves are not well understood.

The sources of brainwaves are neurons in the brain. Neurons fire only in discrete impulses, but brainwave recordings are smooth waveforms. There are no adequate explanations.

Under some circumstances "a smooth increase in a stimulus produce(s) finite jumps in perception" (Stevens, 1972, parentheses added), but under different circumstances they do not (Corso, 1973). This fundamental issue is not resolved and has not been illustrated with brainwave studies.

"At progressively higher levels in the sensory pathways information about the physical stimulus is carried by progressivelv fewer active neurons." (Barlow, 1972). Despite the simple logic of this supposition, studies on the electrophysiological concomitants of perception have not proven that it is valid. Nor have they explained the impression people have of being aware of physical events as they happen. In fact, the activation of the highest level of perception, conscious awareness, follows the occurrence of physical events by as much as 3 / 10 of a second.

Clearly, more information is obtained from simultaneous recordings of brainwaves from various positions on the scalp than single channel recordings (Vaughan and Ritter, 1969; Squires et al, 1975b). Techniques for extracting this information have been known for more than a decade (Clynes, 1965; Remond, 1965). However, few experiments have employed them. Further use of such techniques might foster a greater understanding of brainwaves.

Some relationships between brainwaves and perception are more or less understood. Thousands of experiments on evoked potentials are reported in scientific journals. They give scattered facts from what appears to be a very unsystematic approach to relating brainwaves and perception. Some of these discoveries are summarized in this section.

Tests of the thesis that evoked potential feedback might be used for perceptual fine-tuning could be done in several sensory modalities. In this paper, emphasis is placed on providing a detailed discussion of one sensory modality — auditory perception. This discussion is led toward the formation of recommendations for testing the predicted effects of evoked potential feedback on auditory evoked potentials and pitch judgment.

3.21 Auditory Perception

Auditory perception involves the detection and the analysis of sound. Sound is the sensation induced by waves of pressure in a medium. These waves of alternating high and low pressure radiate in all directions from a vibrating source like ripples spreading outward from a disturbance on water. The farther the waves spread from their source the weaker they become, until they disappear.

A simple auditory stimulus that is used in research on perception, such as short burst of sinusoidal tone can be completely described by three parameters: frequency, intensity, time.

Frequency is the number of complete repetitions of a sound wave in a given period of time. The unit for describing the frequency of sound is the hertz (abbreviated Hz) which is equal to one complete wave in one second or one cycle per second.

A sine tone consists of a single frequency. It is often used in auditory research because of its purity and physical simplicity. More complex sounds are also used, such as sawtooth, triangle and pulse waveforms, "white" or filtered *noise* — a hissing sound with equal probabilities that every audible frequency will occur — and speech sounds.

Intensity refers to the amplitude of the waves of pressure which cause the sensation of sound. It is measured in logarithmic units called decibels (abbreviated dB) relative to a reference value.

Time is used to measure the rate of repetition of sound waves, the rate of change of chunks of sound that are perceived as separate events and the phase relationships between frequencies in a complex sound.

Combinations of frequency, intensity and time describe several complex properties of auditory stimuli including (see figure 3.2):

a priori signal probability: the chance that a particular stimulus will be presented at any given moment;

envelope: the shape of the distribution of intensities of a stimulus including ONSET (rise time), OFFSET (fall time) and DURATION (on time);

information content: the novelty of a stimulus in a sequence of stimuli;

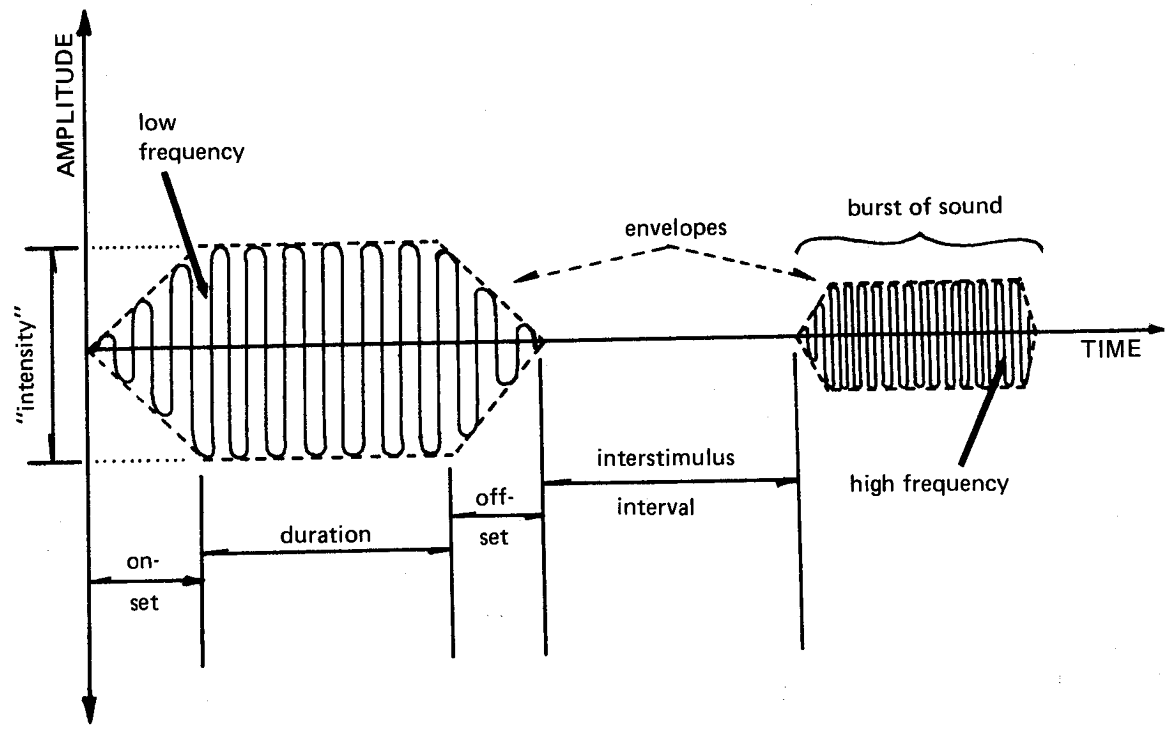
interstimulus interval: the period of time between stimuli which are physically separate;

rate of presentation: the number of stimuli that are presented in a given period of time.

Sound, the perception of auditory stimuli, is not a simple derivative of the physical properties of sound. For instance, pitch is a sensation which is primarily a function of frequency, but is also a function of the intensity and the duration of a stimulus. Also, the sensation of loudness depends primarily upon the intensity, but also the frequency and complexity of a stimulus, as well as the context in which the stimulus is heard. Auditory thresholds, spatial location of sound sources, tonality, consonance and dissonance, the perception of sequence and auditory memory are

An Illustration of Stimulus Properties

figure 3.2



complex aspects of auditory perception which are limited in their accuracy by the variability of the pitch and the loudness of physically identical stimuli.

Sound can be perceived by bone conduction or the activation of resonant cavities. However, most auditory information is received by the outer ear. The ear is a complex transducer for converting sound waves into neural impulses.

Waves of pressure of auditory stimuli set up mechanical motions of the eardrum, the bones in the middle ear and fluid in the inner ear. Motion in the fluid excites receptors to generate neural impulses. The specialized receptors are distributed along a canal. As vibrations in the fluid disturb the walls of the canal, single receptors fire in response to the presence of specific frequencies and amplitudes of vibration.

What happens after the ear sends impulses to the brain and before auditory evoked potentials are recorded is uncertain. Sayers et al (1974) propose one theory after finding that the results of integrating pre-stimulus brainwaves where no response occurs and the results of integrating post-stimulus brainwaves where evoked potentials occur are equivalent. This suggests that impulses from the ear do not add new activity to existing activity. Instead, the impulses probably exert phase-control on spontaneous biological activity in the brain. This idea is consistent with the biofeedback model of perception. However, it remains untested.

The neural impulses from each ear travel to both sides of the brain, but this is not an equal partitioning of information. High amplitude auditory evoked potentials are recorded from the hemisphere of the brain that is opposite to the ear that is being stimulated. Low amplitudes are recorded from the same side as the stimulated ear (Andreassi, 1975). In right-handed people auditory evoked potentials from verbal sounds are larger in thc left hemisphere than in the right hemisphere (Morrell and Salamy, 1971; Matsumiya et al, 1972).

Despite the inequalities in the partitioning of auditory information in the brain, there is a substantial overlap of information in each hemisphere. An interesting technique may permit studies to be performed exclusively on this overlap. Kubovy (1974) reports that the result of playing white noise to one ear and similar noise, except with a small range of frequencies delayed to the other ear, is to hear those delayed frequencies. This is remarkable since those frequencies are not heard in isolation by either ear alone. This is a newly discovered parallel between auditory processing and visual processing (Julesz, 1971) which warrants electrophysiological examination.

3.22 Effects of Stimulus Properties on Auditory Evoked Potentials

This section reviews how the physical properties of stimuli and the waveforms of auditory evoked potentials correlate. The properties that are discussed are: a priori signal probability; duration; frequency; intensity; interstimulus interval; onset and offset; rate of presentation.

a priori signal probability

A stimulus that is repeated in a predictable manner generally elicits evoked potentials which decrease in amplitude as more stimuli are presented (Ritter et al, 1968; Fruhstorfer et al, 1970; Weber, 1970; Weber and Dybka, 1973).

Random sequences of stimuli usually elicit higher amplitudes in auditory evoked potentials than simply patterned sequences (Weber and Dybka, 1973; Wilkinson and Ashby, 1974).

The effects of a priori signal probability are explained by short term and long term habituation. Irregular variations in the frequency of stimuli enhance the amplitudes of auditory evoked potentials by defeating habituation (Butler, 1968). However, after exposure to long sequences of stimuli, the effects of changing the probability that a signal will occur in a given trial diminishes.

duration

Rose et al (1969) tested the effects of the duration of auditory stimuli on evoked potentials. They found that for subjects who are paying attention to stimuli, durations in the range of 30 milliseconds to 300 milliseconds did not affect either amplitudes or latencies of auditory evoked potentials.

frequency

Generally, with stimuli of equal loudness, evoked potential amplitudes decrease as the frequencies of auditory stimuli increase (Davis et al, 1968; Rothman, 1970; Antinoro et al, 1969). However, Antinoro et al (1969) noted that increasing the intensity of stimuli reliably causes increases in the amplitude of evoked potentials only for frequencies of sounds of 2000 Hz and below. This relationship does not hold above 2000 Hz.

intensity

Generally, with an increase in the intensity of stimuli the amplitudes of auditory evoked potentials increase to a limit at high intensities (Davis and Zerlin, 1966; Rothman and Davis, 1969; Antinoro et al, 1969; Picton et al, 1974).

Benson and Teas (1972) showed that the change in amplitude that is due to a change in intensity is not uniform in all components of the auditory evoked potentials. The N_{100} component (a negative volley around 100 milliseconds after the beginning of a stimulus) changes more than other components. Data that was published earlier verifies this (Henry and Teas, 1968). Also, waveforms reported in recent publication (Picton et al, 1974) are consistent with Benson and Teas' discovery.

In a study when subjects gave constant attention (or inattention) to stimuli, components around 120 milliseconds showed smaller effects for changes in intensity (40 to 70 dB) than components around 170 milliseconds (Schecter and Buchsbaum, 1973). Therefore, higher intensity sounds elicit larger evoked potentials than lower intensity sounds, but some components of the evoked potential waveforms are affected more than others.

The P_{300} component (a positive volley around 300 milliseconds after the beginning of a stimulus) does not appear to be affected by changes in the intensity of stimuli. Benson and Teas (1972) report that P_{300} is not affected by changes from 0 to 6 dB above sensation levels. They also note that the same result was obtained with an intensity of 40 dB by Wilkinson and Morlock (1967), 75 dB by Sheatz and Chapman (1969) and 82 dB by Smith et al (1970). Furthermore, several authors report that P_{300} is elicited in the absence of expected stimuli (Barlow et al, 1967; Sutton et al, 1967; Kinke et al, 1968; Garcia Austt, 1969; Weinberg et al, 1970; Ruchkin and Sutton, 1973; Picton et al, 1974; Pitcon and Hillyard, 1974). Except in an isolated case (Tanis, 1972), P_{300} is not influenced by changes in the intensity of stimuli.

In summary, the intensity of stimuli seems to be an important influence on evoked potentials up to 200 milliseconds after the presentation of stimuli. However, intensity does not influence evoked potentials after 200 milliseconds. Therefore, experiments on evoked potential feedback which use the amplitude of P_{300} as a criterion for reinforcement can be performed equally well with stimuli of low and high intensities.

Techniques for standardizing the intensities of stimuli (auditory, kinesthetic, thermal and visual) are summarized in *Stimulus Intensity and Stimulus Intensity Control* (Silverman et al, 1969). W.R. Goff (on page 139 in Thompson and Patterson, 1974) warns that a continuous tone of 70 dB above sensation level may be painful. An absolute intensity of 90 dB can cause permanent injury if it is in the range of frequencies between 1kHz and 8kHz, but more intense sounds outside this range can be sustained without injury. This illustrates the non-linearity of hearing. Allowance for this non-uniformity must be made when the intensity of sound is measured. This is done by using sound-level meters that are equipped with an "A" filter which imitates the sensitivity of humans to the intensity of sounds of various frequencies. Readings obtained with such meters are expressed in dB(A), the letter in the bracket naming the filter used.

interstimulus interval

Davis et al (1966) found that the maximum amplitude for an auditory evoked potential is obtained with intervals of six to ten seconds between stimuli. However, they note that such long intervals would make the collection of data hopelessly tedious. Therefore, intervals of one to three seconds would suffice if a reduction in the amplitudes of evoked potentials can be tolerated.

Davis et al (1966) found the reductions in amplitude of auditory evoked potentials with reduced interstimulus intervals to be graded. Therefore, if an experimental design requires the randomization of interstimulus intervals, then the intervals must exceed six seconds to avoid biasing the data. Irregular intervals generally enhance amplitudes of responses (Rothman and Davis, (1969).

Nelson and Lassman (1968) tested for effects of using intervals between .25 and 10.0 seconds. They found little difference in the latencies of components of the auditory evoked potentials up to 200 milliseconds and no consistent changes in latency afterwards. However, the amplitude of components up to 200 milliseconds increased gradually as a function of increasing the interstimulus interval, but the amplitudes were never as large as those reported by Davis et al (1966).

onset and offset of stimuli

If a stimulus is abruptly switched on or off, a transient pulse may appear. It can sound like a very loud click and it might occur both at the beginning and the end of the presentation of a single stimulus, giving a complex sensation (Milner, 1970 — cited in Regan, 1972, page 164).

To avoid switching transients, electronic circuits are used to shape the envelope of individual stimuli. Schweitzer and Tepas (1974) used stimuli with 10 milliseconds of rise and fall time to analyze evoked potentials from onsets and offsets of stimuli. They found that the responses are similar and that they are both sensitive to the intensity of stimuli. Differences between the responses suggest that they are generated by different physiological processes. For stimuli of short durations it seems that "on" and "off" responses interact.

Generally, the "off" responses due to acoustic transients from sudden fall times are smaller in amplitude than the "on" response (Onishi and Davis, 1968; Schweitzer and Tepas, 1974). The "off" response can occur for fall times up to 100 milliseconds in duration (Davis and Zerlin, 1966). Long fall and rise times are needed to avoid contamination of evoked potential recordings when the content of the stimulus, rather than the abruptness of its presentation, is intended to be the independent variable in experiments.

For stimuli which do not entirely drop to an amplitude of zero in the interstimulus interval, it is usually considered that the interstimulus interval starts and stops when the preceding and the following stimuli are at a small fraction of their total amplitudes (for example, 10 percent — from Davis and Zerlin, 1966; Nelson and Lassman, 1968).

rate of presentation

Both the sensation of loudness and the amplitude of auditory evoked potentials depend upon the rate of presentation of stimuli. Generally, increased loudness and increased amplitudes are associated with slow rates (less than 1 per 10 seconds) and decreased loudness and decreased amplitudes with fast rates (Davis et al, 1966; Milner; 1970 — cited in Regan, 1972, page 164).

Goldstein et al (1972) studied the effects of very fast rates of presentation of stimuli (1 to 15 per second) on auditory evoked potentials. Generally, the amplitudes of responses showed no systematic differences due to the rates of stimulation.

3.23 Effects of Psychological Variables on Cerebral Evoked Potentials

This section presents a framework for organizing various psychological factors which are known to influence the waveforms of cerebral evoked potentials. Although the results of some experiments will be discussed, this section is not intended to be an exhaustive review. Rather, it is intended to be a systematic treatment of a wide variety of factors which must be considered in planning the design of an experiment that will adequately test relevant features and account for irrelevant features of evoked potential feedback.

There are correlations between some measures of the psychological effect of certain stimuli and some features of the waveform of cerebral evoked potentials. These correlations are discussed in detail in publications by Naatanen (1967); Donchin and Lindsley (1969); Karlin (1970); Regan (1972); Shagass (1972); Kornblum (1973); McCallum and Knott (1973); Picton and Hillyard (1974); Naatanen (1975). Their discussions are complex and at times contradictory. Only the most prominent and reported findings will be reviewed here.

In general, later components of the waveforms of evoked potentials are more affected by psychological variables than earlier components. Components which occur before an interval of time or "latency" of 200 milliseconds (approximately) are primarily influenced by the physical properties of a stimulus. Some of the physical properties of stimuli that correlate with the waveforms of evoked potentials are discussed in section 3.21. After a latency of 200 milliseconds, components of evoked potentials are primarily influenced by psychological variables (Picton and Hillyard, 1974).

The discussion in this section is centered around the component of cerebral evoked potentials called P_{300}, a positive volley around 300 milliseconds after the presentation of a stimulus. Evidence from hundreds of experiments (145 are listed by Price and Smith, 1974) show that P_{300} is a sensitive index of psychological variables that affect a person's ability to respond to particular signals. Therefore, P_{300} is discussed in preparation for using it in a biofeedback experiment designed to modify a person's ability to make perceptual judgments.

The psychological variables that will be discussed are: attention; decision-making; information; nonspecific influences; psychological set. Some of these categories overlap slightly, and all depend on the perception of the physical properties of a stimulus (reviewed in section 3.21).

Before discussing each category, it is appropriate to review some general features of P_{300}. P_{300} has only been reported in humans. It is sometimes called P_3 (for example in Picton et al, 1974), because it is usually the third positive volley in the waveform of an averaged evoked potential that is calculated from samples of brainwaves that are recorded during 300 to 700 milliseconds after stimulation. The amplitude of P_{300} is sometimes a peak-to-peak measure, meaning that it represents the voltage between the most positive excursion in the region of 300 milliseconds and the most negative excursion of the negative volley which precedes P_{300}. Otherwise, P_{300} is measured with reference to an arbitrary baseline that is chosen by the experimenter. The amplitude of P_{300} can be increased or decreased by manipulating a subject's task or by manipulating the context in which stimuli are presented, but P_{300} is not significantly changed by altering the physical properties of a stimulus (Donchin et al, 1973).

P_{300} is well-documented as an index of the prominence, significance or salience to a person of a given stimulus. It was chosen as a topic for review here, because it illustrates a typical parameter that might be used in biofeedback experiments to influence perception. Other components of cerebral evoked potentials may be as suitable and perhaps better than P_{300}. For instance, N_{100} has been proposed as a measure of the extent to which a person can "tune in" his attention to one of several simultaneous sounds (Schwent and Hillyard, 1975). Also, N_{100} is postulated to reflect the amount of information (stored and incoming) that is used in making decisions after a stimulus is perceived (Squires et all, 1973b). However, P_{300} is known to reflect psychological variables much better than does N_{100}. Another example is contingent negative variation (CNV), a gradual negative shift in the voltage of a waveform. CNV has been proposed as a measure of the accuracy of perceptual judgment (McAdam and Rubin, 1971). However, P_{300} has more consistently been reported in association with correct detections of appropriate signals than CNV. "Desynchronized" (non-alpha) brainwaves are a well-known sign of attention (Plotkin, 1976). Perhaps they may be fedback to a subject to "keep him on track". However, preliminary evidence shows that the effect of alpha biofeedback on perception is unpredictable and variable, if an effect is found at all.

For a completely different electrophysiological index of the "significance" that a perceptual event connotes, consider pupillary dilation. Like the amplitude of P_{300}, pupillary dilation is related to both the accuracy of signal detection and the probability of occurrence of a signal on each trial (Friedman et al, 1973). However, it may be more sensitive in the visual modality than in other perceptual modalities and it is more difficult to monitor than EEG signals.

The drawbacks in considering the amplitude of P_{300} as a criterion for reinforcement in a biofeedback experiment are that it occurs in a wide range of latencies around 300 milliseconds (within 270 to 550 milliseconds), it occurs long after a decision about a stimulus is made (Naatanen, 1975), there are large differences in the amplitude of P_{300} between different subjects and it is not known exaclty what P_{300} represents, although it is widely held to be part of an orienting response (Ritter et al, 1968; Friedman et al, 1973; Roth, 1973; Roth and Kopell, 1973; Naatanen, 1975). Despite the drawbacks, P_{300} is the best choice among electrophysiological indices of perceptual processing to be used in biofeedback experiments that are intended to train a person to improve the reliability of his perceptual judgment.

attention

Many reports claim to show evoked potential correlates of an independent variable called attention. However, few reports have controlled for nonspecific influences (discussed separately). Generally, the change in evoked potentials when a person pays attention to a stimulus is an increase in amplitude. The amount of change in the amplitude varies in single subjects and between different subjects. In more than 70 percent of people the change exceeds 10 percent (Satterfield, 1965) and can be as large as 138 percent (Schwent and Hilyard, 1975).

Evidence concerning the effects on evoked potentials of distracting a person's attention is inconclusive. When a person's attention is diverted from stimuli by tasks such as reading or attending to other stimuli, smaller amplitudes in evoked potentials of shorter duration have been recorded compared with evoked potentials from tasks such as counting stimuli or recognizing them (Gross et al, 1965; Spong et al, 1965; Ford et al, 1976). However, Cody and Townsend (1973) found that the waveforms of evoked potentials did not change when subjects were distracted. Perhaps this confusion can be resolved by re-examining a relationship that was discovered by Tanis (1972), who reported that "listening intently" and "reading" while stimuli are presented have equally little effect on evoked potentials for intense stimuli. However, "listening intently" elicits a larger amplitude at N_{100} than "reading" for weak stimuli.

When a person follows the instruction to listen to one message while two different messages are presented simultaneously, one to each ear, then his memory for the message on the non-attended side is very poor. Furthermore, evoked potentials in the hemisphere of the brain opposite to the non-attended side are much smaller in amplitude than those in the other hemisphere of the brain that occur in response to attended stimuli (Picton et al, 1971; Hillyard et al, 1973; Robinson and Sabat, 1975; Schwent and Hillyard, 1975).

The P_{300} component of auditory evoked potentials is bigger in amplitude when a subject attends to a stimulus (Hillyard et al, 1973; Picton and Hillyard, 1974; Naatanen, 1975). Attention towards a stimulus and the P_{300} amplitude can be increased or decreased by manipulating a subject's task or the context in which a stimulus is perceived, P_{300} is not significantly changed by the properties of a stimulus.

decision-making

Waveforms of cerebral evoked potentials differ when different decisions are made following stimulation. Such factors as the difficulty of making a decision, the degree of rigor needed for a decision, the time needed to make a decision, the confidence with which a decision is made and the reliability (both in accuracy and in precision) of decisions have been studied. To some extent these factors influence the general state of a person by making him more or less anxious and aroused. Such effects are discussed separately as nonspecific influences on perception.

In this section the specific effects of decision-making on the perception of stimuli and the accompanying cerebral evoked potentials will be discussed. For instance, when a stimulus triggers the performance of a task, the more complex the task, the larger the evoked potential it elicits (Lindsley et al, 1974).

The difficulty of a task in evoked potential studies is determined by what a person must do when a stimulus is presented. Basically, three degrees of rigor can be identified. The simplest variety of tasks requires the *detection* of a stimulus. In the next variety of tasks, the subject is required to recognize a stimulus. *Recognition* is more complex than detection because the subject must recall a particular state to notice a change in state. Discrimination, estimation and differentiation are also forms of recognition. The most complex task involves the *indentification* of a stimulus, meaning that the unique label which describes a stimulus is required.

It may be argued that recognition and identification are equally complex, because they both involve a comparison between incoming sensory information and stored information in memory. However, as most readers who have "crammed for an exam" would agree, it is easier to "recognize" the answers to questions from word "cues" than to "identify" the answers by associating sophisticated concepts in questions and in memory.

Apparently no studies have been reported on the effects on evoked potentials of varying the rigor of the task as an independent variable. However, each level has been studied independently.

The format of signal detection experiments is given in section 4.11. Using this format it has been discovered that the amplitude of the P_{300} component of cerebral evoked potentials is larger for correct detections of an appropriate signal than for correct rejections of inappropriate stimuli, false alarms for inappropriate stimuli or failure to detect appropriate signals (Haider et al, 1964; Hillyard et al, 1971; Tueting et al, 1971; Paul and Sutton, 1972; Squires et al, 1973b; Squires et al, 1975). Also, the amplitude of P_{300} is graded for varieties of stimuli. As mentioned above, P_{300} is largest for stimuli that are sought in a task and then indicated as having been perceived (signals). P_{300} is smaller for non-signals in the same sensory modality as the signals. P_{300} is smallest for signals in different sensory modalities (Jenness, 1972; Ford et al, 1973).

The format of signal-recognition experiments is similar to the format of signal-detection experiments with changes that are reviewed in section 4.25. When changes in signals are recognized, they elicit large amplitudes at P_{300}, but unrecognized changes, false recognitions and correct omissions of unchanged stimuli do not elicit large amplitudes at P_{300}, (Ritter and Vaughan, 1969; Vaughan and Ritter, 1969; Jenness, 1970, 1972; Ford et al, 1973, 1976). However, there is some doubt concerning the reliability of the enhancement of P_{300}. It is not always evident (Hirsh, 1971; Ford et al, 1976).

As the reference for comparison or "anchor" in a task of judging the pitch of stimuli becomes increasingly distant from the pitches being judged, it elicits successively smaller evoked potentials (Sarris and Haider, 1970). With increasing accuracy from practise in judging whether two tones are of equal pitch, P_{300} and later components elicited by identical stimuli become increasingly large (Jenness, 1972; Delse et al, 1972).

P_{300} is enlarged when a stimulus triggers problem-solving (Wilson et al, 1973). The harder the problem, such as discriminating between tones that are close in frequency, the larger the P_{300} that they elicit (Ritter et al, 1972). However, when pitch discrimination is made easier by arranging a different spatial location for the source of each tone, evoked potential amplitudes are enhanced at a shorter latency (N_{100}) than without such an arrangement (Vincent and Hillyard, 1975). Presumably, the time needed to make the decisions was reduced, so the amplitude was enhanced earlier.

The format of signal-identification experiments is similar to that of signal-recognition experiments. No such studies have been performed on pitch judgment while evoked potentials were being recorded. Pitch identification is reviewed in sections 4.23 and 4.24.

As the level of rigor is increased, presumably the spread of reaction time for indicating a decision would increase. Preliminary evidence supports this idea (Bostock and Jarvis, 1970).

Some experimenters have compared the confidence that a person expresses about a decision and evoked potentials. Confidence can be manipulated by varying the probability that a stimulus will occur on a given trial (discussed under psychological set), the strictness of criteria for responding accurately (discussed under psychological set), the duration or the intensity of a stimulus and the speed with which a response must be indicated by the person that is being tested. Placing demands on the speed of responding can contaminate evoked potentials at the latency of P_{300} (Bostock and Jarvis, 1970), but special techniques for the registration of responses can reduce the latency of contamination to less than 50 milliseconds after stimulation (Wilkinson and Morlock, 1967; McGuigan and Boness, 1975). A new technique (Navon, 1975) is available for assessing a subject's confidence in responding by ranking reaction times. This technique does not involve the use of rating-scales or ROC (receiver-operating-characteristic) curves from signal-detection theory (Green and Swets, 1966).

Confidence about a response is associated with larger CNV than doubt about a response, but McAdam and Rubin (1971) did not find any similar effects at P_{300}. Their subjects triggered each presentation of the stimulus themselves while the experimenters varied the duration of the stimuli. The lack of a correlation between P_{300} and confidence was conditionally confirmed in the following study.

When the intensity of a stimulus affects confidence in responding, there are different effects for near-threshold and supra-threshold stimuli. Evidently, confidence is a more important determinant of the enhancement of P_{300} for near-threshold signals than for supra-threshold signals (Squires et al, 1975b). Furthermore, the distributions of P_{300} from an array of recordings from different locations on the scalp indicates that there is parallel processing for orientating and decision-making in different areas of the brain (Squires et al, 1975b). Therefore, P_{300} appears to reflect a variety of psychological processes.

An interesting group of experiments has been performed on subjects who were very confident that there had been no change in a stimulus, despite a subtle change. Such studies of the recognition of change in the short term provide evidence that "subliminal" changes in stimuli produce cerebral evoked potentials which reflect those changes, although the perceiver is unaware of such changes (Shevrin and Fritzler, 1968; Shevrin et al, 1971; Schwartz and Rem, 1975; Shevrin, 1975). This evidence, along with evidence that P_{300} is not always a reliable index of the presentation of a significant stimulus (see section 3.22) suggests that there may be room for improvement in human perceptual judgment that is reflected in this electrophysiological parameter. It is not known how P_{300} – contingent feedback might affect perceptual judgment, but it may improve perceptual judgement and its effects may be different from those of operant feedback that confirms or disconfirms a subject's responses (Squires et al, 1973a).

Information

A person perceives different stimuli to different extents. He may only detect their physical presence. He may decide to initiate evasive actions, because the stimuli are irritating. However, the most sophisticated level of perception determines the identity of stimuli. Correlates in evoked potentials of stimulus-identification have been found.

Evidence suggests that there are at least two aspects of the identification of a stimulus that might be distinguished with evoked potentials. One is the recognition of the salience of a stimulus; a quantitative assessment of information that is part of the orientating response. Another is the recognition of the meaning of a stimulus: a qualitative assessment of information.

Stimuli are salient when there is a large contrast between the stimuli and the contexts in which they are perceived. The salience or "prominence" of sensations is a function of the *rate of change* in a stimulus or the *extent of change* between a stimulus and its context. Fast rates of change, for example, can startle a person when they violate a person's psychological inertia or "set". The effects of set on evoked potentials will be discussed separately.

The extent of change between a stimulus and the context (that is, contrast) is a measure of the information that the stimulus provides. With a greater change, the stimulus is more salient; with a smaller change less salient. This relationship is reflected in the amplitude of evoked potentials. They are generally large for salient stimuli, such as a person's own name, and small for plain stimuli, such as the word "the".

Stimuli are meaningful when a person goes beyond detecting a stimulus to recognizing or identifying it. Detection, recognition and identification are three levels of rigor in the interpretation of a stimulus. Some experiments have examined evoked potential correlates of each level independently. Such experiments are reviewed under the heading of decision-making. No experiments have examined the evoked potential correlates of systematically varying the levels of rigor in the interpretation of a stimulus.

Although few authors have clearly distinguished between qualitative and quantitative aspects of the information of stimuli that they have used to elicit evoked potentials, some of their findings deserve mention.

The following results appear to reflect the influences on evoked potentials of the quantity of information that a stimulus conveys to a person.

Complex stimuli generally elicit larger evoked potentials than simple stimuli (Chapman and Bragdon, 1964; Begleiter and Platz, 1969).

When a person knows what a stimulus will be, but not when it will be presented, the stimulus is more informative and elicits larger evoked potentials (especially at P_{300}) than known stimuli that occur at expected times (Sutton et al, 1967; Klinke et al, 1968). However, P_{300} enhancement is not simply a function of predictability (Corby and Kopell, 1974).

Evoked potentials do not decrease in amplitude for interstimulus intervals that are longer than ten seconds. However, for shorter intervals the amplitudes do decrease (Davis et al, 1966; Klinke et al, 1968; Ritter, 1968; Fruhstorfer, 1971).

When a stimulus provides the last bit of essential information to complete a person's understanding of a problem before he can make a decision with certainty, regardless of the specific nature of the problem, that stimulus elicits larger P_{300} than other bits of information (Shelburne, 1972; Squires et al, 1973a). Also, CNV increases (Delse et al, 1972).

As the difference between a stimulus and its context is increased, the amplitude of the evoked potential which it elicits also increases. (Adams and Benson, 1973).

The following conclusions appear to reflect influences on evoked potentials of the quality of information that a stimulus conveys.

Stimuli which are identical, but which elicit different perceptions due to experimental manipulations, have been shown to elicit different evoked potentials (Begleiter and Platz, 1969). For example, when a person recognizes a word, different evoked potentials are elicited than if he does not recognize the word (Rubin and McAdam, 1971). A similar result is obtained when the stimuli that are used convey similar amounts of information, but slightly different types of information. For example, sounds which are distinctly verbal and non-verbal elicit large responses on different sides of the brain (Matsymiya et al, 1972). However, some evoked potentials have not been found to distinguish words from nonsense syllables (Roth et al, 1970; Shelburne, 1972). Also, Jenness (1972) found differences in evoked potentials which accompany different responses in a task to discriminate higher pitch clicks from lower pitch clicks. In another experiment in which similar stimuli convey different meanings, clicks were heard by a subject after each performance in an auditory recognition task to confirm or to disconfirm each performance. Confirming signals elicited small smplitudes at P_{300}. Disconfirming signals elicited graded amplitudes at P_{300} which increased as the subject expressed increasing confidence about being correct in his response (Squires et al, 1973a).

When evoked potentials for perceptually different signals are compared as a person tries to detect one of the signals, the one that he seeks, which is task-relevant, generally elicits larger evoked potentials than irrelevant signals (Chapman and Bragdon, 1964; Sutton et al, 1967; Donchin and Lindsley, 1969; Sheatz and Chapman, 1969). However, the relevance of a stimulus is not always reflected by large evoked potentials, particularly when randomized presentations of stimuli are used (Naatanen, 1967; Hartley, 1970).

Late components (Later than approximately 200 milliseconds) of the waveforms of evoked potentials can show consistent differences when there are differences in the contexts in which identical stimuli are perceived, particularly when the stimuli are ambiguous. Different meanings can be favored when each stimulus is presented in different contexts. Such differences are reflected in evoked potentials (Johnson and Chesney, 1974).

When the omission of a stimulus provides a subject with task relevant information, P_{300} is elicited. The recording of evoked potentials for omitted stimuli show the effects of set (discussed separately), memory and estimation of time (Barlow et al, 1967; Sutton et al, 1967; Klinke et al, 1968; Garcia Austt, 1969; Weinberg et al, 1970; Ruchin and Sutton, 1973; Picton and Hillyard, 1974; Picton et al, 1974a)..

It is difficult to distinguish between task-relevant and task-irrevelant stimuli in some experiments. If the stimulus that is sought (signal) by a subject is presented randomly, then the occurrence of every stimulus provides task-relevant information. However, if stimuli are presented in a predictable manner, then signals are task-relevant and non-signals are not (Wilkinson and Ashby, 1974).

The P_{300} component of evoked potentials is a feature that is most often discussed in references to the significance of a stimulus (salience of prominence). For purposes in this paper, significance will refer to both qualitative and quantitative aspects of a stimulus. Friedman et al (1973) concluded that anything which increases the significance of a stimulus enhances the amplitude of P_{300}.

In 1967 Sutton et al proposed that fine discriminations between more or less significant stimuli might be made using the amplitude of P_{300} as an index. Ilecki (1974) reported using *"The Auditory Evoked Response as an Index of Differentiation of Complex Auditory Stimuli"*, the title of his paper. If such electrophysiological indices of the significance of perceptual events can either be trained or be used in training, then the proposition in this thesis to use cerebral evoked potentials in biofeedback to fine-tune perceptual judgment might be illustrated by an experiment, such as the one proposed in chapter 4.0 to teach "absolute pitch".

Some recent experiments used alternative methods to the ones that have been reviewed to this point. Such alternatives may be used to test the thesis that evoked potential feedback might be used to fine-tune perceptual judgment.

In 1973, after more than twenty-five years of research, E.R. John and co-workers reported proof that there are at least two separable factors which influence the waveforms of cerebral evoked potentials. First, the incoming sensory information elicits a response which John identifies as being of "exogenous" origin. Second, the registration of sensory information triggers the readout of memories as part of the process of interpreting the sensory information. This "endogenous" activity is accompanied by unique electrical activity in the brain.

John et al (1975) presented data on single and averaged evoked potentials from trained cats. The data show changes in waveforms when different behavioral responses follow separate identical presentations of stimulus.

To obtain these responses, the cats were trained to behave in one way in response to one stimulus and to behave in another way in response to a different stimulus. When the cats were occasionally presented a stimulus with properties intermediate between the two conditioned stimuli, sometimes they responded with one behavior and sometimes the other.

Consistently different evoked potentials were recorded following each stimulus. John et al claimed that the differences were not due to nonspecific influences or psychological set. To account for the differences, John et al reasoned that the animals interpreted the identical stimuli in different ways.

The data presented by John et al in 1975 show successive changes in brainwaves from each stimulus. These changes complement the evidence that they reported in 1963 which proved that the waveforms of evoked potentials reflect the effects of incoming (afferent, exogenous) experiences and the memories of previous (efferent, endogenous, readout, stored) experience. Specifically, evidence from sorting single evoked potentials suggests that some waveforms do not depend as much upon the particular stimulus that elicits the response as the interpretation that is made of the stimulus (Bartlett et al, 1975). More research is needed. That which has been done suggests that single evoked potentials might be used in feedback training to improve perceptual judgment.

nonspecific

Some general influences on perceptual behavior and the brainwave concomitants of it are often confused with attention (Naatanen, 1975). They include activation, alertness, arousal, eye position, motivation, movement, predisposition, readiness, response bias, sensory modality, set, tasks, training methods and vigilance. These terms describe one of three influences of perception:

(1) general states of the body that change according to rhythmic changes in metabolism;

(2) influences of such states;

(3) products of such states.

All three are independent of voluntary control. Unlike such general or "nonspecific" influences on perception, attention is selective, deliberate, somewhat independent of nonspecific influences and directly related to particular stimuli.

Hillyard et al (1973) concluded that nonspecific factors of arousal do not exert such large influences on evoked potentials as specific factors, such as attention or the intensity of stimuli. However, the effects of nonspecific influences are significant.

When a person is made anxious about responding by requiring him to respond quickly in an experiment, his evoked potentials are larger than for responding at ease (Waszak and Obrist, 1969). Similarly, an increase in anxiety occurring when a subject must refrain from indicating his response in a signal-detection task, causes an increase in the amplitude of P_{300} (Karlin et al, 1970, 1971).

With habituation, a gradual decrease in a person's sensitivity to repeated stimuli, there is a slight, but stable decrease in the amplitude of evoked potentials for rates of stimulation in excess of one per ten seconds (Ritter et al, 1968; Fruhstorfer and Bergstrom, 1969; Fruhstorfer, 1970). The decrease in amplitude occurs even when the complexity or the difficulty of a subject's task is varied. It also occurs when attention is diverted from the stimuli by having a subject read. Whereas habituation occurs despite variations in interstimulus intervals for fast rates of stimulation, varying the length and the regularity of stimuli defeat habituation in the short term. Such effects can be observed in the amplitudes of evoked potentials (MacLean et al, 1975).

Evoked potential amplitudes are proportional to arousal (alertness or vigilance), the continuum from wakefulness to sleep (Wilkinson et al, 1966; Fruhstorfer and Bergstrom, 1969; Shucard and Horn, 1973). Day-to-day changes in the accuracy of signal-recognition are also systematically reflected in the amplitude of evoked potentials (Jenness, 1972).

Posture has some effect on the waveforms of evoked potentials. This is probably due to conditioned associations between lying down and resting; sitting and work; standing and action. Therefore, postural effect are probably due to arousal, but they have not been systematically studied (Fruhstorfer and Bergstrom, 1969).

Up to one second prior to a motor response, that is, a muscular contraction that occurs when a person executes a task, as in pressing a button, there is a gradual negative shift in the whole waveform of a brainwave recording called contingent negative variation (Walter et al, 1964; McAdam and Rubin, 1971; Deise et al, 1973).

When a subject's eyes are open and gazing fixedly at a small target, there is less alpha activity (continuous brainwaves of 8 to 13 Hz) and less contamination of evoked potentials than with eyes closed during the recording of evoked potentials (Waszak and Obrist, 1969). Visual inattention promotes alpha frequencies in brainwave recordings (Plotkin, 1976).

A transient perceptual experience less than one second before the presentation of a stimulus to a subject in an experiment to record evoked potentials might distort the evoked potentials considerably (Davis et al, 1972). However, the use of a drone (white noise or a tone) to mask transient stimuli does not alter evoked potentials for perceptible changes in the intensity or the frequency of auditory stimuli (Davis et al, 1968; McCandless and Rose, 1970; Nichols and Tanenholtz, 1970) except where the drone might influence factors such as arousal.

Muscular contractions in the scalp and neck have been reported to contaminate recordings of evoked potentials (Bickford et al, 1963; Bergamini and Bergamasco, 1967). Similarly, eyeblinks enhance positive components of auditory evoked potentials (Satterfield, 1965).

Ideosyncracies in perceptual styles have been suggested to be the cause of differences in evoked potentials between individuals. Schecter and Buchsbaum (1973) found that some individuals had consistent increases in the amplitudes of their evoked potentials as their performance in the experiments progressed, while others had consistent decreases.

In conclusion, the nonspecific influences on evoked potentials that have been mentioned here show the variety and the intricacy of some determinants of evoked potentials. To assure that brainwave recordings reflect psychological activity that is specific to a particular sensory event, nonspecific factors must be controlled by the experimenter to show that nonspecific, short-term changes in the state of an organism are not responsible for variations in the evoked potential data.

psychological set

The effects on the waveforms of evoked potentials due to psychological set have been attributed to such variables as anticipation, differential preparation (that is, knowing as opposed to not knowing what will happen), expectation, predictability, probability of stimulation, readiness and uncertainty. To the degree that such variables influence a person's arousal, they are nonspecific influences on evoked potentials (reviewed separately). However, this class of variables has been used as the independent variable in experiments. Therefore, it is reviewed here as a specific influence on perception and the electrophysiological concomitants of perception.

Evidence shows that a person who expects a stimulus to be presented when it is not presented generates an "evoked potential" at the time that the stimulus is expected to occur. Recordings of evoked potentials for omitted stimuli differ from recordings for stimuli which are physically present in that the early components (that is, any which occur before 200 milliseconds) are not clearly defined, but late components, such as P_{300}, are clearly elicited (Barlow et al, 1967; Sutton et al, 1967; Klinke et al, 1968; Garcia Austt, 1969; Weinberg et al, 1970; Ruchin and Sutton, 1973; Picton and Hillyard, 1974; Picton et al, 1974a).

Similarly, by manipulating a person's belief that a given stimulus will have certain characteristics, physically identical presentations of that stimulus elicit evoked potentials which consistently differ according to the belief. For instance, evoked potentials from a stimulus of medium intensity are similar to those for a very intense stimulus when a person expects such intensity. On the contrary, evoked potentials for the same stimulus of medium intensity are similar to those for a stimulus of low intensity when a person expects such intensity (Begleiter et al, 1973; Porjesz and Begleiter, 1975).

Stimuli elicit smaller evoked potentials if the person whose brainwaves are being recorded determines when the stimuli are presented than if he has no control over them. Similarly, when sequences of different stimuli are presented in repeated patterns so that each presentation can be predicted, evoked potentials for any given stimulus are smaller than if the person had difficulty predicting when identical presentations of that stimulus would be presented (Sutton et al, 1965; Tueting et al, 1971; Donchin et al, 1973; Roth, 1973; Schafer and Marcus, 1973; Weber and Dybka, 1973; Rohrbaugh et al, 1974). Specifically, the amplitude of P_{300} is the most sensitive component of evoked potentials to variations in the probability that a person can predict when a signal will occur (Tueting et al, 1971; Rohrbaugh et al, 1974). Whereas uncertainty about which one of several stimuli will be presented on a given trial may be sufficient to enhance the amplitude of P_{300}, it is not a necessary condition (Donchin et al, 1973). A necessary condition has not yet been determined.

Donchin et al's (1973) evidence is that the amplitude of P_{300} is enhanced when a subject is encouraged to respond accurately and quickly in a task to distinguish between different signals. Similarly, when identical, near-threshold (barely perceivable) or supra-threshold (distinct) stimuli are presented repeatedly while a subject's motivation to respond accurately is manupulated by changing his reward for each response, evoked potentials vary in form. In particular, the amplitude of P_{300} shows a graded increase as the subject's criterion changes from liberal or care-free to stringent or cautious (Benson and Teas, 1972; Paul and Sutton, 1972; Squires et al, 1973b). Jenness (1972) found similar results when similar, instead of identical, auditory stimuli were used. Higher demands for accuracy brought larger amplitudes at P_{300}. Optimal response biases for auditory signal-detection experiments are reviewed by Hume (1974).

When subjects are required to detect signals of near-threshold intensity, the amplitude of P_{300} is affected differently by changing the probability of occurence of a signal, than for signals which are above-threshold in intensity. The amplitude of P_{300} for threshold-level signals is independent of signaling probability (Squires et al, 1975). For above-threshold signals, the amplitude of P_{300} decreases with increasing probability that a signal will be presented on each trial (Tueting et al, 1971).

There may be different preparatory sets. One may be a sensory set which emphasizes readiness to receive sensations. Another may be a motor set which emphasizes readiness to indicate a response. These may be aspects of selective attention or separate operant behaviors (Wong, 1975). Loveless and Sanford (1974) suggest that the difference between these sets stems from the implied emphasis of instructions on the accuracy and the speed of responses. However, no changes in P_{300} were found as a result of manipulating a subject's instructions. Attempts are being made to assess the effects of suggestion on perception (Gheorghiu et al, 1975).

An electrophysiological concomitant of motor set should not be confused with P_{300}. It is contingent negative variation (CNV). CNV is a gradual negative shift of whole segments of brainwave recordings. It appears to be a voltage (direct current) displacement of the waveform. CNV preceding the presentation of an expected stimulus is large when stimulation is likely to occur. This "readiness potential" is correlated with the accuracy of performance in a recognition task (McAdam and Rubin, 1971). CNV following the presentation of a stimulus behaves similar to, but independently of, P_{300} (Walter et al, 1964; Donchin and Smith, 1970; Donald and Goff, 1971; Hillyard, 1971; McAdam and Rubin, 1971; Tecee, 1971; Kornblum, 1973; McCallum and Knott, 1973; Papahostopoulos and Crow, 1974; Donchin et al, 1975).

4.0 HOW TO TEST THE EFFECTS ON PERCEPTION OF EVOKED POTENTIAL FEEDBACK

The preceding chapters have introduced many concepts of auditory perception, biofeedback and cerebral evoked potentials. This chapter discusses the design of experiments to test the thesis that biofeedback with cerebral evoked potentials might be used to fine-tune perceptual judgment. In particular, methods are discussed for using feedback of auditory evoked potentials in training a person to have unusually reliable judgment of pitch ("absolute pitch").

4.10 Techniques in Evoked Potential Research

The first section of this chapter reviews some techniques that have been used by researchers to study the evoked potentials correlates of behavior. Since there is not a single, "standard" method in evoked potential research, twenty-eight experimental designs are reviewed from research that resembles the sort of work that must be done to test this thesis, to assist in determining how to design a good experiment.

4.11 The Signal Detection Format

In order to study event-related, bioelectrical activity, researchers have devised a class of experiments to systematically present stimuli and to examine a person's responses to such stimuli. The experiments are called signal-detection, signal-differentiation, signal-discrimination, signal-estimation, signal-recognition or signal-identification experiments. They are variations of one experimental format that is discussed in detail by Green and Swets (1966).

Briefly, a signal-detection experiment involves the presentation of a sequence of stimuli to a person. The stimuli must be physically discrete events, although they may be perceptually alike, meaning near-threshold. Sometimes the stimuli are identical, but usually they are different. When different stimuli are used, they may be presented in patterns which are more or less difficult to remember, ranging from regularly alternating pairs to practically random sequences of large varieties of stimuli. The task that the subject must perform is to indicate when he notices a particular sensation.

A person is usually given only one "momentary-contact" pushbutton with which to indicate his response. This gives a binary choice, on or off. These two choices produce four categories of responses; correct rejection; false alarm; hit; miss. These categories are not as complex as they might sound.

When a *signal* (the sensation that a person seeks in a signal-detection task) *is not presented*, but another stimulus occurs in its place, a person may appropriately indicate that the signal is absent. Usually this is done by not depressing the pushbutton. This is a *correct rejection*. Otherwise, a person may inappropriately indicate that the signal is absent. This is a *false alarm*.

When a *signal is presented*, again a person has two options. He may inappropriately indicate that the signal is absent by not depressing the pushbutton. This is a *miss*. Otherwise, he may appropriately depress the pushbutton to indicate that the signal is present — a *hit*.

Although it is essential for an experimenter to keep this lengthy explanation of signal-detection behavior in mind, it need not be given to persons who participate in experiments. They may simply be told "press the button only when the signal occurs."

Especially when a person must respond quickly or to barely discernable signals, the four categories of responses mentioned above are inadequate. Forced to choose between *yes* and *no* ("on" and "off"), a person may contaminate any of the four categories with guesses as a result of indecision. Once done, the experimenter has lost some control in the experiment. Therefore, a third option, *po*, must be provided. *Po* means that a person has considered the information that is available and he knows that new information may be sufficient, but further consideration is necessary before responding *yes* or *no*.

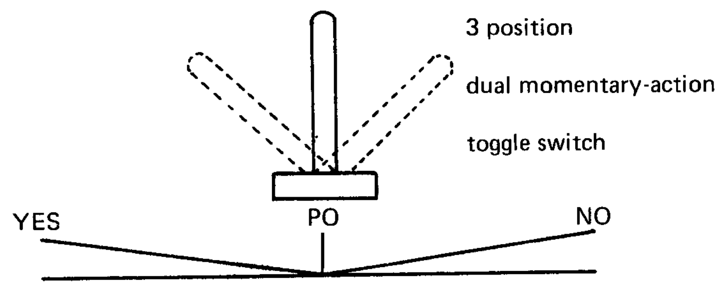
Consequently, when a person wishes to indicate a *deliberate miss* he signals *po* by depressing a second pushbutton. To eliminate the dilemma of *yes* and *po* being indicated simultaneously, the subject may be given a triple throw, dual momentary-action, toggle switch which may have the three positions assigned to *yes*, *po* and *no*.

Even with the supplementary option of responding *po*, a subject can be encouraged to declare *yes* or *no* with a reward. Therefore, a subject may inadvertently miss the presence of a signal at times. For such *unintentional misses*, indicated by an inappropriate *no*, the term "default" is suggested.

To distinguish between five categories of responses — namely, correct rejections, defaults, false alarms, hits and misses (see figure 4.1), is specially important in studies of the electrophysiological correlates of event-related behavior. Although no experiments have yet been performed to determine whether *defaults* are accompanied by unique cerebral evoked potentials, it is likely that this will eventually be proven. Already it is clear that hits can be distinguished from non-hits by examining the amplitude of P_{300} (for an example, see Squires et al, 1975a) and undetected signals elicit evoked potentials (for an example, see Schwartz and Rem, 1975). More research is needed to show the relationships between evoked potentials and the non-hit responses in signal-detection, namely, correct rejections, defaults, false alarms and misses.

figure 4.1

A Table of Signal-Detection Outcomes and Responses



OUTCOMES / RESPONSE	YES	PO	NO
APPROPRIATE	HIT signal present		CORRECT REJECTION signal-absent
INDETERMINATE		MISS deliberate pass	
INAPPROPRIATE	FALSE ALARM signal-absent		DEFAULT signal-present

figure 4.2 A Table of 28 Experimental Designs

AUTHOR	DATE (year)	SUBJECTS	ELECTRODES	CONTROL	TASK	LATENCY (ms.)	CHANGE	A PRIORI SIGNAL PROBABILITY	MODALITY	ONSET/OFFSET (ms.)	DURATION (ms.)	INTENSITY (dB)	FREQUENCY (Hertz)	INTER-STIMULUS INTERVAL (seconds)	% CORRECT DETECTIONS	TRIAL-TO-TRIAL REINFORCEMENT	ARTIFACT MONITOR	HARDWARE AVERAGER	SOFTWARE AVERAGER	NO. SAMPLES PER AVERAGE
BENSON, D.A.	72	7	Cz^e	DF/IS	IT	~300	LARGE		A	.1	50	0–6	NOISE	4	MANY	± ve	EMG	HAVOC	— —	12–20
CORBY, J.C.	73	12	Cz^m	PR	SD/ID	~233	SMALL	RA/.5/1	V		50			2.05			EOG	CAT	— —	64
DONALD, M.W.	71	6	Cz^e	PS	ID	230–360	10–35%		A		32		1K–1.5K	8–14		−ve	EOG	— —	LINC	432
DONCHIN, E.	73	10	Cz^m	PR	GS/ID	200–400	LARGE	RA/PA/.5	V		100	— —	— —	5–7.2			EOG			50
FORD, J.M.	73	12	Cz^m	CX	ID	270–500	30%	LOW	A/V					1–5			EOG			50
FRIEDMAN, D.	73	8	Cz^e	PR	GS/ID	280–350	LARGE	.2–.8	A					10–14		· ve	PUPIL	CAT	— —	200–500
HILLYARD, S.A.	71	3	Cz^m	IS/DF	SD	260–340	LARGE		A		50	60	1K	.25–1.2	50–90	· ve	EOG	— —	PDP9	50–400
HILLYARD, S.A.	73	3	Cz^m	PS	SD	250–400	LARGE		A		50	50	.8K–1.6K	.25–1.2				CAT	— —	1024
HIRSH, S.K.	71	30	Cz^m_f	IS	IG/AT/SD	290–385	LARGE	1	A	1.5	20	60	1.2K	2.5	100		EMG/EOG	HAVOC	— —	?32
JENNESS, D.	72a	4	Cz^e	PS	SD	~300	200%	.5	A/V		3	60	1K–1.2K	1.6	<40>60	· ve	EOG	CAT	— —	?150
JENNESS, D.	72b	4	Cz^e	DF	SD	250–450	LARGE		A			60	1K–1.2K		<40>60	· ve	EOG			140–300
KARLIN, L.	73	10	Cz^e	LR/PR	ID		LARGE	.12–.87	A		20		.9K–3.6K	5			EOG	CAT	— —	64
McADAM, D.W.	71	10	Cz^m	CT	SD/ID		LARGE		V		11.2		— —				EOG	NUC	— —	9–14
NAATANEN, R.	70	5	Cz^e	IS	ID		−13–40%		V		1		— —				EOG	CAT	— —	45
PAUL, D.D.	72	4	Cz	PR/PO	SD	~400	GRADED	.25/.5/.75	A		3	VA		1.95	60–75	· ve	EOG			
PICTON, T.W.	74a	20	Ar^m	IS/IN	AT	50–300			A		50μ-50	85					EMG/EOG	CAT	PDP12	100–8000
PICTON, T.W.	74b	7	Cz^m	IS	IG/SD		LARGE		A			60						CAT	PDP12	1024
RITTER, W.	72	8	Cz^m	PS/DF/CT	SD/ID	250–550	Latency	.1	A	5	50	60	1K–1.1K	2.5			EMG/EOG	— —	LINC	150
ROHRBAUGH, J.W.	74	4	Cz^e	CS/IN	ID	250–700	LARGE	HIGH	V		30	— —	— —	0–.48			EOG	— —	IBM	60
ROTH, W.T.	73a	18	Cz^e	PR	IG	~217	36–78%	.03/.06/.13	A	2.5	100	70	100/NOISE	1			EOG			10–300
ROTH, W.T.	73b	18	Cz^e	PR	IG	179–253		.03/.06/.13	A	2.5	100	70	1K/NOISE				EOG			
SQUIRES, K.	73a	8	Cz^m	IS	SD	300–450	LARGE		A		50	70	1K	3–4	75	· ve	EOG	— —	PDP9	10–280
SQUIRES, K.	73b	8	Cz^m	CT	SD	300–450	SMALL		A		50	70	1K	4–6	75	· ve	EOG	— —	PDP9	10–800
SQUIRES, K.	75	4	Cz^m	PR/SD	SD/CR	250–450	GRADED	.2/.5/.8	A		50	65	1K	4–6	75		EOG	— —	PDP9	20–200
TEUTING, P.A.	71	4	Cz^e	PR	GS	300–500		.2–.8	A				1K–2K	5–7		· ve	EOG	CAT	— —	40–640
WEBER, B.A.	72	12	Cz^m	PS/CS	SD			LOW/.5/1	A	25	300	60	.5K–2K	.7						512
WILKINSON, R.T.	72	12	Cz^m	PS/FS/IS	SD	~300	LARGE		A		52	78	135–3K	.3–1.76	92–95		EOG			64
WILSON, L.E.	73	6	Cz^e	IS/CS	SD/ID	250–350	LARGE		V	20	40	— —	— —	.5		· ve	EOG	CAT	— —	32

4.12 A Review of 28 Experimental Designs

One aspect of experimental design involves the clinical features of evoked potential research, such as the arrangement and the operation of equipment. This is discussed in detail by Myers (1971, 1972), Regan (1972), Shagass (1972) and Thompson and Patterson (1973, 1974). Another aspect of experimental design involves the specification of the dependent and the independent variables in an experiment. That is the topic of this review.

There is not a "standard" technique in evoked potential research, because of the wide variety of studies that have been conceived and tested in such a short time that few studies have been replicated and deemed exemplary. Part of the difficulty arises from the inadequacy of published accounts of experimental designs in stating the variables in the experiments. This is clearly illustrated in this review and the exemplary accounts in this regard, are few.

Figure 4.2 summarizes the parameters of 28 experiments that examined how a person's performance in signal-detection (or signal-recognition) experiments and cerebral evoked potentials correlate. The symbols that are entered in the table were obtained from the published accounts of experiments that were performed by the people who are named above each column (stating first authors only). The measures that are shown in the table were not always stated in the accounts. When they could be inferred from the text, the inference is shown in the table. When figures were not applicable, a dotted line is shown in the table. Blanks in the table show that information was missing from the published accounts.

The headings of each row are generally self-explanatory:

SUBJECTS shows the number of people that were tested;

ELECTRODES gives the positions of the recording electrodes according to the 10 / 20 system that is described in Regan (1972). "Cz" is the vertex of the skull. Lower case letters refer to earlobe (e), forehead (f), mastoid (m) and nasion (n);

CONTROL is the independent variable which elicited a response, the dependent variable. The controls are coded as follows:

certainty about a response	CT
complexity of a stimulus	CS
context in which a stimulus occurs	CX
difference between signals and context	DF
frequency of a stimulus	FS
intensity of a stimulus	IS
interstimulus interval	IN
lateness of response (reaction time)	LR
pay-off for responding accurately	PO
pitch of stimuli	PS
signalling probability	PR;

TASK refers to the behavior that the subject was required to perform. The tasks are coded as follows:

attend to everything	AT
estimate time	IT
give a confidence-rating	CR
guess what comes next	GS
ignore everything	IG
recognize a signal	ID;

LATENCY is an interval of time (in milliseconds) measured from the start of a stimulus to the component of interest (for example P_{300});

CHANGE is an indication of the percent, size or direction of change in the P_{300} component of cerebral evoked potentials;

A PRIORI SIGNAL PROBABILITY states the chance that a signal (the sensation that a subject must notice) might occur during each presentation of a stimulus. "RA" means random. "PA" means that the sequences of stimuli were presented in a pattern that the subject could remember and anticipate;

MODALITY is the sensory pathway that a stimulus excites. Visual (V) and auditory (A) evoked potentials are included. (All sensory-evoked potentials are similar after 200 milliseconds, so evoked potentials from stimuli in different modalities can be compared in the late components);

ONSET, OFFSET, DURATION, INTENSITY, FREQUENCY and *INTERSTIMULUS INTERVAL* describe the properties of the stimuli that were used in each experiment. (Generally, intensity is measured in decibels (dB) for sound and millilamberts (mL) for light);

% CORRECT DETECTIONS is given to show the difficulty of a subject's task or to show that factors in a subject's surrounding or preparation influenced his performance;

TRIAL-TO-TRIAL REINFORCEMENT indicates whether negative (-ve) or positive (+ve) feedback was give to subjects. "±ve" indicates that both were used;

ARTIFACT MONITOR is an indication that some attempt was made to show that the effects of the CONTROL on the EEG were not due to EMG, EOG or pupil dilation;

HARDWARE / SOFTWARE AVERAGERS tells which instruments were used to analyze the EEG data, special-purpose computers or general-purpose computers;

NUMBER OF SAMPLES PER AVERAGE gives the total number of single evoked potentials that each averaged evoked potential represents.

The format of figure 4.2 makes it very easy to draw conclusions at a glance about evoked potential research.

Most striking is the number of omissions in the table. In the matrix of 560 spaces, 124 data are missing. Clearly, it must be difficult to validate experimental results in independent laboratories when around one fifth of the variables in an experiment are not reported.

Among the authors whose papers are cited in figure 4.2 there is total agreement on the use of vertex (Cz) position [included in the array (Ar) of electrodes used by one author] for one of the EEG recording electrodes. However, there is no agreement on the position (earlobe, forehead, mastoid or nasion) of the electrodes with which the vertex recording is electronically compared in a differential amplifier. Regan (1972) and Thompson and Patterson (1973) discuss the difficulties that are presented by using these positions and it is clear that these positions are not equally 'neutral" or "indifferent" as references. Since the mastoid position does not lie over muscles and is out of the subject's way, it is recommended in preference to earlobe, forehead and nasion (also, chin, chest and neck) positions.

A total of 260 subjects were tested in the papers that are cited in figure 4.2. All subjects generated evoked potentials which included a positive component in the range of latencies between 200 and 700 milliseconds that was identified as P_{300}.

The physical properties of stimuli vary considerably throughout figure 4.2. In general, the stimuli that were used were abrupt, intense and short. Each stimulus followed an interval of 0 to 14 seconds, usually 5 seconds. The predominant audio frequencies were around 1000 Hz and none of the changes in frequency related to the American Standard Music Scale which would be the most common scale experienced by North American subjects. Consequently, the presentation of each stimulus was probably a startling event for most subjects.

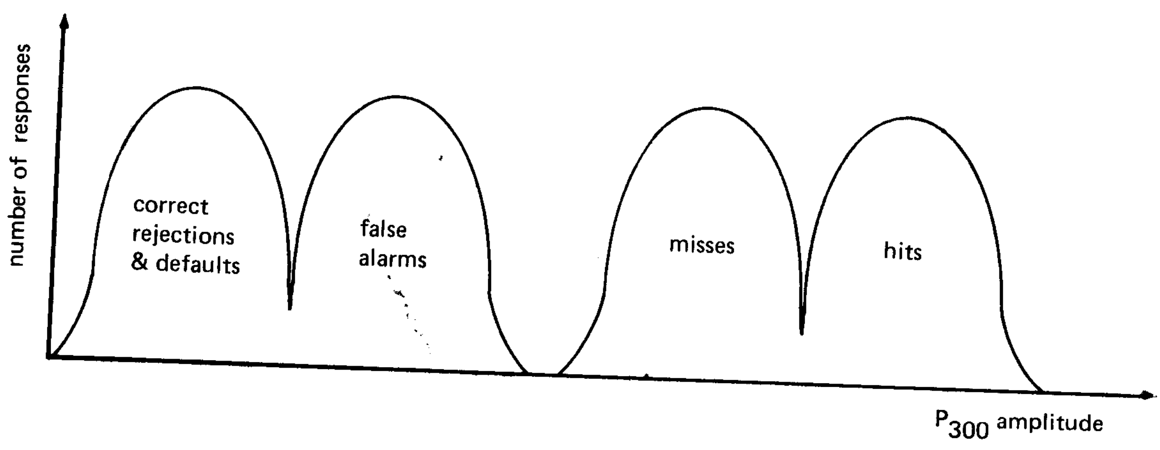
The number of samples of EEG activity per average ranged from 10 to 8000. This is a vast range. Averaged evoked potentials representing 10 samples would be contaminated by short-term variations in brainwaves which are not synchronized to each stimulus and averages of thousands of samples could bear little resemblance to any single evoked potential. The number of samples per average should be the least number which allows a distinct waveform to be seen which does not change significantly as successive samples are added.

Following this brief analysis of 28 experimental designs, two recommendations seem appropriate. First, a standard table which is similar in format to the one in figure 4.2 should be published at regular intervals in scientific journals to summarize from the reports that it publishes, the techniques and the results in a single field of science, such as the effects on evoked potentials of recognizing a change in a stimulus. The motive in doing this is to encourage scientists to adequately report the methods that they use and to encourage them to adopt conventions, so that their data could be meaningfully pooled. Also, such tables would make it easier for readers to compare the work of different authors and to monitor trends in the development of techniques.

The second recommendation concerns evoked potential data. Most researchers would agree that the scientific goal of evoked potential research is to resolve the mysteries which relate brain and behavior. Unfortunately, the great variety of "hardware" and "software" techniques for the collection and the analysis of evoked potential data is hindering progress in reaching that goal, because the results of each technique differ. Therefore, individual researchers are trying to solve problems which are distorted by their particular choice of techniques and people who are attempting to compare data from different sources are encountering difficulty.

Part of the solution to this problem will come as some techniques are established as conventions and others are discarded. Another part of the solution could result from pooling data. The collection of evoked potential data is laborious and slow. Most researchers record their data on magnetic tape. After analyzing and reporting on their recorded data, some researchers re-analyze their recorded data using the most recent techniques to appear. This should be done to as much data as possible. Therefore, the second recommendation is that researchers pool their recordings of evoked potentials after they have reported the results of their own analyses. Researchers should have access to libraries of such data in a form which cannot be destroyed, so that existing and future techniques might be used to analyze the data. Such a collective effort is a necessary step if an understanding of the relationship between brain and behavior is to be realized, because scientists are presently considering such small samples of the human population that they cannot distinguish between idiosyncrasies and characteristics of the population. For example, it seems clear that P_{300} is a graded response which is a function of cognitive activity. The finding that the amplitude of P_{300} is larger for hits than for non-hits appears to be true for most subjects. However, the relationships of P_{300} to non-hits may be more difficult to determine, because idiosyncratic factors might be large enough to obscure them. An intuitive approach to the solution of the relationships between the amplitude of P_{300} and all signal-detection responses predicts the relationships in figure 4.3. However, without considering large samples of population, it can neither be validated nor invalidated.

The Distribution of Amplitude at P_{300} in the Human Population? — figure 4.3



4.13 Features of the Recommended Design

This section summarizes several features of the experimental design that are recommended for a test of the thesis that biofeedback with auditory evoked potentials might be used to train a person to have "absolute pitch". Absolute pitch is discussed in section 4.24 and evidence which supports this summary is reviewed in sections 3.21, 4.11 and 4.12.

The a priori signal probability should be lower than .5 and higher than .05 to elicit large amplitudes at P_{300} and to minimize the time that is required to collect evoked potential data.

The times of onset and offset of the envelope of each stimulus should be 25 milliseconds to avoid acoustic transients.

The duration of each stimulus, including onset and offset, should be 150 to 200 milliseconds long to leave the subject with an adequate impression of the pitch of each tone and to avoid having the offset of stimulus occur during the range of latencies between 250 to 550 milliseconds in which P_{300} is generally found.

The intensity of auditory stimuli should be maintained near 40 dB (A).

The interstimulus interval should be constant to promote habituation to the regular occurrence of a stimulus. This should not interfere with the subject's ability to attend to changes in pitch. An interval of three seconds should give enough time to analyze evoked potentials and to allow a subject to indicate a response, receive feedback and then settle down before receiving the next stimulus. Such a short interstimulus interval would allow a large amount of data to be collected in a short time to minimize contamination by factors which are not related to the task.

Surface electrodes to monitor evoked potentials should be placed at the vertex and the mastoid locations. Surface electrodes to monitor EOG activity (intra-orbital and extra-orbital muscle contractions) should be placed around the eyes. Similar electrodes to monitor EMG activity should be placed over the frontalis and the temporalis muscles. Continuous correlating should be done to assure that EMG and EOG activities are not in phase with aspects of evoked potentials. Significant correlations would suggest that the sources of the evoked potentials recordings was extra-cranial (that is, muscles).

The start of an evoked potential recording should actually include an interval of time preceding the onset of each stimulus. This allows the experimenter to verify that averages of this portion of the waveform tend toward zero. If they did not, then sources of contamination must be sought and eliminated. The readiness potential (CNV) is not a form of contamination, but its presence would only be known if the segment of the brainwave was sampled before the presentation of each stimulus as recommended. A pre-stimulus interval of 100 milliseconds would be sufficient. Recording should continue for at least 600 milliseconds after the beginning of each stimulus. The beginning, like the ending of a stimulus occurs after 10 percent of the final amplitude is reached. Therefore, for a rise time of 25 milliseconds to a peak intensity of 40 dB (A), the beginning of an evoked potential would occur 3 milliseconds after the start of each stimulus and 103 milliseconds after the start of each recording.

Computation of averaged evoked potentials is a well-established procedure. The amplitudes of single evoked potentials account for most of the components of waveforms in averaged evoked potentials. Little of the variation in components of averaged evoked potentials results from EEG activity that is not phase-locked to the presentation of stimuli (Salamy, 1974).

However, averaging obscures much of the information that evoked potentials contain. In response to this problem, Ruchkin (1971) devised a method of sorting single evoked potentials according to patterns that can be recognized in the statistical properties of the waveforms. The method is programmed in a computer with the result that an experimenter's biases do not influence the categorization of data beyond designating what the categories should be. The program is revealing some very interesting data (John et al, 1975) and results (Bartlett et al, 1975). If the computer program can sort evoked potentials very rapidly, then it would be the best system that is available for evoked potential biofeedback and would be a working model to show how a brian might "sort" its own evoked potentials. Brief discussions on the use of such techniques (averaging and sorting) to perform tests of the thesis that biofeedback with cerebral evoked potentials might be used for perceptual fine-tuning are given in section 4.33 and 4.34.

More features of the recommended experimental design will be discussed in section 4.26.

4.20 How to Test Perceptual Judgment

This section reviews several concepts of perception and perceptual judgment in preparation for recommending a test of the thesis that biofeedback of cerebral evoked potentials might influence a person's reliability in making perceptual judgments. The auditory perception of pitch is discussed in detail to illustrate how a test of this thesis might be performed in the auditory modality.

4.21 Auditory Perception of Pitch

The perception of pitch is not fully understood.

There are five major divisions in the theory of auditory perception. They are briefly reviewed here to give some of the principal findings of each one. These findings must be considered when designing experiments to test whether biofeedback with auditory evoked potentials will influence a person's accuracy in judging the pitch of sounds.

The *biological foundation of auditory perception* is reviewed by Stevens (1951), Rosenblith (1959), von Bekesy (1960), Gulick (1971), Moller, (1973), and Uttal (1973). They show that hearing, like other senses, has dual mechanisms. The sensation of pitch is partly due to the activation of particular neurons and partly due to the rate of repetition of volleys of neural activity. Sounds with frequencies above approximately 500 Hz are processed by particular neurons. Sounds of lower frequencies cause volleys of neural activity.

There are no differences in the nerve endings that are sensitive to different pitches. The nerve endings are distributed along a coiled,tubular membrane — the cochlea. Each nerve is activated by movement in the region of the membrane in which it is situated. Due to the shape of the cochlea, sounds of different frequencies activate different portions of the membrane, so in general, individual nerves are mostly stimulated by a small band of frequencies. The activation of nerves is not changed when a person's psychological state changes (Picton et al, 1971). Furthermore, it seems that the nerves are activated only by the change of movement and not by the direction of movement, because people hear sounds to be identical whether they are inverted or not inverted.

Development of systematic methods for assessing auditory perception is arising from new applications of *information theory in auditory communication* (Miller, 1956; Broadbent, 1958; Green and Swets, 1966; David and Denes, 1972). Some of these developments are discussed in sections 4.11 and 4.25.

Deutsch (1970; 1972 a, b; 1975 a, b), Massaro (1970 a, b), Wicklegren (1966; 1969) and Aiken et al (1974) are developing a *theory of operations in the memory and judgment of pitch*. Some of their findings are reviewed in section 4.22.

An *understanding of the physical characteristics of sounds which produce sensations of pitch* is being developed through a collection of publications by authors including: Harris (1952); Henning (1966); Nordmark (1968); Attneave and Olson (1971); Gulick (1971); Roederer (1973); Wightman and Green (1974). Some of their findings are reviewed in sections 3.21 and 4.22.

4.22 Characteristics of Memory for Pitch

This section reviews some of the results of experiments which reveal the characteristics of a person's memory for the pitch of tones. These characteristics form a sketchy impression of auditory memory, because only preliminary studies have been done. This section considers the followingaspects of memory for pitch: general characteristics of memory of pitch; effects of amounts of information on memory for pitch; effects of types of information on memory for pitch; effects of experience on memory for pitch, effects of retention-time on memory for pitch; forms of interferencewith memory for pitch.

general characteristics of memory for pitch

The modern concept of memory for pitch comes primarily from the work of Deutsch (1970; 1972 a, b; 1973; 1975 a,b). She presents evidence to show that memory for pitch should be conceived as an array of elements which are arranged logarithmically. Each element is activated by a sound of a single pitch (a pure tone) and the elements which are activated by pure tones that are close in pitch are adjacent in the array. Also, elements which are activated for the *first harmonics* (sounds which are one octave above or below) of pure tones are adjacent in the array.

Recognizing a pitch involves the selection of an appropriate match between incoming sensations and memory elements in the array. It is not known how the right elements are selected to match the sensation of a given stimulus, but numerous theories for this have been conceived (de Bono, 1969). Once a match is found as part of the process of recognition, it is known that activation of elements which are adjacent to a matched element is inhibited. The effects of this inhibition are to sharpen the perception of tones which differ by a critical amount and to increase errors in judging tones which differ by less than that amount. Such inhibitory networks are known to exist in other sensory modalities as well.

An interesting study on "tone deafness" revealed that cultural factors exert a strong influence on a person's ability to judge pitch (Tanner and Rivette, 1964). Therefore, it may be important to consider cultural factors when designing experiments to study perceptual judgment.

effects of amounts of information on auditory memory

Miller (1956) reasoned from studies on ranking different numbers of tones of various pitches, that only about six different tones can be held in memory and accurately differentiated by most people. However, Neu (1947), Bachem (1955) and Ward (1963) reviewed reports that skilled musicians can identify many more tones than six, quite accurately. This skill is discussed in section 4.24.

The difference in pitch between pairs of stimuli, which is detected half of the time, is the *difference limen* (threshold) for pitch (refer to Stevens, 1951; Rosenblith and Stevens, 1953; Rosenblith, 1959; Gulick, 1971, for detail). Generally, the best listeners can detect a difference of .1 percent in the pitch of one sound from another, 75 percent of the time (Ward, 1970). To detect this change is much easier than to determine the direction of the change (Jesteadt and Bilger, 1974).

Plomp and Levelt (1965) found that subjects who had no experience in music consistently judged pairs of tones to be more pleasant if they were separated by a *critical bandwidth* — the extent of a change in the physical properties of a stimulus which, when reached, produces a sudden change in the sensation of the stimulus. The critical bandwidths for pitches are exponentially related to frequency (Scharf, 1970). Above 500 Hz, the critical bandwidth can be coarsely estimated as one-fifth of the frequency of a tone. Below 500 Hz, it is steady, near 100 Hz.

A separate discussion of the effects of irrelevant stimuli on memory for pitch is given under the heading: "forms of interference with memory for pitch."

effects of types of information on memory

The even-tempered musical scale has become the standard musical scale after 200 years of use in Western music (refer to Roederer, 1973 for details). Remarkably few experiments have been conducted to determine whether this scale is naturally preferred to just, pythagorean or other scales (just, pythagorean and tempered scales are compared, pitch by pitch, in Weast, 1974). One might expect that culturally induced preference for the even-tempered scale probably exists. However, evidence suggests that the pythagorean musical scale would actually be more consistent with the natural tendencies of the musically trained. When musicians are requested, in the absence of cues of other than the pitch of tones, to adjust the intervals between two tones to one octave, their estimates are slightly large, meaning sharp (Ward, 1970a). Similarly, musical performers generally sign or play (on stringed instruments that have no frets) the higher notes in intervals of major thirds and major sixths, slightly sharp (Ward, 1963).

The musical interval which separates intervening tones (non-signals) from tones that are being compared (signals) in a recognition (delayed comparison) experiment exerts a systematic influence on errors in pitch judgment. Deutsch (1972) found that a non-signal which differs from a signal by two-thirds of a tone induces more errors in judgment than non-signals which are more or less different, with 1 / 16 of a tone as the smallest interval. Another musical interval that is difficult to identify accurately is the first harmonic of a tone. Ward (1963) observed that they are often confused, by skilled musicians and non-musicians alike.

Whereas many musicians can name notes from a piano with an average error of five to nine half-tones, Bachem (1955) reported that some musicians commit errors of less of 1 / 11, 1 / 14 and 1 / 16 of a half-tone. The difference in accuracy between these groups of musicians probably arises from differences in perceptual style. Some musicians would only accept the challenge of recognizing a note. Others would try to recall it. Just as it is easier to recognize a melody than the key in which it is played, *it is probably easier to recognize any stimulus than to recall it* (Jesteadt and Bilger, 1974; refer to Watkins and Tulving, 1975, for a detailed analysis of recognition compared with recall).

Van de Geer et al (1962) examined the preferences of people who did not have musical training, for the pitch separation of pairs of tones played simultaneously. The most preferred intervals were sixths, thirds and fourths. This suggests that one axis of the array of elements in pitch memory is spaced in a manner which makes it easier for members of Western society to appreciate the Western, twelve-tone scale of music, than other scales. Furthermore, access to the elements in each category of elements along this axis may not be equal. Guilford (1954) found that subjects rated the pleasantness of tones as increasing as their pitches decreased.

Vitz (1971) identified an inverted U-shaped curve in the results of experiments to assess the judgment of pleasantness as a function of frequency in the range of 60 to 5000 Hz. Perhaps some regions of the array of elements in pitch memory are analogous to the fovea in the retina which detects sharp images in color, in contrast to regions in the retina which are outside this central viewing area that gives blurred monochromatic images. It is much more stimulating and pleasant to see in color and in focus than to see monochromatically and out of focus.

During performance in signal-recognition tasks and signal-identification tasks, a person's sensitivities to pitches or changes in pitch do not change after he receives feedback on the correctness of his responses. The outcome of his decisions does affect whether he will continue to use certain labels to distinguish between stimuli. Consequently, feedback probably affects whether a person will use the memory of a preceding stimulus in this judgment of subsequent stimuli (Aiken, 1967; Kopp and Udin, 1969; Aiken et al, 1974).

effects of experience on memory for pitch

Neu (1947) observed in several experiments that individuals who are able to judge pitches very accurately are almost always skilled musicians. The effects of systematic practice on memory for pitch are discussed in section 4.23.

effects of retention-time on memory for pitch

There is no decrease in the accuracy of pitch recognition for intervals of .1 to 1 second. However, a decrease in accuracy does occur for longer intervals. A person's memory for the pitch of a sound decays spontaneously with time. The amount of decay is negligible for silent intervals which are shorter than 15 seconds (Harris, 1952; Deutsch, 1972).

Forgetting during the retention interval is especially small when only one stimulus is used in an experiment (Wickelgren, 1969).

For brief tones (around .2 seconds in duration) memory of pitch is facilitated when a silent interval follows each tone, but this is not true for long tones (around .5 seconds in duration). Presumably, time to consolidate memory is necessary for a person to remember the pitch to tones and consolidation occurs after .2 seconds and before .5 seconds (Massaro, 1970).

As the retention interval is increased, the similarity of intervening stimuli must be reduced to maintain a constant level of retention (Wickelgren, 1966, 1969; Kinchla, 1967).

forms of interference for memory of pitch

Between separate experiments for studying pitch judgment which run in quick succession with the same subject, researchers often wish to minimize interference from previous experiments. Ward (1970) reviews several methods for "erasing" memory for pitch, namely, conversation, playing distracting sounds, encouraging a subject to read and presenting bursts of noise. A systematic study of filling pitch-retention intervals with sounds which are not related to the task has begun to develop from this need to interfere with memory for pitch.

Inserting tones in the intervals between presentations of tones in a delayed-comparison experiment interferes with memory (Wickelgren 1966, 1969; Massaro, 1970a). Similarly, when the objective is to remember a tone, the task is more difficult if the tone occurs in the middle of a sequence than if it occurs at the end (Hartman, 1954; W. Siegel, 1971).

Deutsch (1972) has found that tones in the retention-interval which are two-thirds apart from the signal, cause more interference with memory for the signal than other tones, excluding harmonics.

Concluding from sections 4.21 and 4.22, the modern concept of auditory perception is indeed sketchy. The mechanisms of encoding the physical properties of sounds in neural activity, are not completely understood. Even less understood is how sensations of sounds are derived from the neural activity that represents sounds after being encoded.

As indicated by the recent dates of publication of many references that appear throughout these sections, most of the statements which are assumed to be legitimate are such recent findings that they have not been validated. However, it is apparent that — (1) the mechanical and neural mechanisms of the ear between the eardrum and basilar membrane, (2) the sensitivity of hearing to the frequencies of sound shown by differential limen, (3) the accuracy of hearing that depends on recurrent inhibitory networks, (4) the precision of hearing that is suggested by critical bandwidths, (5) the preferences of people for certain "musical" intervals and (6) the interference with memory for pitch that is cause at critical times or by certain types of stimuli — are different properties of a process for analyzing sound, that has many stages.

The multistaged process of auditory perception is identified in theoretical terms in section 2.20 and psychophysical terms in sections 3.20 and 4.20 (this section). It seems reasonable to assume that somewhere between the stages of processing in the ear and conscious processing that constitutes awareness of a sound, there are stages that are "noisy" and not finely "tuned". The looseness of definition in such stages causes people to make errors in perceptual judgment. The following sections develop the idea that it should be possible to experimentally intervene at these stages in non-destructive fashion using biofeedback from cerebral evoked potentials to "fine-tune" perceptual judgment.

4.23 Methods to Improve Pitch Judgment

Many studies show that pitch-naming improves with practice (Ward, 1963, reviews this body of literature). This improvement can be represented by a graph of decelerating change that approaches a limit after many trials.

One form of training by practising involves *prompting*. This means that the stimulus which must be recognized or identified (the signal) is presented throughout the period of rehearsal to reinforce the memory of it. Another method of augmenting practice is to use *confirmation*. Whereas in prompting, the signal is presented before or during each test in an experiment, confirmation is given by presenting the signal during or after each test in an experiment.

Aiken (1967) found that confirmation is more effective than prompting in improving the accuracy of perceptual judgment of pitch, in a delayed-comparison task. However, both methods have been used separately to reduce errors in pitch judgments (Hartman, 1954; Ward, 1963; Cuddy, 1965). Therefore, both methods should be used simultaneously to optimize the improvement of pitch judgment with practice. Supplementing such training with biofeedback from cerebral evoked potentials may extend the limit of improvement of the method of rehearsal and shorten the time that is required to reach that limit.

A common method of improving one's accuracy in judging the identities or the relationships between points in a sensory continuum is to memorize the qualities of a single point. The memory of this point serves as a reference or "subjective anchor", to help in estimating other points in the continuum. This method is known to improve accuracy in pitch judgment (Cuddy, 1965, 1970; Adamson, 1972). However, the effect of the anchor decreases as the differences between the stimulus that must be identified and the subjective anchor, increases (Sarris and Haider, 1970; Adamson, 1972). This inverse relationship which governs effective associations cannot be a steep function. Alternatively, it is irregularly related to physical contunua, because people systematically associate such diverse sensations as the pitch of sounds and the brightness of lights (Marks, 1974) and perceptually handicapped people are capable of learning to "perceive" in their deficient sensory modality by learning to judge substituted sensations in another sensory modality (Bach-y-Rita, 1972).

The decrease in the value of a subjective anchor for pitch judgment as a function of the difference between its pitch and the pitch in question is large enough that it is not useful to use a single anchor to improve the judgment of all audible pitches. Realizing this, Cuddy (1970) encouraged some subjects to memorize a few scattered musical pitches and found their performance in pitch judgment to be better than the performance of other subjects who were encouraged to memorize all of the tones which follow consecutively in a portion of the musical scale. Consequently, an improvement in pitch judgment throughout the audible spectrum of frequencies will result from memorizing a few scattered pitches.

Taking extreme care to provide prompt and consistent feedback when training a person to improve the accuracy of his perceptual judgments (as was done by Swets et al, 1962) does not overcome a person's limitations in being able to correctly identify only about six alternatives (Miller, 1956). Swets et al (1962) discovered this when a computer was experimentally programmed to be a teaching machine for perceptual learning. Users of the machine did not show higher than usual rates or extents of improvement in accuracy of their pitch judgments. The contention in this thesis is that the limitations which are reached after the effects of practice in making perceptual judgments are exhausted, might be extended by using biofeedback from cerebral evoked potentials.

4.24 Absolute Judgment of Pitch

This section briefly reviews the phenomenon of "absolute pitch". To teach absolute pitch is the goal of an experiment which is proposed as a test of the thesis that *training with biofeedback of cerebral evoked potentials might improve the accuracy of perceptual judgment.*

"Absolute pitch" is one category of a well-documented topic in psychophysics — absolute judgment. Absolute judgment is the ability of some people to accurately scale and sometimes label some stimuli. Little proof exists that humans have noteworthy abilities in accurately judging color, length, weight, texture or odor (Lenneberg, 1961; Beare, 1963; Glanzer, 1963; Massaro, 1970: Uttal, 1973; MacMillan et al, 1974). However, the literature would lead one to believe that the ability of some individuals to accurately judge and identify the pitches of sounds is exceptional.

Ian Howard (advisor to the author) suggests that absolute judgment is not exceptional; rather, it is a natural alternative to relative judgment. He proposes that these are two general classes of perceptual judgment in which most people have particular skill. Some examples of these skills are listed below under appropriate headings.

absolute judgment	**relative judgment**
auditory localization	brightness of light
direction of straight ahead	loudness of sound
one's own posture	temperature
salinity of food	texture
verticality	weight

Neu (1947), Bachem (1955) and Ward (1970) refer to relative judgment of pitch as an ability which is separate from absolute pitch. Unfortunately, no theory has been developed to account for the biological significance of these abilities and none explains the mechanisms of these abilities satisfactorily.

Three somewhat similar mechanisms have been proposed in the accounts of Neu (1947), Ward (1963), Siegal (1971) and Deutsch (1975) to explain absolute pitch. The first is the *sensory acuity hypothesis*. It has been developed from two approaches. In the first approach, the proposition is that some people are born with generally high perceptual acuity. This is "wideband" acuity. The other approach considers "narrowband" acuity. In this case, people are said to be endowed with highly tuned pitch-analyzers. It is not clear in such propositions whether the special acuteness results from the particular composition of the cochlea, particularly low-noise networks of neurons in the auditory pathways or uncommonly accurate memory (labeling, storage and retrieval).

The second mechanism is discussed in the *subjective standard hypothesis*. In it, people who show extraordinary ability to identify the pitches of sounds or to generate requested pitches are said to carry a reliable reference with which to anchor a scale that they have learned. Such conjecture points to (a) resonant cavities in the sinuses and the lungs, (b) the lowest vocalized pitch or the fundamental pitch that a person produces in speech, and (c) the tinnitus or "ringing in the ears" as the sources of reference frequencies from which to base relative judgment.

The third mechanism attributes absolute pitch to *accurate memory for pitch.* Unlike the previous hypotheses which propose that possessors of absolute pitch are "born with it", this hypothesis suggests that a person may acquire absolute pitch with training. The central idea is that pitch memory can hold accurate analogues of one or more sounds in memory for use as a template ("engram") with which to compare sensations.

Of the three hypotheses, the accurate memory for pitch is the most likely to be substantiated by experiments. No method has been devised to test the subjective standard hypothesis. There is evidence that cochlear composition and auditory cortex in the brain can sustain extensive damage without appreciable loss of function (Luria, 1973).

Generally, models of psychophysical judgment distinguish between the sensory or "input" aspects and the memory or "output" aspects of decision-making. Sensory and memory components are both sources of limitations in the accuracy (the extent of difference between the mean of several responses and the correct response) and the precision (the extent of spread of several responses around the correct response) of psychophysical judgment. The fact that there are consistent differences in the accuracies of different individuals in making judgments of pitch suggests that the limitations which are imposed by the sensory component are significant. However, the overall precision that is shown in the responses of many individuals suggests that the major limitations in the reliability (meaning accuracy and precision) of pitch judgment are due to output and correlation processes in decision-making (Jesteadt and Bilger, 1974).

4.25 Methods for Testing Pitch Judgment

There are four standard techniques that may be used to test a person's skill in judging pitch. They are discrimination, identification, production and recognition. This section briefly describes each technique.

pitch discrimination

To study discrimination, experimenters ask subjects to compare stimuli that are presented simultaneously. In the auditory modality, stimuli may be presented simultaneously in two ways. In the first, no overlap in the stimuli that are presented to each ear may be arranged by using separate channels from mutually exclusive sources of sound to drive separate speakers which are arranged so that each ear hears sound from only one source. The second method involves mixing both auditory channels together, so that some overlap exists in the stimuli that are presented to each ear.

pitch identification

To study identification, experimenters ask subjects to label stimuli according to a scale that is familiar to both of them. Simple binary or tertiary scales, such as higher / lower or high / medium / low, are not as demanding of a person's judgment as more complex scales, such as the standard twelve-tone scale of Western music. Therefore, experiments involving binary or tertiary responses are really signal-detection experiments in which the signal may be a change in pitch. The term identification refers to experiments in which many labels are possibilities for each response, though only one is the correct label. Only one or two stimuli are used in studies on human signal-detection.

pitch production

The most demanding test of a person's skill in judging pitch is to request that he produce a given pitch without any prompting. To do this, a scale must be agreed upon by the experimenter and the subject. The subject should be permitted to choose his preferred method of generating the pitch, because evidence suggests that familiarity with the sounds of particular musical instruments influences accuracy in judging pitches (Neu, 1947; Bachem, 1955). Therefore, subjects should be given the opportunity to choose whether to sing, whistle, play an instrument or tune a tone-generator to produce a requested pitch.

pitch recognition

A subject's task is to recognize a pitch when a tone is designated as the one which the subject must indicate in a sequence of tones. Labels of stimuli are not necessary for recognition, but they are necessary for identification. Recognition is more complex than detection because widely diverse stimuli may be used in a recognition (or estimation) experiment. Only one stimulus is used in studies of detection.

on monitoring responses

Evidence indicates that covert responses, such as auditory evoked potentials, should be monitored in preference to overt responses, such as depressing a pushbutton, when an experiment is conducted to test perceptual judgment. In a carefully devised study on the effects of practising on a teaching machine to improve perceptual judgment, Swets et al (1962) discovered that requiring a person to mechanically indicate his judgments causes him to make more error than not requiring such responses. They also discovered that feedback on the outcome of responses in a very difficult task to discriminate between stimuli, promotes errors. In other words, being distracted from a task by either cause, having to respond or learning of the outcome, reduces the reliability of performance. This reveals the limitation of a person's capacity to handle information (Miller, 1956). Fortunately, the results of recent experiments (such as, Jenness, 1972; Ilecki, 1974; Bartlett et al, 1975; Squires et al, 1975a, b) suggest that reliable covert responses have been found in cerebral evoked potentials. When validated, using covert responses instead of overt responses will greatly advance knowledge in neuropsychology. One application of this knowledge may be the fine-tuning of perceptual judgment with evoked potential feedback.

4.26 A Recommended Task In Pitch Judgement

Several recommendations about a task in pitch judgement that may be used in an experiment to test this thesis, can be drawn from the discussions in sections 3.21, 4.12, 4.21, 4.22, 4.23, 4.24 and 4.25. They are reviewed in this section under the following headings: task; waveforms of stimuli; durations of stimuli; frequencies of stimuli; interstimulus intervals; sequences of stimuli; generation of stimuli; delivery of stimuli; feedback.

task

A person may be taught to have better than usual reliability in pitch judgement with a variety of techniques. Some are better suited to improving particular levels of performance than others. Performance may be classified according to Ward's (1970) observations that most people have difficulty in reliably recognizing tones which are separated by 2 or 3 tones, good listeners can distinguish tones separated by up to 1 / 4 tone and a few people can reliably identify differences of less than 1 / 4 tone.

Some one who has difficulty in recognizing differences between pitches may be trained to detect changes in pitch more reliably than usual by practising to notice gliding changes in the pitch of a continuous tone (that is, signal detection), differences in the pitches of two tones which are presented simultaneously (that is, signal-discrimination; for an example, see Ford et al, 1976) and differences between discrete tones which are presented serially (that is, signal-recognition by delayed comparison while requiring a "yes" or "no" answer; for an example, see Sarris and Haider, 1970).

People who are moderately accurate in judging pitches may be asked to perform a more difficult signal-recognition task. The level of difficulty in judging a change in pitch may be increased by requiring (1) "high" or "low" responses, instead of "yes" or "no" responses, (2) increasing the intervals of time between stimuli, (3) reducing the extent of changes in pitch and (4) decreasing the ratio of the number of prompting tones to the number of stimuli in a sequence. A sequence consisting of 5 prompting tones, followed by 15 stimuli which are presented at intervals of 2 seconds, is recommended to start. Most people performed well with this pattern of events in preliminary experiments.

People who are very skilled in pitch judgement should be tested in pitch identification and pitch production to assess their abilities to make absolute pitch judgements. These are difficult to study with standard electrophysiological techniques, because a subject may respond at different times after different commands. This would present a problem in averaging because the responses would not necessarily be related equally in time to the presentation of each stimulus. However, the promise of new pattern-recognition techniques is to locate and to sort electrophysiological signs of reading out memories and correlating them (for an introduction to this, refer to John et al, 1975, and Bartlett et al, 1975).

Due to a limitation in the capacity of short-term memory, people can accurately recognize only about 6 tones (Miller, 1956). Therefore, subjects should not be required to learn more than 6 tones at a given time. Preliminary experiments showed that remembering a single tone was a difficult challenge when shifts in pitch were subtle, and the lengths of the sequences between prompting tones were long.

One problem in the method of delayed-comparison is that the experimenter does not know whether the subject is vocally rehearsing the prompting tone during the trials (Wickelgren, 1969). This should be known to ensure that a consistent interpretation of the task is being made by each subject. One way to ascertain if the subject is vocalizing the signaling pitch is to place a "contact microphone" on his throat to monitor sounds.

waveforms of stimuli

Pure sinusoidal tones, meaning sounds consisting of single frequencies, are recommended for tests of pitch judgement, because their pitches are equivalent to their frequencies when their intensities are derived from equal-loudness curves for tones of different frequencies. Using such intensity-compensated sinusoids of equal pitches and frequencies would greatly simplify an experimenter's job by obviating assessment of the pitches of complex tones. This assessment would unnecessarily complicate tests of this thesis.

Although few musicians who might be interested to learn "absolute pitch" use pure sinusoids in their music, knowing how to accurately identify a sinusoid, such as A_4 — 440.0 Hz, would help such people to identify the fundamental frequency of most musical tones. Skilled musicians would have a particular advantage in identifying tones once they learn an "anchoring tone". The Western tradition in music emphasizes relative intervals more than absolute points on a scale. Evidence of this is that skilled musicians can judge a "perfect fifth" quite precisely (Ward, 1970). Therefore, skilled musicians who train to learn one anchoring tone or a few scattered anchoring tones, could use their skill in relative judgement to identify tones of many different pitches.

durations of stimuli

A choice may be made regarding the duration of stimuli. Between 150 and 200 milliseconds in duration for each stimulus provides sufficient time to perceive a pitch, if a silent pause follows for a person to consolidate his short-term memory of the sound (Massaro, 1970). Also, the offset of such pulses precedes the time of measurement of P_{300}, which would reduce the chance of contaminating that index of the psychological impact of each stimulus.

Alternatively, the offset of each tone may be triggered at the end of the period for recording the EEG, giving tones of long duration. Sarris and Haider (1970) used tones that had durations of 1 second. However, a difficulty is posed when using such long tones. They tend to establish new anchors in short-term memory. This interferes with the original anchors that were established by prompting as soon as the capacity of the short-term memory is filled. Therefore, prompting must occur more frequently with tones of longer duration, than tones of shorter duration. As a result of this complication, use of the shorter tones is recommended in preference to the longer tones.

frequencies of stimuli

Tones should be chosen from the American Standard Scale of Musical pitches which is measured from A_4 — 440.0 Hz, unless one of the objectives of an experiment is to determine the effects of deviating from this standard.

Prompting tones should have the same envelopes as the stimuli that are to be judged. The precision of reproducing the frequencies of all tones must not exceed .1 percent, because good listeners can detect such a change (Ward, 1970).

Successive tones in a sequence of tones that are being judged, should change by a critical bandwidth (refer to Scharf, 1970). This maximizes the arousing value of the pitch of each stimulus. However, the closeness of the pitch of any stimulus to the pitch of the prompting tone may not be large. The minimum pitch-distance between signals and non-signals may be adjusted to manipulate the difficulty of the task, as mentioned earlier.

The frequencies of tones should be varied in steps. Gliding changes in pitches are somewhat predictable and probably more suitable for tests of relative judgement than absolute judgement, because they make it difficult for all but the most skilled people to judge pitches accurately and often their judgements depend on the pitch where the glide begins.

Most people confuse the identities of the first harmonics of a harmonics of a signalling tone as well as tones which are 2 / 3 of a musical tone apart from the signalling tone (Deutsch, 1972). Therefore, to eliminate this source of systematic errors in judgement which might bias the results of experiments, responses to such tones should be analyzed separately from other data, or such tones should be excluded from the stimuli which are used in tests of pitch judgement.

interstimulus intervals

The interval of time between successive stimuls should be constant. This may promote habituation to regular appearances of stimuli. That should not interfere with a subject's ability to attend to changes in pitch and it may increase the novelty of pitch changes, by providing a contrast.

The recommended interstimulus interval is 2 seconds. This results from a compromise. On one hand, intervals are desired which are sufficiently long (A) to elicit large evoked potentials, (B) to permit evoked potential recording to begin before the onset of each stimulus to enable comparisons to be made between prestimulus and poststimulus segments of the brainwave recordings, (C) to permit the evoked potentials to be recorded before a subject indicates the result of his decision (which might contaminate the recordings of brainwaves if done during the recordings), (d) to permit the recordings to be analyzed and (e) to allow the subject to receive feedback on the outcome of his decisions and the amplitude of his evoked potentials. On the other hand, a short interval is desired to permit a large amount of data to be collected quickly and to prevent the contamination of the data by nonspecific factors. Since the recommended duration of each stimulus is between 150 and 200 milliseconds, it will also be possible for a person's memory of each pitch to consolidate in the silent interval which follows each stimulus and precedes his indication of a decision (as mentioned earlier).

sequences of stimuli

The probabilities of occurrence of a signal for each presentation of a stimulus must be controlled, as well as the patterns in the sequence. This is done to maintain the arousing value of stimuli throughout a test and to manipulate a subject's motivation to perform.

The a priori signal probability should not exceed .2 in order to maintain large amplitudes and "significance-related fluctuations" in the amplitude at P_{300}. No two successive presentations of a signal must occur, except in prompting. The sequences of stimuli should be unpredictable.

generation of stimuli

Auditory stimuli can best be generated on general-purpose or special-purpose computers to give the experimenter maximum control and minimum effort. Music-writing software is widely available. However, for the greatest convenience to the user, an electronic musical instrument (really an analog computer) is expressly made to produce sequences of stimuli which may be easily controlled and modified. For an example of how to generate auditory stimuli on an electronic musical instrument, see appendix B.

It is recommended that all stimuli, timing cues, pauses and instructions for a single session of an experiment be recorded on a continuous tape-recording. By playing this tape for each subject, the experimenter standardizes the treatment of the subjects to enable him to compare their responses to identical stimuli.

delivery of stimuli

Audio stimuli should be presented to subjects through earphones in preference to speakers. Spontaneous fluctuations in the waveforms, particularly the amplitudes, of evoked potentials are smaller when earphones are used, then if remote speakers are used (Worden et al, 1964).

The stimuli should be delivered monaurally and equally loudly in each side of the earphones. This is suggested to prevent unequal distributions of evoked potentials in the hemispheres of the brain (Matsumiya et al, 1972) and to focus attention on the changes in pitch rather than including binaural cues on the spatial localization of sounds (discrete spatial localization of sounds was found to improve the accuracy of subjects in discriminating pitches by Schwent and Hillyard, 1975).

feedback

Learning the absolute judgment of pitch may be accomplished with extensive and systematic rehearsal (Cuddy, 1970). With prompting, memory of an anchoring tone can be reinforced for all levels of difficulty in making judgements. With confirmation, judgement can be made more precise with immediate feedback than with delayed feedback, but it does not help, and may hinder, the reliability of responses in difficult judgements (Swets et al, 1962). Tests of pitch judgement using bogus and no feedback may be dispersed among tests using real feedback to monitor this effect. The level of difficulty in discriminations should be such that subjects receive more than 50 percent and less than 80 percent positive feedback when they are highly confident about their responses, so that they are motivated to do better. Around 20 percent positive feedback would be discouraging and would suggest that the task is too difficult and should be made easier.

4.30 Experimental Designs

The amplitude of the P_{300} component of cerebral evoked potentials is known to reflect the psychological implications more than the physical properties of a given stimulus. Recent discoveries suggest that the relative amplitudes of P_{300} can be used as an index of various kinds of psychological activity. In particular, when a stimulus arouses a person's attention and the person quickly makes an appropriate decision (hit) about a familiar, complex and unpredictable situation which the stimulus creates and which the person must resolve, then the amplitude of P_{300} is relatively larger than under less arousing (correct rejection), less familiar, less complex or more predictable conditions with inappropriate outcomes for the decisions (default, false alarm, miss). The intention in this section is to outline the major elements of experimental designs to apply this knowledge in evoked potential feedback for improving the reliability of perceptual judgement.

4.31 The Objectives

Several approaches may be used to determine whether perceptual fine-tuning can be encouraged with evoked potential feedback.

One category of approaches involves training a person to enhance the amplitude of P_{300} for appropriate indications of the occurrence of the signal (meaning hits) in (1) signal-detection, (2) signal-discrimination, (3) signal-recognition, (4) signal-identification and (5) signal-production tasks. Such training is based on reinforcing a person for making accurate judgements which are accompanied with gradually increasing amplitudes at P_{300} for hits, but not for non-hits. This training might encourage a person to be more reliably aroused than usual by a given stimulus. The reason for expecting this is that the significance to a person of a given stimulus is reflected in the amplitude at P_{300}. Therefore, by training a person to increase the amplitude of P_{300} after hits while discouraging him from making incorrect judgements, the person might learn to associate particularly strong significance with the stimulus — any stimulus. The unresolved problems of this hypothesis are that (1) an increase in the amplitude of P_{300} might be achieved without the subject's awareness of it, (2) it may not be possible to isolate the increase for hits only and (3) since the amplitude of P_{300} is such a coarse measure of activity in the brain, neither the mechanism of an increase nor the by-products of an increase can be predicted with confidence.

However, it seems that changes in the amplitude of P_{300} could be obtained and it is known that high amplitudes at P_{300} indicate something about the significance of a stimulus to a perceiver.

Another category of approaches does not require a person to make an overt response. Hits are accompanied by relatively larger amplitudes at P_{300} than non-hits, namely correct rejections, defaults, false alarms and misses. Therefore, while a person performs a task (detection, discrimination, recognition, identification or production) without indicating a response overtly, the amplitude of his evoked potential should indicate his response. Consequently, an experimenter may select a particular amplitude which a person's P_{300} response spontaneously exceeds for hits, to serve as a criterion with which to assess his covert responses. Above this amplitude, a hit would be registered; below it, a non-hit would be registered. Immediate feedback to a person of the result of this analysis following each stimulus, might encourage him to perform more reliably than usual in a task. Part of the reason for expecting this to happen is that some messages ascend in sensory pathways without being noticed, as indicated by misses and responses which have been found to "subliminal stimuli" (Schwartz and Rem, 1975; Shevrin, 1975). Also, the commission of errors in judgement must be due, in part, to unreliability in heeding these ascending messages. Therefore, immediate feedback on the significance that a person attaches to a stimulus (the amplitude of P_{300} appears to be an index of the significance to a person of a stimulus) might help him to keep his interpretations of the stimulus aligned with the objective to learn to be reliably aroused by that stimulus. Therefore, training with biofeedback from the amplitude of P_{300} might encourage a person to pay unusually strict attention to presentations of a particular stimulus. One problem with this hypothesis was pointed out by S.A. Hillyard (1975, a personal communication). He interpreted available evidence to suggest that P_{300} feedback would be redundant, because the amplitude of P_{300} was believed to be related to confidence in responding to a stimulus. Accordingly, feedback from a high-amplitude response would only restate what a subject already knows, namely, that he responded with confidence. However, confidence was found to be unrelated to the amplitude at P_{300} by Squires et al (1975b).

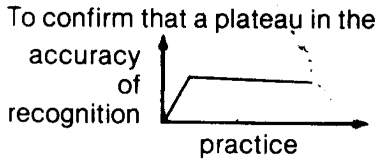
Among the objectives of preliminary experiments should be to determine the effects on evoked potentials of varying the parameters of sounds, other than intensity. These have not been reported. Consequently, a full understanding of pitch perception has not developed. Systematic studies of varying the waveforms of auditory stimuli (including sinusoidal, sawtooth, triangle, pulse and noise), the modulation of waveforms (amplitude-modulated and frequency-modulated tones), the complexities of sounds in speech and music, and perceptual illusions (beats, periodicity pitch, missing fundamentals and "cyclotean perception" — Kubovy, 1974) are required.

The P_{300} component of cerebral evoked potentials has been clearly identified in studies on pitch judgement by Sarris and Haider (1970); Hirsh (1972); Delse (1972); Jenness (1972); Hillyard et al (1973); Schwent and Hillyard (1975); Ford et al (1976). However, none of the experimenters used stimuli with pitches from the American Standard Scale of Musical Pitches and the duration of each stimulus was generally too brief to elicit a distinct sensation of pitch, except in the work of Sarris and Haider (1970). Therefore, an objective of preliminary studies should be to determine the effects on cerebral evoked potentials of including various vocalized and electronic sounds in sequences of stimuli which are tuned to different musical scales and unconventional scales. Similarly, one might validate the conjecture that a person's name elicits larger cerebral evoked potentials than other stimuli.

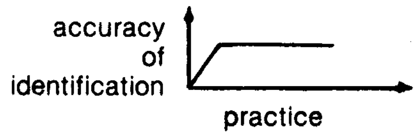
The following summarizes a sequence of objectives in experiments which may be performed to test this thesis:

To confirm that the amplitude at P_{300} can be obtained for a signal-recognition task and that hits give larger amplitudes than other responses;

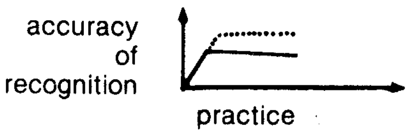
To confirm that a plateau in the accuracy of recognition can be obtained with extensive practice,

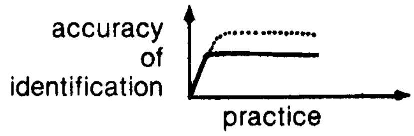


To confirm that the accuracy of signal-identification is improved to a limiting value after practice in signal-recognition;



To demonstrate that biofeedback training to enlarge the amplitude at P_{300} for hits will improve a person's accuracy in signal-recognition and signal-identification;





To demonstrate that a more accurate indication of the category of a person's response to each stimulus can be obtained from an analysis of a covert response, such as the amplitude at P_{300}, than an overt response, such as indicating the result of a decision by depressing a pushbutton;

To demonstrate that feedback based on a covert response, such as the amplitude of P_{300} after each stimulus in a signal-recognition task, promotes improvement in the reliability of pitch judgements;

To demonstrate that an improvement in the reliability of pitch judgements follows the use of evoked potential biofeedback in a signal-recognition task.

The proposition to use the amplitude at P_{300} as a criterion for the presentation of a stimulus to encourage an improvement in the reliability of perceptual judgements may be challenged in several ways.

By adding to a difficult task an extra stimulus for encouraging a person to generate particular cerebral evoked potentials, an experimenter may risk interfering with a subject's performance, because the amplitude at P_{300} is too variable for feedback to be meaningful to a subject. S. Sutton (1975, a personal communication) proposed that a reason for this variability is that the correlates in evoked potentials of a task in judging pitches are very complex.

C. Shagass (1975, a personal communication) questioned the relationship between the amplitude of P_{300} and the correctness of decision-making. He proposed that P_{300} probably relates more to exercising a decision than the correctness or a person's confidence about the outcome.

E. Donchin (1975, a personal communication) cautions that P_{300} feedback might be meaningless, because there is no evidence to convince him that large amplitudes at P_{300} do not occur for correct rejections or false alarms and evidence from Squires et al (1975b) does suggest that such amplitudes are not seen in averages due to temporal variation in the latencies of responses to correct rejections and false alarms.

The recent developments in techniques for recognizing and distinguishing patterns in brainwaves may eventually answer those challenges adequately. It is presently possible to scan brainwaves to determine more or less coarsely what "readout" from memory implies about the nature of a few perceptions (John et al, 1975). However, it is not yet possible to predict from the patterns in brainwaves more or less when an individual will respond to such perceptions (Bartlett et al, 1975). Given the present course of research, it will eventually be possible to detect the patterns in brainwaves which represent scanning and correlating memories in thinking. However, at the present time, the characterization of patterns and brainwaves which encode unique responses to various stimuli is vague and incomplete (for examples, refer to "Toward a View of Man," by M. Clynes in Clynes and Milsum, 1970; Naatanen, 1975).

Given the present state of knowledge it is only fair to conclude that this thesis on a new application of brainwave biofeedback may only be tested empirically.

4.32 A Summary of the Recommended Methods

This section outlines a summary of the methods that have been recommended throughout this thesis for a test of the hypothesis that biofeedback with cerebral evoked potentials might be used to train a person to improve his perceptual judgement.

TASKS: (1) signal-detection (2) signal-discrimination (3) signal-recognition (4) signal-identification

RESPONSE OPTIONS: (1) yes, po, no (2) high, same, low

POSITIONS OF ELECTRODES: (1) vertex / mastoid for EEG (2) frontalis / mastoid for EMG (3) temporalis / mastoid for EMG (4) supraorbital / mastoid for EOG

TYPE OF ANALYSIS FOR EEG SAMPLES: (1) average (2) weighted average (3) sorting by pattern-recognition

PRESTIMULUS EEG SAMPLING INTERVAL: 103 milliseconds

POSTSTIMULUS EEG SAMPLING INTERVAL: 597 milliseconds

RANGE OF P_{300} AMPLITUDE-ANALYSIS: 275 to 375 milliseconds (more or less according to each person's characteristic responses)

A PRIORI SIGNAL PROBABILITY: $.05 \leqq$ probability $\leqq .5$

SENSORY MODALITY: auditory

ONSET / OFFSET OF STIMULI: 25 milliseconds

DURATION OF STIMULI: 150 to 200 milliseconds

INTENSITY OF STIMULI: 40 dB (A) above sensation levels in silent surroundings

FREQUENCY OF STIMULI: precision of a generator in reproducing the stimuli must exceed .1 percent; the frequencies must be stepped rather than glided in changes; the intervals between successive stimuli must be musical intervals; the tuning of the musical scale must conform to the American Standard Scale of Musical Pitches which is centered at A_4 = 440 Hz; the range of variation of the pitches in the experiment is two octaves with a center frequency of 440.0 Hz; harmonics and tones which are separated from 440.0 Hz by ⅔ of a musical tone interval must be excluded from the sequences of stimuli; successive stimuli in a sequence must be separated by a critical bandwidth; no two signals in a sequence which follow one another may be the same pitch

INTERVAL BETWEEN STIMULI: constant interval of 2.0 seconds; the interval between successive presentations of the signal that is sought in the subject's task must not exceed 40 seconds

SIGNAL THAT IS SOUGHT IN THE SUBJECT'S TASK: 440.0 Hz

METHOD OF DELIVERING STIMULI: equally balanced monophonic sound in earphones

DIFFICULTY OF TASK IN PERCENT CORRECT DETECTIONS: 50% to 80%

CRITERIA FOR ASSESSING ABILITY IN PITCH JUDGMENT: (1) precision of ± 2 tones in pitch-identification (2) precision of ± ¼ tone in pitch-identification

TYPE OF FEEDBACK SIGNALS: coloured lights

DURATION OF FEEDBACK SIGNALS: until the end of the interstimulus interval

ARTIFACT MONITORS: EOG; EMG

VOCALIZATION MONITOR: contact microphone on throat

INDEPENDENT VARIABLES: pitch distance; task; time-limit for responding; response options; criterion for P_{300} amplitude to exceed before the subject receives reinforcement

4.33 Using a Special-Purpose Computer-Averager

(An Instrument for Evoked Potential Feedback)

This article outlines the design and the operation of an electronic instrument that can be used in conjunction with a modified signal averager to conduct experiments with evoked potential feedback.

An *evoked potential* is an electrophysiological response to a stimulus. For instance, when a person is startled by a sudden sound there occur muscle movements, changes in the resistance of tissues and volleys of neural activity. Each of these result in electrical changes which can be monitored. (This is discussed in section 3.11.)

Feedback is the return of an output of a process to an input of the same process. It is a common technique for bringing an erratic process under control. For a new application of feedback-control, by displaying evoked potentials to a person it may be possible to train him to control them. With this control a person might be able to respond to stimuli with evoked potentials that are different from the usual responses that occur without such training. This might influence a person's perception of stimuli. To examine this possibility is the major objective in a new branch of biofeedback research to study evoked potential feedback.

To explain the factors involved in the development and the use of this new biofeedback instrument, this article begins with reviews of research on evoked potentials and the technique of signal averaging. Then, the preparation of a signal averager for evoked potential feedback is discussed. Finally, the design and the operation of the biofeedback instrument are presented. An instrument "patch", a schematic diagram, a circuit diagram, a list of components, a time-series of operations and a glossary are included.

Although the instrument may be used to feedback any evoked potential, it was expressly designed for experiments using brainwaves. Therefore, cerebral evoked potentials are discussed to illustrate the operation of this device.

Research on Evoked Potentials

Research has shown that segments of the waveform of cerebral evoked potentials contain information about perceptual activity. For example, the amplitude in a segment of cerebral evoked potentials around 300 milliseconds after the presentation of auditory, tactile or visual stimuli is a function of the significance of each stimulus to the perceiver. One hundred and forty-five references to this phenomenon in research reports are listed by Price and Smith in *The $P_{3(00)}$ wave of the averaged evoked potential: a bibliography* (published in Physiological Psychology 2:387-391, 1974).

There are many significant stimuli, such as emergency warning lights, that people should notice, but often do not. Therefore, it would be useful to develop a technique for training people to be reliably aroused by certain stimuli in the same way that they are aroused by the sound of their own names. Evoked potential feedback may help to do this.

Preliminary attempts to operantly train (that is to establish a particular behaviour by promoting it with rewards after a subject spontaneously performs the behaviour) subjects to modify their evoked potentials have all been successful (they are reviewed in section 2.3). Since changes in recordings of the amplitude of the P_{300} component of cerebral evoked potentials (a positive volley around 300 milliseconds after the presentation of a stimulus) indicate differences in the significance of stimuli to a perceiver (this is discussed in section 3.22), it may be possible to operantly train a person to elicit for a particular stimulus, P_{300} responses of a different amplitude than usual, with the result that he may perceive the stimulus differently than usual. A predicted consequence of such training is that a person might associate a new significance with a particular stimulus. In other words, after such training, a person's attention might become as reliably aroused to any given stimulus as it is to his own name.

The Technique of Signal Averaging

Cerebral evoked potentials are small signals that are buried in other electrical activity in the brain. The other electrical activity does not seem to be related to the presentation of stimuli, because unlike evoked potentials, that activity does not become synchronized to the rhythm in which stimuli are presented.

In evoked potential research, the brainwaves which are not synchronized by the presentation of stimuli are called "noise".

Since noise obscures cerebral evoked potentials, a common technique for reducing the noise and thereby increasing the signal-to-noise ratio is to add together segments of brainwave recordings which are related in time by the onsets of identical stimuli (this is discussed in section 3.12). Such signal *averaging* can be done on a general-purpose computer, but many laboratories are equipped with less expensive special-purpose computers called "hardware averagers" (the term "hardware" refers to electronic equipment, while the term "software" refers to operations that may be programmed on a general-purpose computer).

A hardware signal averager is a device which performs only one operation, the averaging of recorded signals. Averaging is done by breaking up the waveforms of recorded signals into a fixed number of equal intervals and then assigning a voltage to represent the average level in each interval. This gives a series of discrete voltages. Each voltage is then applied across a capacitor to leave a series of stored charges "in memory". As successive representations of recorded signals are applied across the capacitors, the charges that they store adjust to an average value of the voltages that are applied. Therefore, the memory is continually updated.

When enough of the recorded signals have been processed to increase the signal-to-noise ratio so that the average signal can be discerned, a waveform representing the average signal can be constructed for display by scanning the memory, a series of charged capacitors.

A Modified Averager

Normally, long time-constants (the time required for a resistor-capacitor network to charge or to discharge to within e^{-1} of completion, where e is the base of natural logarithms near 2.718 in value) are used in an averager's memory, because one would not usually want the averaged signal to degrade significantly between successive inputs of the signals being averaged. However, in evoked potential biofeedback, controlled degradation is desirable.

For a subject in an experiment to learn with evoked potential biofeedback, he must be able to observe changes in the feedback which relate to internal states. Therefore, the feedback that is displayed to a subject must more strongly reflect his most recent state and less strongly reflect previous states. This can be done by lowering the time-constants of an averager's memory and displaying to him the portion of the averaged evoked potential that he must control. Lowered time-constants would cause the memory to degrade between successive inputs of the signals being averaged when the memory is being scanned. To control this degradation, the number of times that the memory is scanned between successive inputs to the memory, must be held constant.

There is a trade-off between the increased weighting of the average in favour of the most recent input and a decrease in the signal-to-noise ratio. An optimum value for these can be determined for each hardware averager. For example, in one Princeton Applied Research instrument when the time required for each scan of the memory is 50 milliseconds, for a memory time-constant of one second, the degradation of the memory for a single scan would be 100 (e^{-1}) (.05%1.0s.) = 1.8%. During compounded continuous scanning for two seconds (that is two time-constants), 59.5% of the memory of a three volt signal would be degraded, with noise created by the averager of 60 millivolts added to the memory, for a time window on the P_{300} portion of cerebral evoked potentials of 100 milliseconds. Consequently, the weighted average that would be displayed to a subject using these figures for one hardware averager, would be a function of the interaction of the most recent cerebral evoked potential with the residual averaged evoked potential in the memory, in a ratio of 59.5 to 40.4 or about 3:2. Using this technique, the average would be noisier than without the weighting factor, but large sample-to-sample variations in the amplitude of P_{300} should be detectable.

Instrument for Evoked Potential Feedback

Waveforms of the weighted averages of evoked potentials could be displayed to subjects in their raw form. However, such complex feedback might cause interference in an experiment by distracting a subject's attention from his task, so a simple form of feedback is needed. To provide this, an instrument was designed to indicate by turning on a light, when the amplitude in a prespecified segment of an evoked potential exceeds a predetermined ("threshold") value.

The instrument also provides feedback on the outcomes of each response in a signal-detection experiment. Furthermore, both forms of feedback may be linked, so that one does not happen without the other. With such dual criteria for feedback, a subject's pushbutton responses and cerebral evoked potentials must conform to predetermined specifications before the subject is rewarded with feedback.

A subject may be trained with this device in three ways. He may be given indications of the outcome of his signal-detection responses with lights that turn on for each category of response, namely, correct rejections, defaults, false alarms, hits and misses. Such feedback may improve his accuracy in responding to the extent that practise would help. Secondly, a light may be used to indicate when the P_{300} component of his cerebral evoked potential exceeds a specified level which may be increased as the subject's performance improves. Finally, the subject may only be shown a light when both responses are present: a particular signal-detection response and a particular amplitude at P_{300}. Such training is proposed as a test of the thesis that evoked potential feedback might train a person to fine-tune his ability to judge the physical characteristics of a stimulus.

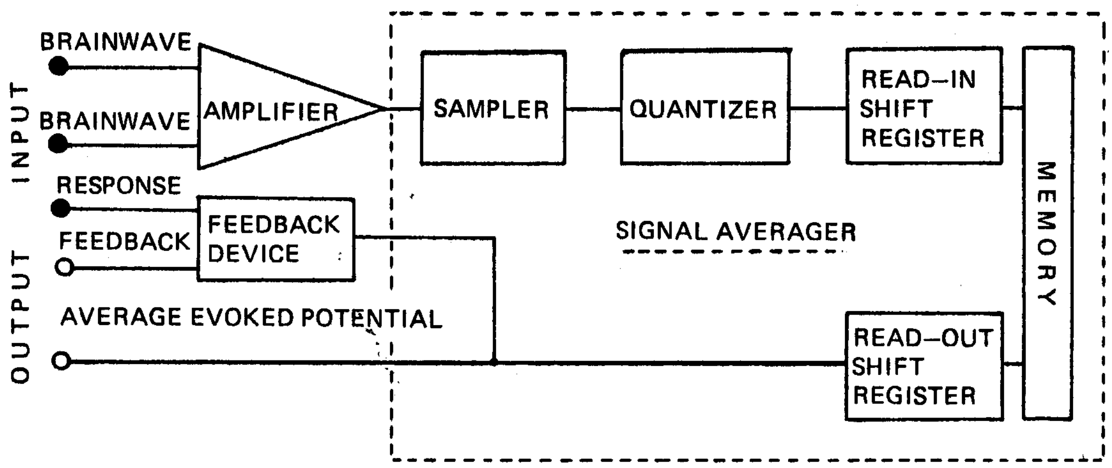
The way that the instrument for evoked potential feedback was designed to be used with other instruments is shown in figure 4.4. The text and the diagrams that follow show how the instrument could be constructed and how it operates.

Circuit Design

The design that is presented here for an evoked potential feedback device describes a hybrid electronic instrument. This instrument performs digital timing and feedback operations and compares an analog measure of the absolute magnitude of average evoked potentials to a value which can be set by the experimenter.

A schematic diagram of this device is shown in figure 4.5, a detailed circuit in figure 4.6, a time series of operation in figure 4.7, a table of component values in figure 4.8 and a picture of a prototype of this device in figure 4.9. A power supply must be added.

Instrument Patch for Biofeedback — figure 4.4



EVOKED POTENTIAL FEEDBACK DEVICE

figure 4.5

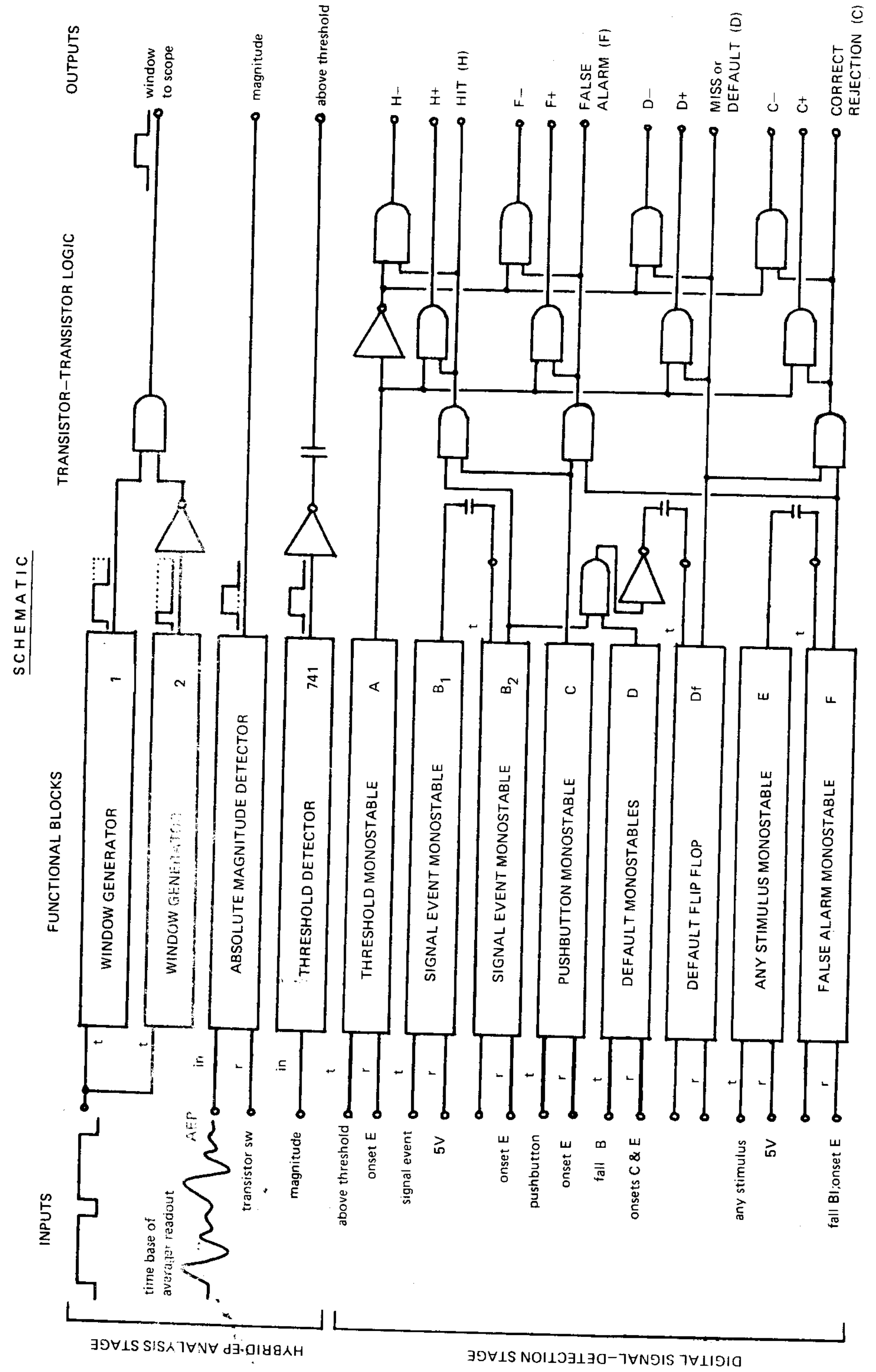
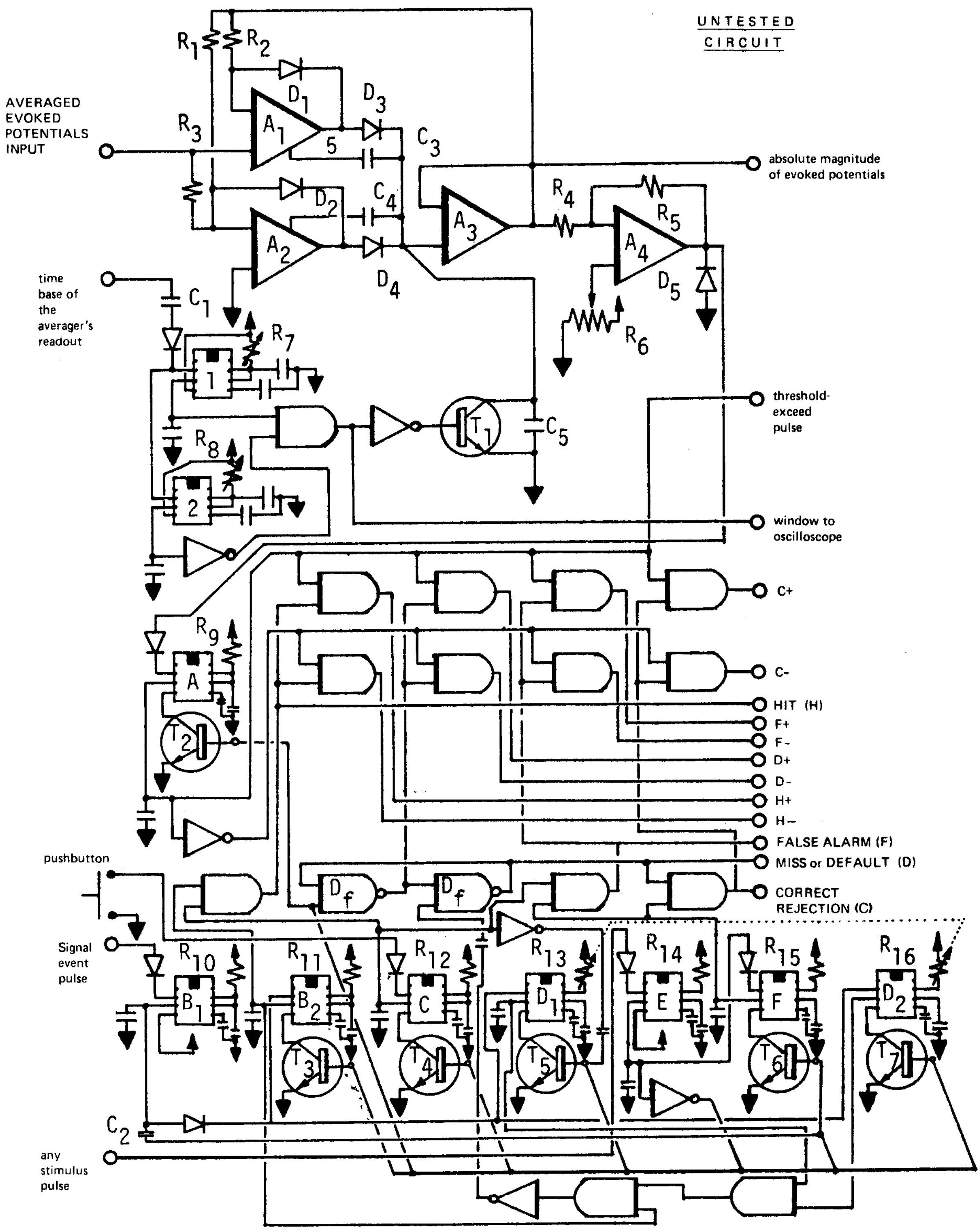


figure 4.6

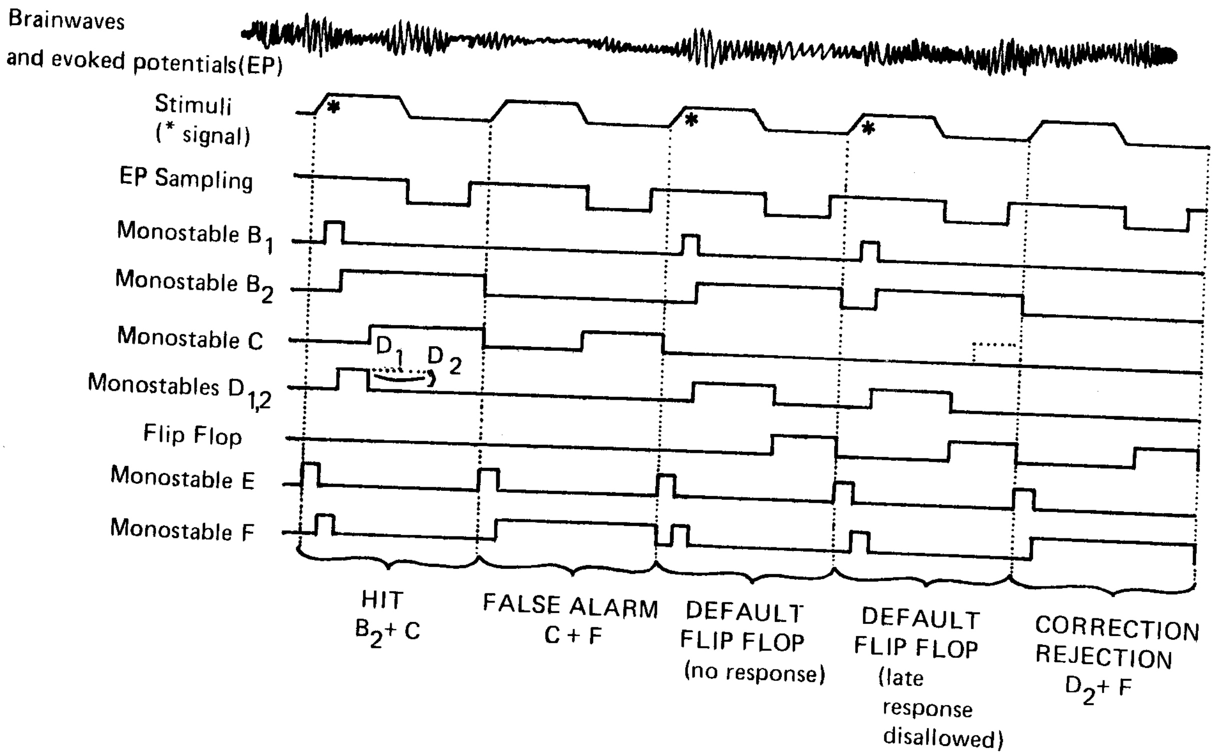
EVOKED POTENTIAL FEEDBACK DEVICE



TIME SERIES OPERATION OF EVOKED POTENTIAL FEEDBACK DEVICE

Figure 4.7

A. Signal Detection Stage



B. Evoked Potential Amplitude Analysis Stage

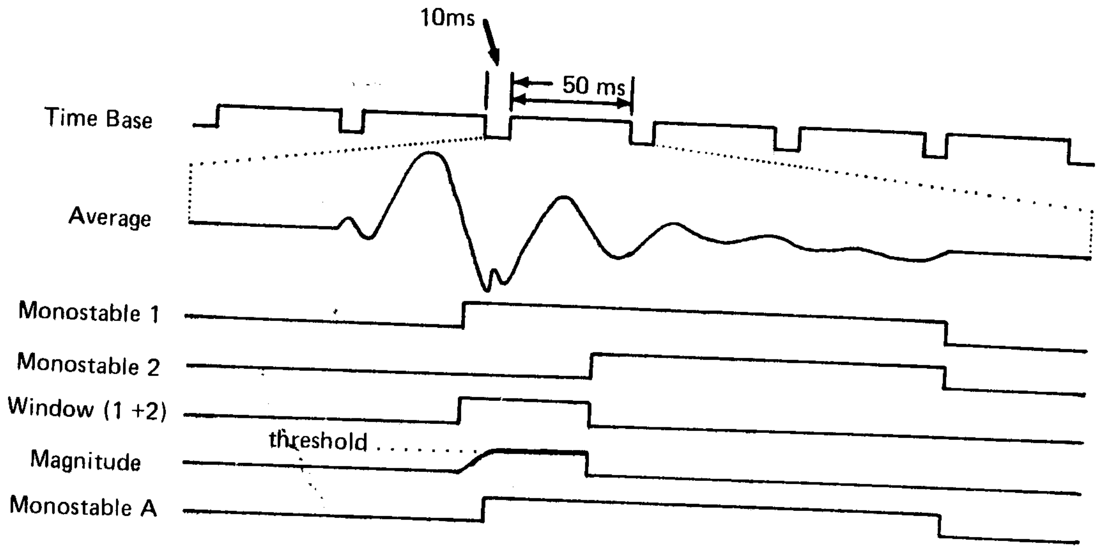


figure 4.8

COMPONENT VALUES FOR EVOKED POTENTIAL FEEDBACK DEVICE

Label	Items	Component Name	Component Number
A_1–A_3	3	operational amplifiers	BB 3550 J
A_4	1	operational amplifier	741
D_1, D_2	2	diode	1N4145
D_3, D_4	2	diode	1N5605
D_5	1	zener diode (5.1 volt)	1N4733A
R_1–R_5	5	resistor (¼ watt)	5 kiloohm
R_6	1	potentiometer	10 kiloohm
1, 2; A,B_1,B_2,C; D_1,D_2,E,F	10	timer (monostable configuration)	555
T_1–T_7	7	transistor switch	2N5140 or 2N3639
Unlabeled Diodes	7	diodes	1N4148
All Monostables	10	capacitor (pin 3 to common)	1000 picofarad
	10	capacitor (pin 5 to common)	.01 microfarad
A,B_2,C,D_1,D_2,F	6	capacitor (pin 5 to common)	10 microfarad
B_1,E	2	capacitor (pin 6 to common)	.1 microfarad
R_7,R_8,R_{13}	3	potentiometers	1 megaohm
R_9,R_{10},R_{14}	3	resistor (¼ watt)	10 kiloohm
R_{11},R_{12},R_{15},R_{16}	4	resistor (¼ watt)	10 megaohm
C_1,C_2	2	capacitor	.01 microfarad
C_3,C_4	2	capacitor	1000 picofarad
transistor	4	quad "and" gates	7408
transistor	1	quad "nand" gate	7400
logic module	1	hex inverter	7404

FIGURE 4.9


EVOKED POTENTIAL FEEDBACK UNIT
coarse
THRESHOLD
coarse
Δ1
Δ2
fine
fine
only right
hits
misses
false alarms


G
audio
-15

Glossary

absolute magnitude detector (operational amplifiers A_1, A_2 and A_3) measures the amplitude of an averaged evoked potential within the interval that is set by the experimenter on the window generator.

any stimulus monostable registers the presentation of every stimulus in an experiment. It resets all functions in the instrument before each averaged evoked potential is analyzed.

correct rejection (C) is the appropriate outcome in a task to detect or to recognize a signal, when the occurrence of a non-signal is not indicated by the subject.

default monostable and flip flop automatically registers a miss after a preset length of time in which the subject fails to indicate a response.

false alarm (F) is the inappropriate outcome in a task to detect or to recognize a signal, when the occurrence of a non-signal is indicated by the subject to be a signal.

false alarm monostable registers false alarm responses.

hit (H) is the appropriate outcome in a task to detect or to recognize a signal when the occurrence of the signal is identified by the subject.

miss (M) is the inappropriate outcome in a task to detect or to recognize a signal, when the occurrence of a signal is not identified by the subject.

pushbutton monostable registers the responses of a subject when he indicates his response.

signal event monostables are triggered at the onset of presentation of a particular stimulus that is designated as significant in an experiment.

threshold detector compares the measure from the absolute magnitude detector with a value that is set by the experimenter which the amplitude of the subject's evoked potential must exceed for a reward.

threshold monostable is triggered by the threshold detector to indicate that a reward, designated as '+', should follow; when not triggered, the feedback is designated as '–'.

time base is a signal from the averager which identifies the beginning and the end of averaged evoked potentials as they are being read from the memory of an averager.

window generator is set by an experimenter to determine the range of latencies that the instrument will analyze. For instance, an interval from 275 to 375 milliseconds after the presentation of a stimulus may be chosen to analyze the P_{300} component.

Circuit Operation

The circuitry of the evoked potential feedback instrument follows two timing cues: the *time base* and the *presentation of every stimulus*. The circuitry that is synchronized by the time base is primarily analog. The circuitry that follows the presentation of stimuli is digital.

The *time base* is a sequence of pulses which synchronize the circuitry that analyzes each averaged potential with the readout of each one from the averager's memory. This synchronization is similar to that in an oscilloscope when the time base is used as an external trigger of each sweep of the screen to give a stable, "single-frame" display of each waveform.

The onset of each pulse of the time base triggers the *window generator*. the window generator provides a single pulse after being triggered. The times of onset and offset of this pulse are separately adjustable. These times must be set by the experimenter to determine which range of latencies in averaged evoked potentials that the instrument will analyze. The first latency in the range is set by adjusting the variable resistor (labeled △ 1 on the front of the instrument) which is at pin 4 on monostable multivibrator 2. Similarly, the last latency in the range is set (△ 2) with monostable 1.

The pulse from the window generator opens and closes the transistor switch, TR_1. This gates the operation of the *absolute magnitude detector*. When the window pulse goes "high", the switch grounds a capacitor, C_5. When "low", the capacitor charges and the output of the operational amplifier labeled A_3 reads the absolute magnitude of the averaged evoked potential. The circuit for this absolute magnitude detector, consisting of A_1, A_2 and A_3, was published by Graeme, 1974.

The output of the absolute magnitude should resemble this waveform:. If it is found to resemble a sawtooth waveform (), then the capacitor, C_5, must be replaced by a capacitor which is lower in value, because it is being reset at a faster rate than the rate that is required for it to change.

The operational amplifier, A_4, is used as a variable comparator. By adjusting the variable resistor, R_6, an experimenter may set the threshold above which the amplitude of the averaged evoked potential will be registered as having met or exceeded ("+") the objective of the experiment. Below the threshold, the amplitude will be registered as having failed ("-") to meet the objective. Having met or exceeded the objective causes the output of this *threshold detector* to go "low", triggering the *threshold monostable* multivibrator (A).

The threshold must be set to suit the evoked potentials of each subject in every experiment. If the threshold detector is unable to resolve the variations in the amplitudes of each waveform, then an extra amplifying stage must be added. This can be done by adding a small resistor in the feedback loop of the buffer amplifier labeled A_3.

The presentation of every stimulus must be identified by a negative pulse at pin 2 of monostable E, *any stimulus monostable*. The onset of the output of monostable E resets the signal-detection circuitry in preparation for registering the next event. Therefore, a triggering device, such as a schmitt trigger, should be used to monitor the audio signals that are presented to the subject in order to give this pulse. Otherwise, if the stimuli are recorded, a separate track should be used to record pulses that are synchronized with the onset of every stimulus that is presented to a subject. Using either method, the resulting pulses are used to synchronize the signal-detection circuitry to the presentation of each stimulus.

Some method is needed to distinguish a signal from non-signals for the instrument. Be it recorded or generated for each presentation, the same pulse that triggers the sampling of EEG activity by the averager must also identify the occurrence of signals in the evoked potential feedback instrument. The onset of this pulse must be negative-going and it triggers the *signal event monostables* (B_1 and B_2).

A device such as a pushbutton is needed to register the responses that a subject must indicate in a signal-detection experiment. For this instrument, the responses must be registered as negative-going pulses to trigger the *pushbutton monostable* (C). If the onset of the output from the pushbutton monostable occurs too late, then a miss or a default is registered. In this instrument, misses and defaults cannot be distinguished.

The *default monostables* are triggered for every presentation of a signal. They set the latency at which a miss or a default is registered and this latency is adjustable. It can be changed by setting two ganged potentiometers (R_{13} and R_{16}) on both default monostable multivibrators. One of the default monostables (D_1) is reset by the onset of the output from the pushbutton monostable (C) and the other is not. If the default monostables are synchronous when their outputs go "low", they trigger the *default flip-flop* (D_f) to register a miss or a default. However, if the default monostables are not synchronized, then a response must have been registered before the end of the default time, so D_f is not triggered.

For every presentation of a non-signal the *false-alarm monostable* generates a pulse. If the pushbutton is depressed on such occasions, then a false alarm is registered.

The outputs of the evoked potential feedback instrument may be used in many ways. It is suggested that the outcomes of signal-detection responses be registered by illuminating light emitting diodes (LEDs) with the pulses at each output labeled C,D,F or H. The threshold-exceed pulse may be used to identify on a chart recorder beside a continuous recording of brainwaves, each time that the subject's evoked potential meets the amplitude criterion in the experiment. The absolute magnitude of the pulses may be plotted as a function of time throughout the experiment to represent the subject's performance. Another output is the window. It is a pulse that can be displayed on a dual-trace oscilloscope with averaged evoked potentials. By adjusting $\wedge$ 1 and $\wedge$ 2 on the evoked potential feedback instrument while observing the screen, an experimenter may select the best range of latencies for the instrument to analyze for each experiment.

4.34 Using A General-Purpose Computer

This section briefly outlines the use of a general-purpose computer to test the thesis that biofeedback training using cerebral evoked potentials might influence perception. This is an alternative to using a special-purpose computer.

The advantage of using a general-purpose computer is that it is much more flexible than a special-purpose computer. However, it is more expensive. For instance, at the time of writing this paper, it would have cost approximately $2500 to have a computer program written plus $150 per hour of "on-line" computer time to run an experiment. The total cost of an adequate experiment would have exceeded the price of purchasing a special-purpose computer. The source of this estimate was the manager of the Computer Research Facility at the University of Toronto. His interactive terminal is an example of the type of set-up that is needed to test this thesis.

A general-purpose computer can be programmed to analyze evoked potentials and signal-detection responses to obtain exactly the same results as a special-purpose computer (discussed in section 4.33). For instance, a weighted average can be obtained by multiplying an existing average by a factor of β and by multiplying the incoming input to the average by a factor of $(1 - \beta)$ before adding them together.

The diagrams in figure 4.10 outline all of the stages in an analysis of scalp-recorded brainwaves during a signal-recognition experiment in which human subjects receive evoked potential feedback. On-line access to the computer is necessary to give the experimenter the ability to adjust parameters of the computer program to suit the characteristics of each subject. Also, on-line interaction is necessary to perform analyses of data and to provide a subject with feedback as quickly as possible after the presentation of each stimulus. The longer the interval is between a response and feedback, the less effective is the feedback as a reinforcer.

The inputs to the computer program are similar to the inputs to the hardware signal averager that is discussed in section 4.33: brainwaves, pulses to identify signals and pulses to identify every event. In addition, any number of non-signals may be identified and movement artifacts such as EMG and EOG signals may also be identified to the computer program.

The evoked potentials in the brainwaves may be sorted by one of two methods. The method that is shown in the diagram sorts them according to the type of signal-detection response that they accompany. This type of sorting is a function of the identity of the stimuli which appear on each trial. An alternative method which is described by Ruchkin (1971) is an automated pattern-recognition program which sorts evoked potentials according to classes of statistically significant variances of many points in the waveforms of single evoked potentials. Ideally, both methods would operate simultaneously so that correlations could be sought between their results in order to explore the relationships between evoked potential waveforms and the information that they encode. However, for a practical test of this thesis, the method that is illustrated should be adequate.

The sources of signals in figure 4.10a are (1) the subject's brain — brainwaves or EEG signals, (2) his eye-muscle — EOG signals, (3) pushbuttons on which he indicates his judgements and (4) a generator of sinusoidal tones — stimuli (a method of generating auditory stimuli with electronic music is discussed in appendix B). The amplifiers are differential and they provide optical isolation (explained in appendix C) between the subject and stages which follow the amplifiers. All of the remaining boxes in the figure refer to operations in the computer.

In order to begin sampling the EEG signals at a fixed interval of time before the presentation of each stimulus to the subject, the auditory stimuli which he hears are delayed. When the stimuli occur (unsounded) before being delayed, they trigger a sampler window to pass a segment of the EEG recording to the short-term memory. The beginning of the recording is held in the memory until the window closes to end that segment. If eyeblinks or large deflections of the eyes occur during the recording of the EEG signals, then the sample is labeled E on the plotter, but it is not averaged.

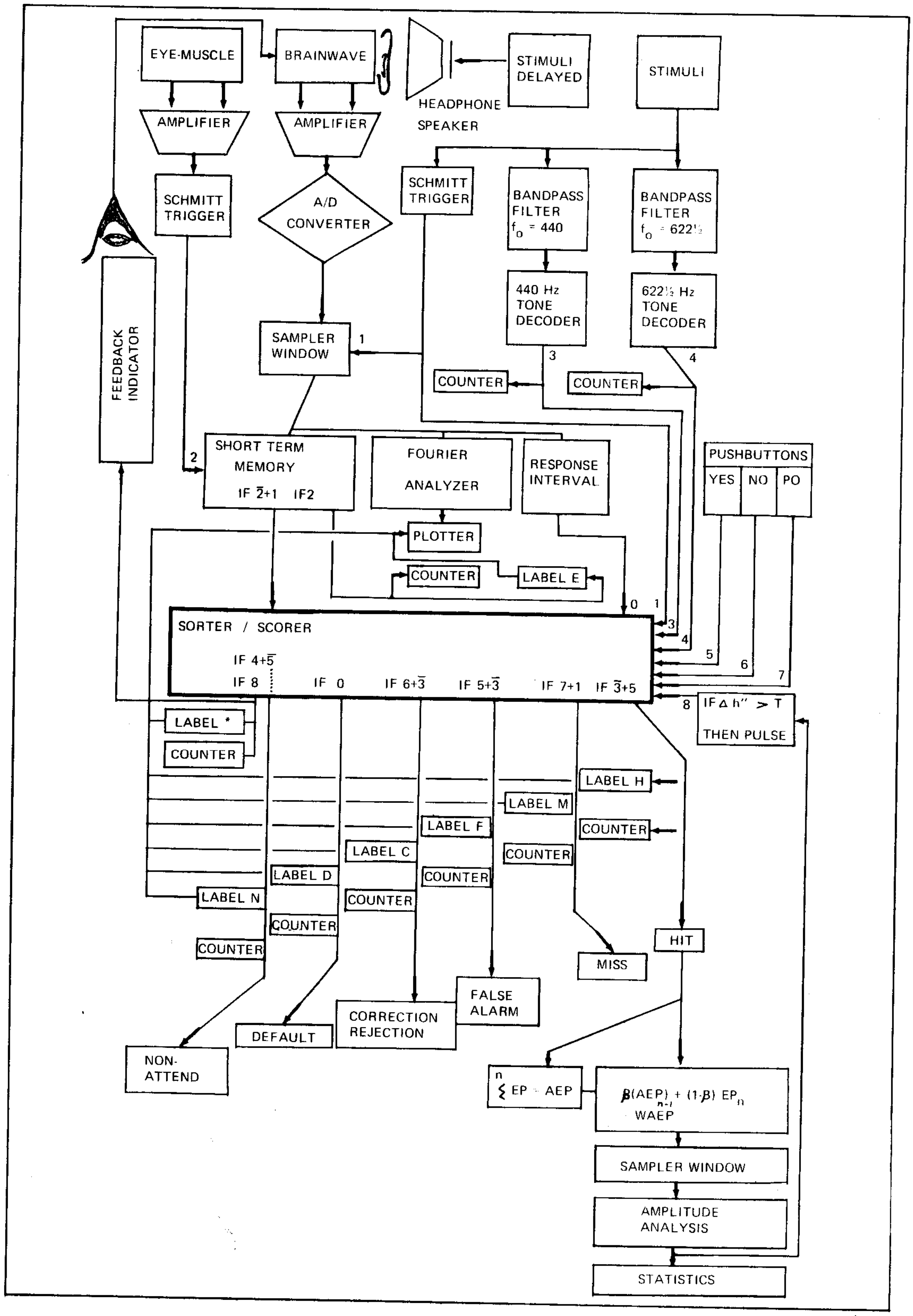
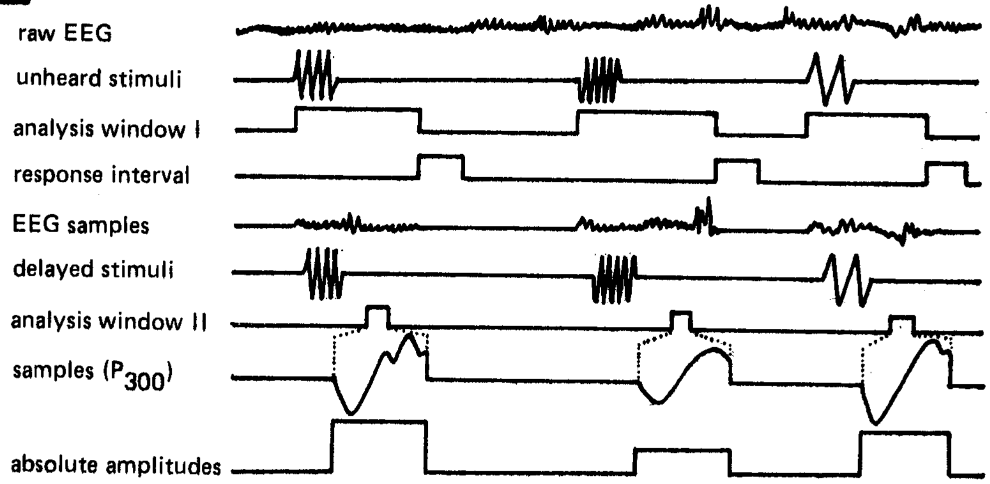

EYE-MUSCLE
BRAINWAVE
STIMULI DELAYED
STIMULI
HEADPHONE SPEAKER
AMPLIFIER
AMPLIFIER
SCHMITT TRIGGER
A/D CONVERTER
SCHMITT TRIGGER
BANDPASS FILTER f_o = 440
BANDPASS FILTER f_o = 622½
440 Hz TONE DECODER
622½ Hz TONE DECODER
FEEDBACK INDICATOR
SAMPLER WINDOW
COUNTER
COUNTER
SHORT TERM MEMORY IF 2̄+1 IF2
FOURIER ANALYZER
RESPONSE INTERVAL
PUSHBUTTONS
YES
NO
PO
PLOTTER
COUNTER
LABEL E
SORTER / SCORER
IF 4+5̄
IF 8
IF 0
IF 6+3̄
IF 5+3̄
IF 7+1
IF 3̄+5
IF Δ h" > T THEN PULSE
LABEL *
COUNTER
LABEL H
LABEL M
COUNTER
LABEL F
COUNTER
LABEL C
COUNTER
LABEL D
COUNTER
LABEL N
COUNTER
COUNTER
COUNTER
HIT
MISS
FALSE ALARM
CORRECTION REJECTION
DEFAULT
NON-ATTEND
$\sum^{n}$ EP ÷ AEP
$\beta(AEP_{n-1}) + (1-\beta) EP_n$ WAEP
SAMPLER WINDOW
AMPLITUDE ANALYSIS
STATISTICS

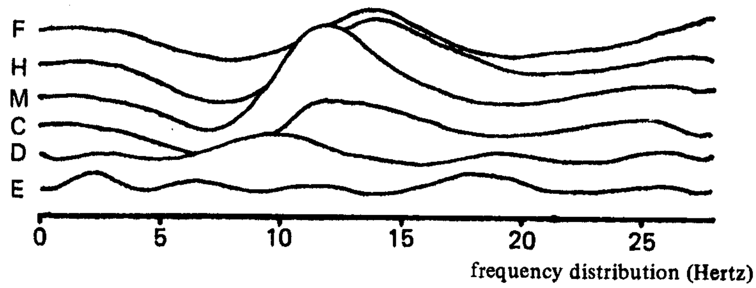
Figure 4.10b

FIGURAL ANNOTATIONS TO FIGURE 4.10a

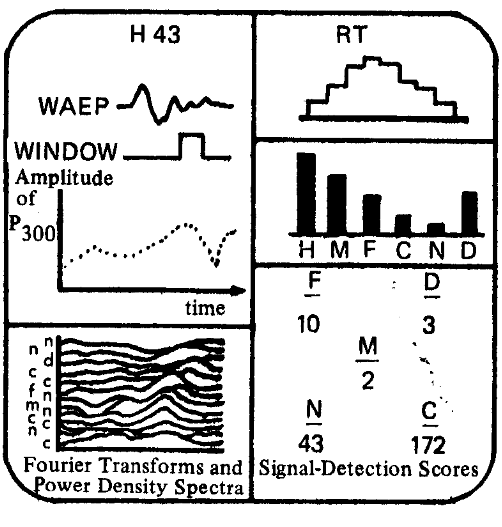
a) Timing



b) Fourier Analysis of Samples with Signal Detection Scores



c) Interactive Computer Readout Monitor



Legend

- C correct rejection
- D default
- E contaminated by eyeblink
- F false alarm
- M miss
- N non-sttended stimulus
- RT reaction time
- WAEP weighted averaged evoked potential (or SEP, "single evoked potential", in the method of sorting by pattern-recognition)

Some stimuli which are to be sought by the subject in his task (signals) are identified by a band-pass filter and a decoder. For example, the signals may be tones with a frequency of 440.0 Hz. A non-signal which occurs the same number of times as the signal is also identified to the computer. For example, it may be a tone with a frequency of 622.5 Hz, as indicated in figure 4.10a.

A block in figure 4.10a represents a sorting and scoring operation. It distributes successive samples of the person's EEG signals to various "bins" in which samples are pooled according to (1) the outcome of the subject's judgement (correct rejection, default, false alarm, hit, miss), (2) the latency of the response (A time-limit is set in the block which represents the "response interval") and (3) whether the tone of 622.5 Hz occurs. The criteria for sorting are found in "IF statements". For example, one reads "if there is a pulse at 4 and no pulse at 5, then the tone of 622.5 Hz occurred and the sample of the person's EEG signal should be added to the pool of non-attended stimuli which are labeled N". In figure 4.10a this statement is started with "IF 4 + $\bar{5}$" and continues downward in the diagram. Counters give the number of samples in each bin. The experimenter can use these tallies to monitor the subject's performance.

Conventional and weighted averages are performed on the samples in each bin. An analysis of the amplitudes at P_{300} of each sample is used to provide histograms on a monitor that is depicted in figure 4.10b. If the amplitude of P_{300} in an evoked potential for a hit(Δh) exceeds a value 'T,' set by the experimenter, then the subject receives feedback to encourage him to repeat this performance. A fast fourier analysis of each sample is recommended, using a staggered method of plotting data as shown in figure 4.10b. This provides the frequency spectra of each waveform. A similar plot with the fourier values squared and divided by the length of the sampling interval in seconds gives another measure of sample-to-sample variations — power density spectra.

An illustration of the timing of operations that are shown in figure 4.10a is shown in figure 4.10b.

CONCLUDING REMARKS

Although some electrical activity in the brain must be meaningful to a person, he may not be aware of, nor be capable of becoming aware of other electrical activity in the brain. Which sort of brainwaves is P_{300}, meaningful or meaningless to a person, is not known.

P_{300} is large in voltage and broad in spread relative to other components of cerebral evoked potentials. The start of P_{300} occurs after the physical sensation of a stimulus is registered by sensory organs. The fact that P_{300} can be recorded at a time when an expected stimulus is omitted shows that P_{300} reflects psychological factors in perception. Many psychological factors other than expectation influence the amplitude of P_{300} also. However, P_{300} is independent of the physical properties of stimuli.

Therefore, P_{300} is clearly an index of "higher" activity than simple registration of a sensory event in the brain. Around 300 milliseconds after the presentation of a stimulus which triggers a decision, the time when P_{300} is usually found, is also around the time of the fastest reaction-time that a person is capable of achieving after making a decision. The consensus of researchers is that the amplitude of the P_{300} component of cerebral evoked potentials is an index of the orienting response — a compelling drive to investigate the perceived source of a significant stimulus.

Preliminary studies on the operant modification of evoked potentials consistently report success. For any component of an evoked potential to be modified by operant training, that component must be functionally significant to an experimental subject. Consequently, if P_{300} can be modified with biofeedback training, then it must be functionally significant to a person.

It is probable that P_{300} can be modified with such training. It is possible that the neural activity which P_{300} accompanies is meaningful to a person. Consequently, it is possible that the result of an attempt to modify the amplitude of P_{300} as the main objective of an experiment will be to achieve a sophisticated non-verbal communication.

The occurrence of P_{300} strongly correlates with a response that alerts a person's attention to a significant stimulus. Ideally, training to generate large amplitudes of P_{300} for a particular stimulus will be accompanied by conscious arousal to occurrences of that stimulus. In other words, such training might assign a particular significance to any given stimulus.

Such training might be useful for people such as airline pilots, who should be immediately aroused by emergency signals. It might be used to train autistic individuals to react consistently to a particular stimulus. This might give them a point of reference with which to judge appropriate responses. People who are unconscious may be "communicated with" if they have two intact sensory channels: one for administering a stimulus and the other for administering a feedback stimulus to encourage the person to modify his evoked responses. Another application might be to teach musicians "absolute pitch".

This paper has introduced a new application of brainwave biofeedback. It may find some useful applications in medicine, music and elsewhere. Therefore, evoked potential feedback deserves attention in research.

APPENDIX A

A Misconception About Correlation Analysis of EEG

Several attempts to test the thesis that biofeedback with cerebral evoked potentials might be used to "improve" perception were frustrated because of misleading specifications for an instrument.

A Princeton Applied Research Model 101A Correlation Function Computer was available to analyze brainwave recordings when the work began. The plan was to gate the sampling operation of the correlation computer and to use it like an averager, an idea that was supported by an article written by Ledley (1965) which referred to averaging as a special case of cross-correlation. The article states that *the correlation* of a spike waveform that is synchronized with a stimulus that is presented to a subject and a subject's brainwave recording *is theoretically equivalent to an average.* This is shown mathematically by:

$$\Omega(\tau_i) \cong \frac{1}{T}\int_0^T \nu(t)\, s(t+\tau_i)\, dt \cong \frac{1}{n}\sum_{j=1}^{n} \nu(t_{ij})$$

(for $\Omega(\tau_i)$, a cross-correlation function; $\nu(t)$, an EEG waveform) s(t) a spike waveform; τ, a small interval; T, a sampling period). This explanation is accompanied by a diagrammatic explanation in Ledley's book on page 363.

The misconception arose from the specifications of the Model 101A correlator. Although the specifications state that this correlator uses multipliers to feed a delay line, this correlator does not use multipliers which satisfy the standard definition that there be a zero output when either input to a multiplier is zero. In fact, the output of the "multiplier" is random when either input is zero. Therefore, the Princeton Applied Research Model 101A Correlation Function Computer *cannot* be used to perform averaging as one might easily, but incorrectly, infer from its specifications, Ledley's article, and similar articles by Barlow (1959), Letzter (1975) and Regan (1972).

APPENDIX B

Generating Auditory Stimuli with Electronic Music

This article reviews a novel technique for generating auditory stimuli for evoked potential research by using concepts and equipment of electronic music.

Stimuli for evoked potential research on the recognition of equally loud sounds of different pitches must fulfill two requirements. One is that auditory stimuli occur as a sequence of discrete tones which have adjustable envelopes and adjustable interstimulus intervals. Another requirement is that the stimuli are marked, so that samples of EEG activity can be sorted according to the identity of stimuli which elicit the evoked potentials that are contained in the samples.

The first requirement is easy to satisfy with conventional methods in electronic music. Almost any choice or combination of auditory waveforms may be selected for each stimulus from audio oscillators. A variety of tones of different frequencies may be obtained from a single voltage-controlled oscillator using a sample-and-hold circuit. The sample-and-hold circuit can be programmed to select voltages from almost any desired range of voltages to control the frequency of the oscillator. The rate of selection of the voltages may be controlled independently of the range of voltages. Also, the duration of each voltage that is selected may be programmed independently of the rate of selection and the range of voltages. The combined operation of these two modules, a voltage-controlled oscillator and a sample-and-hold circuit, produces a sequence of audio signals in which the frequency of tones, the duration of tones and the interstimulus intervals are adjusted separately.

To control the envelope of each tone requires two more modules: an envelope shaper (an attack (A), decay (D), sustain (S) and release (R) circuit) and a voltage-controlled amplifier. The envelope shaper sets a sequence of voltages which controls the amplification of each tone.

Since tones of equal intensity, but different frequency, are not perceived as being equally loud, something must be done to make different tones equal in loudness. A simple solution is to condition the tones by passing them through an "A" filter which imposes limits on the amplitudes of tones of different frequencies. These limits imitate the sensitivity of humans to loudness as a function of frequency (see data on this function from Fletcher and Munson in Gulick, 1971, page 146), so the tones sound equally loud. (The use of the "A" filter is discussed in section 3.12 and in *Acoustic Handbook* by Hewlett-Packard Company (1968)).

The second requirement of auditory stimuli is that they be marked. One way to do this is to switch off the sampling control of the sample-and-hold circuit between tones, while simultaneously switching a second channel to the pulse which controls the holding time of the sample-and-hold circuit. Consequently, the sampling voltage is removed so that the output of the oscillator returns to its center frequency, and a pulse appears on the second channel which is synchronized with the beginning of the next tone which is at that center frequency. Therefore, the experimenter may program the switching to be done during any interval between the tones in a sequence and whenever the sampler is disconnected, the center frequency of the oscillator will be heard while a pulse appears to identify that tone on another channel. Since the pulse is used "to gate" (to turn on and to turn off) the sampling of EEG activity and it is usually desirable to begin sampling at a fixed interval before the presentation of a stimulus, the tones may be delayed by any interval of time in a "tape delay" (an arrangement for recording and playing back a sound after an interval of time that depends on the distance between "record" and "playback" heads on a tape-recorder and the speed of the tape). A schematic diagram of this method is shown in figure B-1.

This is a schematic diagram for patching (arranging and interconnecting instruments to achieve a desired result) a channel of tones which vary in frequency, but not loudness, as a pulse on a second channel identifies the occurrence of the central frequency to which the oscillator is tuned.

The advantages of the foregoing method are that the differences in frequency between the unmarked tones and the marked tones may be very small without danger of having the wrong signal accidently marked, and it is easy to arrange with standard equipment of electronic music. The disadvantages are that only a single tone may be marked, and in some instances that tone may be sampled by the sample-and-hold circuit without being marked with a pulse.

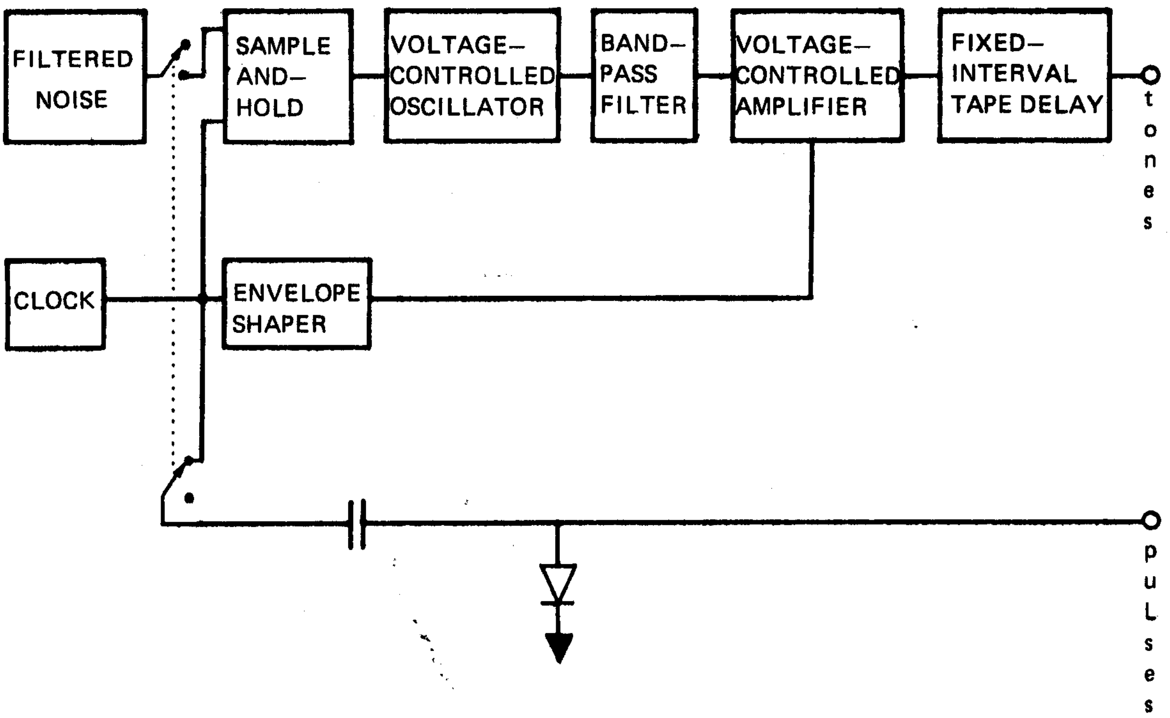
APPENDIX B

figure B—1
Generating Auditory Stimuli with an Electronic Musical Instrument: Schematic

This diagram shows an arrangement for components of an electronic musical instrument. Such an arrangement can produce two channels of sounds described as follows:

1. One consists of a series of equally loud sinusoidal *tones* of various arbitrarily selected frequencies.
2. The other consists of a series of *pulses* which occur only at the times of onset of certain tones on the other channel. Those "certain" tones are ones that have the same frequency as the central frequency to which the oscillator is tuned.

Accordingly, when the switch is in the position shown below, tones of one frequency appear on one channel and pulses that mark the onsets of those tones, appear on the other channel. When the switch is moved to the other position, only tones appear and they have various frequencies (pitches). Therefore, by controlling the position of the switch, one controls the occurrence of certain tones at the central frequency, which are marked by pulses on another channel.



To overcome the limitations of the foregoing method, the following alternative to using the switch may be used to mark several tones without errors provided that the differences between the frequencies of the tones are not too small. Therefore, the frequencies of the tones must differ by more than a critical bandwidth.

A circuit that is commonly used to decode the tones of a "touch-tone" telephone is sensitive to audio frequencies, reliable and inexpensive, making it ideal for identifying when particular audio frequencies are present. "Tone decoders" can be programmed to produce a pulse whenever a tone of a particular frequency appears at its input. For an example of the application of this circuit, consider that the occurrences of two tones which occur randomly in a sequence of tones must be separately identified: a signal (A_4 — 440.0 Hz) and a non-signal (D_5 — 622¼ Hz). A signal is distinguished from a non-signal by its relevance in a signal-detection task. The circuit to recognize these tones is shown in figure B-2. Accompanying the figure are two tables. One relates the sensitivity of the circuit to inputs of several frequencies. The other relates the values of the resistor (R ohms) and the capacitor (C microfarads) to set the center frequency to which the decoder is tuned.

The values of the components were selected to satisfy the following criteria:

oscillators that are usually found in electronic musical instruments are accurate to within ± 1 percent;

the intervals between tones will be those intervals which are defined by the American Standart Scale of Musical Pitches;

since it is easy, even for people who possess "absolute pitch" (discussed in section 4.24), to confuse octaves of a tone, octaves of the signaling tone will not be included in the non-signals. Also, since tone decoders are occasionally falsely triggered by octaves of their center frequencies, such non-signals must also be excluded.

(The American Standard Scale of Musical Pitches is published in the *Handbook of Physics and Chemistry*, 54th edition, 1974, by Chemical Rubber Publishing Company (R.C. Weast, editor). The specifications of the 567 tone decoder are published in the *Linear Integrated Circuits* catalog of products that are produced by National Semi-Conductor Company (1975). The *Acoustics Handbook*, application note 100 by Hewlett-Packard Company (1968) can be obtained from Hewlett-Packard Company, 1501 Page Mill Road, Palo Alto, California, U.S.A.).

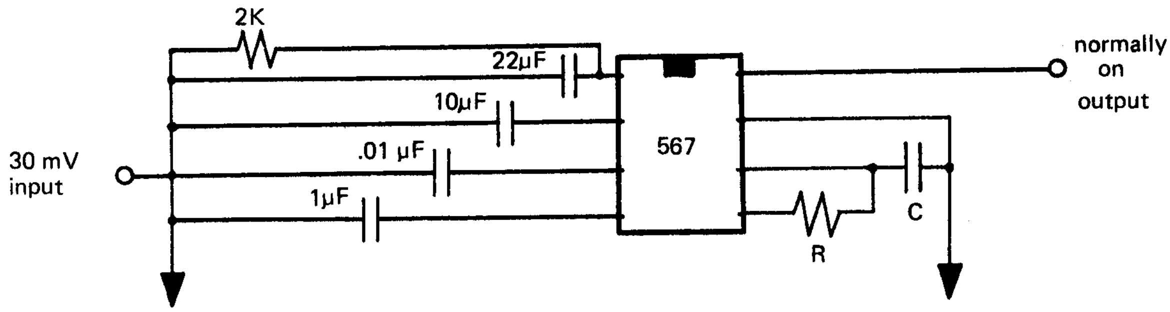
APPENDIX C
Safety in Studying Bioelectricity in Humans

This article on safety is one outcome of my attempts to perform experiments at different institutions to provide data for my thesis. I encountered markedly different standards of care regarding the use of human subjects in research. My own neglect was pointed out after I had performed experiments for several months. Consequently, I have summarized in this article, the main features of documents which other researchers may wish to prepare and to file. Such documents would demonstrate that the research which is undertaken on bioelectricity in humans is planned with reasonable care to ensure the safety and to protect the rights of human subjects. Such a file would provide tangible support for unfortunate experimenters, subjects and sponsoring institutions, if undesirable consequences of an experiment that were reasonably thought to be "impossible" outcomes, should occur.

TOPIC: Brainwave biofeedback. This involves (1) recording a person's brainwaves, (2) analyzing the recordings in a computer and (3) immediately indicating to the person the results of the analysis.

OBJECTIVES: To determine the effects of brainwave biofeedback on the recordings of brainwaves following the presentation of particular stimuli and to assess the effects of this on the perception of the stimuli. I predicted that this training would help a person to perceive any given stimulus as reliably as he perceives his own name.

Tone Decoder Circuit — figure B–2



Sensitivity of the Circuit

center frequency (f_o)	musical pitch	critical bandwidth (%f_o)	critical bandwidth (Hz)
220	A_3	3.95	8.96
311	$D\#_4$	3.20	9.95
440	A_4	2.79	12.27
622	$D\#_5$	2.35	14.62
880	A_5	1.97	15.75

Table of RC Values to Set f_o

center frequency (f_o)	musical pitch	R Ω	C (µF)
311.13	$D\#_4$	6,839	.47
440.00	A_4	10,330	.22
622.25	$D\#_5$	4,870	.33

RECRUITING SUBJECTS: Advertisements stating that biofeedback experiments were being conducted to study the relationships between brainwaves and perception, requested volunteers to be subjects. Volunteers were promised free hot beverages and bibliographies on biofeedback for participating.

INDUCTION: Subjects were invited to make appointments in the laboratory after agreeing to sign a consent form which read as follows:

CONSENT FORM

I have been asked to participate in a study to investigate pitch-recognition and brainwaves. I understand that I will be asked to attend three one-hour sessions. Electrodes will be attached to my head and I will be wearing earphones. I will listen to a tone being repeated. Then I will be asked to learn to identify that tone in a sequence of various tones.

The risks are minimal. The electrodes will be attached with adhesive to the surface of my head, face and ears. They will be filled with a salty jelly which is unlikely to cause skin irritation during a session of the experiment. There is no danger of hearing loss, because the time of exposure is too short and the intensities too low. Moreover, I can remove the earphones at any time.

I understand that there is no payment for my participation in this study. I also understand that all information arising out of this study will be treated in a confidential manner and I may withdraw from the study at any time.

Dated at Toronto this ____________ day of ______________________, 197______.
(signed and witnessed).

RECORDING TECHNIQUE: Cup-shaped silver / silver chloride electrodes filled with a gelatinous electrolyte were applied to (1) the vertex of each subject's head, (2) each mastoid and (3) around one eye. These were secured with elastic bands and adhesive tape. Two preamplifiers equipped with optical isolation connected the electrodes and a computer.

PROCEDURE: Each subject was prepared, seated and requested to stare at a target and to remain still during trials. The task was explained. Subjects were asked to remember a sample of a tone and to indicate by depressing a pushbutton when they recognized that tone in a sequence of various tones which followed the sample. This was repeated up to eight times in one hour with rests between each sequence. On some trials the subjects were also requested to try anything except move or look away from the target, to keep a light on. The reason for this was not explained to the subjects, but they were told that it was desirable to keep the light on as much as possible. The light indicated that a particular amplitude in the brainwave had been met or exceeded. Part of the training was to increase the amplitude of a segment of the brainwave. Another goal of the training was to improve the reliability of the subject's perceptual judgement.

RISKS: Risks were minimal. Electrodes were placed on the surface of the skin. Since they were not implanted, *abrasions of the skin* would not occur. The jelly for the electrodes was primarily salt and water. This may cause *chemical irritation* with prolonged contact over many hours. However, single sessions of the experiment were shorter than one hour and the jelly was removed afterward with warm water. Subjects were told in advance that they may wish to wash their hair after experiments, because of the use of jelly and elastics in their hair.

Connecting a person's brainwaves through an amplifier to a computer presents a potential danger of *electric shock*. However, the high impedence of the differential amplifiers virtually eliminated the possibility of passing harmful electric current (either 10 milliamperes of alternating current at 50 to 60 Hz or 50 milliamperes of direct current). The amplifiers were powered by batteries and as an optimal safeguard against electric shock, they were equipped with optical isolators. *Optical isolators* use emitters and detectors of light to interrupt the path between the inputs and outputs. This means that no wired path for current to follow, connects the subject and any device equipped with optical isolation.

No danger of sustaining a *hearing impairment* could follow from participating in the study. The intensities of the stimuli were moderate, around 40 dB (A) above sensation levels.

The subjects were not *abused with excessively high expectations*. They were asked to perform to the best of their ability. They were not required to maintain unnecessarily intense vigilance. Subjects were invited to interrupt the session for clarification of instructions or to relieve any discomfort. Each subject could be readily removed from the "set-up", because they were only connected by easily removable pin-plugs. A typical session of the experiment lasted one hour including a recorded musical introduction (1 minute), a recorded verbal introduction of the task with practice (2 minutes), 8 trials of the experiment (40 minutes), 6 rests between trials (12 minutes), plus time to apply and remove the electrodes (5 minutes).

The identities of the subjects remained *confidential*. Names or initials of subjects, or any other identifying trait were deleted from my files once the data was abstracted. Nothing to suggest the identities of the subjects appears in any documents or publications that I have written or will write.

The above documents were approved by a committee of people who were unfamiliar with the project before reading the above. The committee consisted of experts in audiometry, physics (electronics), psychology and law.

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When The Virus Kills The Body And Is Buried With It, The Virus Can Be Said To Have Cut Its Own Throat

by
Robert Ashley
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for
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The idea is the vast width of the space signifying the enormous number of variety of speeds. The width of the space would be enormous. Wider than one person can comprehend. The knowledge of its width is knowledge of the sort known to the collective. One of us could not have the knowledge of the width of the space. Contrast the width to the length (traverse) of the space. This length is very human. Something the oldest or a baby could hope to traverse. Not greatly long. Like ten paces or maybe less. And across the length of the space and throughout the vast width of the space the races and movements. From one end of the space to the other. Across the length of the space. Not racing one against the other, but racing to see what the length of the space will give up. In all forms. Perhaps at one point an enormous snail moving even slower than a snail, and across the length of the space — inside the space! — the fastest jet plane. Beyond the speed of sound. If you are sitting in a chair watching across the length of the space (ten paces) and there is no length beyond the length of the space, the jet plane must be as though in a dream. Who would describe it? And likewise if the snail moves slower than a snail, the snail must be as though in a dream. But these are not the only things. Some are slow. Some are fast. Some are within a lifetime and some are not. Some are even faster than the jet, probably. And with this race the reading of a text that must be read as fast as possible. I mean the text will never be heard (in nature?) except as spoken as fast as possible.
Many Movements Describing the Enormous Spirit of Moving of Bob Rauschenberg, from *Joy Road Interchange* by the *Once Group. First New York Theater Rally,* May 7, 1965. Text: September 10, 1972.

For me the relation between creative tendencies and music notation deteriorated during the past two decades to a point of no reconciliation. I can't imagine I will ever use notation again in any sense that we could agree on now. Of course, I speak for only a few of the musicians of the world. The majority by far have never used notation. A smaller number, but large in our world, will never imagine there exists any music except the music it knows from notation. A smaller number yet, but still much greater than the group whose ideas I speak of, continues to explore musical notation. Finally, there are the few, of which I am but one. On the basis of these numbers it is obvious that I am either among visionaries or among eccentrics (or both).

Creative tendencies are to leave music behind. (as such!) Everything (else) video laser digital survival is too much of a temptation. (The difficulty is to speak of one's ideas now as a product of the last two decades. I feel because of the new ways I have discovered for myself that music now is an invention of last week, as though the door long closed just opened to me, as though the last two decades are the prehistory of music. That feeling might not appeal to you. But it's just the relief I needed, one more step toward the realization of living in the present, replacing the old with the new as the generations pass. A natural sense of rhythm.)

When I say notation is useless to me, I realize that the product of notation might mean enjoyment to you — Mozart and the modern Viennese and something even more current — and I would not take away from you what you need to live and be happy. But I am supposed to talk about "creative" tendencies: to distinguish between dreams and manipulations; to distinguish between creation and production. And I have to tell you the way things are for me. I am oppressed by the old notation music. It is being used against me, both ideologically and politically. In America at least, the antiquated major musical organizations are sustained at the expense of virtually every ounce of support that might go to creations by living composers. And the question of notation — what (or whether!) music is — is at the heart of this problem. The closer one approaches the sources of money and power in American musical society, the more often one will encounter the dead stare, protestations of ignorance or outright hostility. For that reason I am not confident this condition of oppression will end gracefully. Interests are being served that have nothing to do with the people's desires. The governments of money and power have nothing to do with territories or nationalities (and those governments were bad enough, but visible.) It reminds me of our hated war in Vietnam.

I address myself as a composer: what does it mean when the example of your music teaches that music reaches its ideal in professionalism and authority — that is to say, money and power? Whom have you served? This is a serious matter: one of the places "where art and life meet." Are we to concern ourselves with making our fantasies less fantastic? Maybe something has been turned upside down: we are constantly "auditing" art — every penny accounted for, or consternation all around. When was the last time you worried that the transactions of the *stock exchanges* of the world are so arcane? Truly only read by experts. (deputized to *manage* our wealth, I would remind you. Try to explain to your next visitor from another galaxy that Mr. So-and-so *owns* the North Sea or most of the fuel you need for heat and that you are perfectly pleased to have your child live out his life in pain in order that these relationships among beings and things do not change. If, in addition, he wants to know what "pain" is, you are in trouble.)

How else am I to approach the problematics of today's music notation? It seems to me the puzzles are what I have just spoken about. Why after twenty years will there be no young americans on the season of expenditures for the New York Philharmonic (*Our* orchestra / our hero)? Why is notation dying? Who wants to know?

Guideline: to bring more ingredients under the control of the score. The good part was that the execution of any particular composition made you give up what you hoped would happen at every note. But the peculiar accuracy of the score posed the ugliness and arrogance of the notion of the urtext legacy testament library bound. Now everybody is embarrassed to have thought the thought. In retrospect this tendency seems to have been caused at least as much by the "approach" of electronic music and the need to think of the ingredients of sound in different ways (and some unnamed anxiety: probable reflection of incipient fascism in the culture body) as by the more commonly cited historical reasons.

The bad part was the recognition that notation is a form of order, like ownership or the police. Not to lecture you on order, or whether or not beauty has to have order. But to notice that the simile springs to mind pejorative and all, and everyone would understand it whether or not he agreed that the police or ownership as human inventions needed any rethought. In other words, we have common ground for believing that there is a *reason* for hoping that we can do without notation. The composer, obliged to put the very notes on paper, comes upon this fact first. Everything weights against following the logic, but that's no excuse. I don't speak for everyone, but among *my* friends the discovery that the increasing detail of control that freedom from the old notation made possible brought with it — or was synonymous with — a new responsibility to govern the players' lives in increasing detail and (during the performance?), to govern the listerners' lives in increasing detail and to apply increasing control to one's own life in order to gird up for the chore was an embarrassment of political dimensions: the composer as jailer. If you live among the prisoners, eat among the prisoners, fight among the prisoners, and have only prisoners for friends, whose side should you take when the breakout comes?

Guideline: to make scores of visual beauty that encouraged more diversity of interpretation. John Cage: "you don't know you're learning." A perfect kind of observation (testable at home without special equipment; not discriminatory), but wrong in fact, I'm afraid. It seems you can recognize learning: a passing feeling of confusion, of having suspended the burden of what you know, and of exertion, as real as the recognition that you're running a fever or that you're drunk. The confusion is: you don't know *what* you're learning. (italics mine.) Amazing. The inexpressible. Could we in order to survive begin now genetically to develop organisms like ourselves but with the capacity and tendency to "learn" more and to "know" less: to spend more time in the condition of learning and to spend less time watching the baggage? PUN: astral interviewer to man circa 2050, "Things were getting pretty tight there a while back. We didn't think you'd make it. How did you survive?" answer: "We couldn't come to any conclusions."

Graphic notation: a tendency during the past 20 years in particular and now increasingly refined to place signs on the page whose meaning has no habitual interpretation for the performer: substitution of context; sign into symbol; lead into gold. Irresponsibility, or the last echos of an old habit? This is the problematic. Unresolvable. Language says that in graphic notation we have reverted to pictures. As if (first language of indignation) something infinitely complex had been destroyed. A fundamental lie. Something finitely complex wore out. Pictures were an attempt to rescue something from the fire. Gallant but hopeless.

Notation, if we are talking about "notation" and not some other form of storage, is dead. Who would have guessed it in 1950? Perhaps John Cage. Who else? Make no mistake, the younger (than Cage) composers I refer to when these thoughts come up are not trying to save anything except in themselves the habit of communicating *about* music, and another decade may prove that even that habit can be forgotten.

Wake up. Musical notation was never a diagram of the experiences we are promised. It was a diagram of the obligations of the delegates and a REstatement of our aspirations for and identification with the design technology of 1) the instruments and 2) the social organization (ensemble.) Otherwise, everybody would read music. Unless we want to preserve the instruments or the social organization, we have no use for the notation.

Stop being sentimental. How much can we afford to *preserve?* A museum of musical experiences is *not* an alternative to the present state of things. It *is* the present state of things.

During two decades we rediscovered that notation and music are not synonymous. Crises of intellect and integrity for composers of music for electronic instruments, of music generated by computer, of music originating in the listener's mind: the incongruity of assigning picture symbols to those kinds of sounds takes the breath away.

Notation as we know it can only describe musical ideas derived from instruments designed (if not made!) two hundred years ago. Or analogs of those instruments. Designs based on endurance parameters that have no relevance in the electronic world: breath / pressure / metabolism / weight / etc. (And speaking of survival wouldn't you like to be rid of those?)

Resourcefulness, good humor and invention have flourished (it is a crisis, after all), but after two decades the promise of liberation in graphic symbols seems largely exhausted, the apparent wealth of signs an illusion: the dot or circle or variations still the "note," with frequency place and manipulations mostly included; the "staff" or some like reference to harmony; the vertical axis or variant reference to synchronicity. Try it for yourself.

Guideline: to describe what it is like here on the threshold of electronic city so they would know we lived and suffered too. Mixed media to describe what it means to leave your flag stuck in the moon in 3000 words or less. The question of notation: What do they take with them having survived? "skill" (?) "knowledge" (?) simple words. After the sorting, one more try at reaching the inexpressible through exercise of the expressible. How often before (in all history) have we worried about notation?

What to do about knowledge and the forms it comes in. We are worried now. We are carrying too much junk around with us. Not trusting, and perhaps justly, that when the need arises, it can be fulfilled from the environment. Answer: take your environment with you. That knowledge must be hundreds of thousands of years old. This is going to take some education and fast. The problem: separating out real demands (providing for sufficient water on the desert) from ephemeral needs (to be able to attend a concert if ever you so desire) proves what they've always said: we live not by bread alone. (Cold comfort.) The plan we use now, which is why we have put certain composers in the position of writing music for uninterested readers, is deputization: give everybody some tool to carry; the usefulness of what he carries will determine his fate. The main problem with this plan is that it appears to be wrong. We may sort out some things we really need. For instance, see exchange of correspondence between composer and philosopher. *Composer:* one perceives thought in exactly the same manner (i.e., same definition of *perception*) as one perceives light or sound or taste or smell. True or False? (my landlady says the rule for the 70's is No Entertaining.) R.S.V.P. *Philosopher:* Answer: one perceives meanings in language in the same way that one perceives meanings of light, sound, smell, etc. EG., the sound of *a tree falling,* the smell *of fried onions,* the sight *of something I can't quite make out,* etc. Question: how did you just perceive that thought? *Composer:* you didn't get the answer, but it's my fault. I should have said*, "one perceives one's own thought in exactly the same manner (i.e., same definition of *perception*) as one perceives light or sound, etc. True or False. I didn't mean to get into language. *and I realized my mistake as soon as I sent the card. *Philosopher:* I have thought about your problem a lot and decided it was false. Take the perceiver-mind as a Klein-form and you see that there is really no inside or outside of yourself — thus no "own" (i.e., purely contained) thoughts. The question is false (i.e., partial) because it splits its horizon of answers in two — one part for the *outside,* eg., perceiving sounds, sights, etc.; and one part for the *inside,* i.e., ideation or perceiving your "own" thoughts., why not, either no parts or: hearing ≠ seeing ≠ thinking etc. etc. Let me know. *Composer:* a physiological explanation of Deja-vu suggests that we don't (as an organism) distinguish too well between what is *thought of* and what is *perceived of,* but that we are aware of the fact of the bundle, or package, or (if you will) idea, whether it be a thought or a perception. The notion of the bundle or idea or "impression" being the manifestation of *modality* is what made me ask the question. Ps. my point of view is that, for the purposes of this argument, everything is "inside." Pardon my language. *Philosopher:* I am beginning to *see* your question. And the cheese loaves *looked* delectable ... if only my ideas of them had been stronger." ... (in forbearance and generosity) he follows with about 500 words describing four different kinds of answers philosophy has produced. None of them in my opinion is an answer to the question, because I did not understand from his answer that he has understood the question: I haven't reached him. (And he hasn't reached me!) Do I need more technique? Is there a vast amount of information having bearing on my conception (misconception) that I do not have access to simply for lack of specialization, "talent," intelligence on my part? What part does the special knowledge the philosopher has to play in my survival? Or in his? Answer: Who cares?

Guideline: to discover ways to make the music lighter (see John Cage: free the sound from our intentions). We must have refreshment! Nourishment is all over the place, if we need sound that remind us of our intentions. The problem always to make the compromise between the inexpressible and the expressible reached through the inexpressible through technique through experience through immersion? The expressible is boring on authority (Wittgenstein), but the truth was known even before we heard the news.

Assume everybody's brain life is equally busy or not one fly more thoroughly a fly tree less a tree throughout the cosmos uniform diversity all minding the store? The inexpressible for Beckett or Nixon no more rarified valuable spiritual inexpressible than the inexpressible for me (to cite, simply, an example of bad health). The expressible for them as much more rarified valuable spiritual expressible so much for size strength speed adaptibility success in finding food and art.

Now is the time to start thinking about survival. Some doubt that man will make it through the next five decades. Some say three. Some say an unusual number will not make it through one decade. "Desperate" in slang. Some say this will be just a sorting. I feel fear. The notion was developed in me a long time ago that I was not to compete for food. (nice idea.) I can see it now in my son. Morality. Who will get the food? The rich, obviously. To compete for food is bred in them. (A fair generalization!)

Plan # 2. Fire the deputies who control the earth's resources. (We the people are in the throes of a merciless famine. They have failed. It was too big a job for the kind of mentality they brought to it.) Discard for the crisis our concerns with preserving what's preserved through notation. Consider every work to be an attempt to describe something other than music. As if everybody is carrying an unmarked seed. There has been resourcefulness with the ruins of notation beyond anything we might have expected, but the composers have been conservative — under inhuman pressures (the question of "notation" is an example. Why not a symposium on the indignities to man forced to live emotionally in another time. Exile, in the media century.)

The problems facing this symposium might almost be solved, solving themselves through exhaustion. I think my problems are just beginning. (I am talking about America. I can't speak for the European composer, although I would guess his situation to be almost as bad. The other continents, having their own problems, are beyond my imagination.)

Sentences I couldn't find a place for:

. . . much as the banks do.

. . . that the selflessness of providing your habits for ulterior reasons makes a refuge for the ego (like a sword: doesn't hurt the one who has the handle.)

Cage's notion that we can do without syntax sometimes (a form of order like ownership or the police (?)) (condition of maximum ambiguity brings maximum senses into play; maximum compassion.)

(can we find a way to discover if the experiences are obtainable in another way: 1) electronically — note that the notation for preserving the chronology of the experiences would be different from the notation for preserving the chronology of the obligations or the characteristics (potentialities) of the instruments (tools); 2) mnemonically — to "remember" music is a paradox, of course (relative to our current *use* of music: time object), but any efficiency-test of the system (music through notation) would probably have to consider memory (in the listener!) as an alternative, if only for popular reasons; 3) —; 4) —; etc.)

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