

# Brain and the Structure of Narrative

Karl H. Pribram  
*Radford University*

## 1. INTRODUCTION

As I was completing the manuscript for a recently published set of lectures (Pribram, 1991), I realized that an especially interesting way to account for the functions of the far frontal cortex of the cerebral hemispheres is in terms of narrative structure. The frontal cortex makes possible effective action based on ordering contextualized events. These, in turn, depend on processes organized by the systems of the limbic forebrain. In this essay, I have therefore excerpted, modified, and extended the material that appears in the earlier text to address the manner in which the frontolimbic forebrain contributes to the structuring of narrative.

Most of my research career has been devoted to distinguishing so-called "associative" functions of the posterior cortical convexity from those of the frontolimbic forebrain. This front-back difference in processing is as pervasive in organizing all mammalian life and mind — and therefore as important — as is the currently popular right-left hemisphere difference for humans. The front-back distinction in processing can be summarized succinctly and formally as follows: The associative systems of the posterior cerebral convexity are committed to extracting invariances from the variety of sensory inputs; the associative systems of the frontolimbic forebrain are engaged in establishing covariations between consequent actions. Posterior processing leads to the identification and classification of objects in space and time. Frontolimbic processing leads to ordering events composed by episodes, and expressing them in coherent narrative. This essay delineates some of the evidence that implicates the frontolimbic forebrain in structuring episodes, events, and narratives.

In order to clarify the role of the several systems composing the frontolimbic forebrain it is necessary to distinguish between episode, event and narrative. These words are often used synonymously. Here *episode* refers to a unit of action that is initiated and terminated by an orienting reaction. An episode provides the context within which contents, text (texture) can be processed.

*Event* is used in the sense of eventuality, a subset of possible outcomes: for example, the outcome 8 on the throw of dice. Out-come is, in fact, the Saxon equivalent of the Latin event (*ex-venire*). And, outcome is synonymous with consequence, especially when the event, the outcome is valued, that is, consequential.

*Narrative* is the act of making known the particulars of the course of events, their consequentiality.

As is detailed below, there is considerable evidence to support the view that the amygdala systems of the forebrain are critically concerned in delineating episodes. In turn, the hippocampal systems are involved in recombining episodes (contexts) to produce novel events. Finally, the far frontal systems of the brain order these contextualized events into narrative structures.

## 2. THE LIMBIC FOREBRAIN, EPISODES AND EVENTS

### 2.1. INSTINCT AS SPECIES-SHARED BEHAVIOR

In order to analyze the complex of effects produced by total resection of the temporal lobe, I devised surgical techniques to make possible restricted resections of the medially lying amygdala and hippocampus (reviewed by Pribram 1954, 1958, 1991, Lecture 7). When resections were restricted to the amygdala and adjacent pole of the temporal lobe, the marked taming of the monkeys which had followed resection of the entire temporal lobe, (Klüver & Bucy, 1939; Sanger-Brown & Schaefer, 1888) was reproduced (Pribram & Bagshaw, 1953). Just what might this behavioral change signify?

First it was determined that not only were the monkeys tamed, but they also put everything in their mouths, gained weight, and increased their sexual behavior — all effects that had also followed the total temporal lobectomy. These changes in behavior were summarized under the rubric of the "four Fs": fighting, fleeing, feeding, and sex (Pribram, 1960).

Historically these apparently disparate behaviors were classified together as "instinct" (a term still used to describe the processes underlying such behaviors in the psychoanalytic literature). More recently this concept came into disfavor (see e.g., Beach, 1955) and ethologists substituted the category "species specific" behaviors for instinct because these behaviors can be shown to have a common genetic component. But this substitution loses much of the meaning of the older terminology: Human language is species-specific but not instinctive in the earlier sense. My preference is to retain the concept of instinct as descriptive of the four Fs: What these behaviors have in common is the fact that their patterns are shared by practically all species. What makes the study of geese and other birds so interesting is that we recognize our own behavior patterns in the descriptions provided by ethologists (see e.g., Lorenz, 1969). It is therefore *species-shared behavior-patterns* that are of interest in tracking the effects of amygdalectomy.

## 2.2 THE BOUNDARIES OF AN EPISODE

The apparently disparate behaviors that characterize the 4 Fs were shown by careful analysis to be influenced by a common process. It is worth summarizing the highlights of this analysis because identifying a common process operating on apparently disparate behaviors is a recurring problem in behavioral neuroscience. In behavioral genetics the same problem entails identifying genotypes from phenotypical behaviors. Thus, qualitative and quantitative determinations were made in each of the four Fs with the following results. In a social hierarchy fighting and fleeing were both diminished provided there was a sufficiently skillful antagonist (Rosvold, Mirsky, & Pribram, 1954). As in the study reported by Sanger-Brown and Schaefer (1888), when a monkey was returned to the social colony after amygdectomy, he "voluntarily approaches all persons — and fellow monkeys indifferently." Also, having just interacted with his fellow monkey, and perhaps having been trounced, "he will go through the same process, as if he had entirely forgotten his previous experience."

This behavioral change was dramatically demonstrated by displaying a lighted match to such monkeys. They would invariably grab the match, put it into their mouth, dousing the flame, only to repeat the grab when the next lit match was presented. This behavior could be elicited for a hundred consecutive trials unless either the monkey or the experimenter became bored before the session was ended (Fulton, Pribram, Stevenson, & Wall, 1949).

The increases in feeding and sexual behavior that follow amygdectomy were also shown to be due to a failure in placing limits on actions. For instance, as reported by Sanger-Brown and Schaefer, monkeys with such resections appear to be indiscriminate in what they pick up, put in their mouths, and swallow. But when tests were performed and a record was kept of the order in which the food and nonfood objects were chosen, it turned out that the order of preference was undisturbed by the brain operation; only now the monkeys would continue to pick up additional objects beyond those that they had chosen first (Wilson, 1959). In fact amygdectomized animals may be a bit slow to start eating but continue eating far past the point when their controls stop eating (Fuller, Rosvold, & Pribram, 1957).

The fact that amygdectomy impairs the stop — the satiety — mechanism, might suggest that amygdectomized monkeys are hungrier or have greater appetites. This is not so, however. When deprived of food for from 24 to 72 hours, amygdectomized monkeys do not eat more rapidly than they did before deprivation whereas, of course, their control subjects do (Weiskrantz, 1956).

Also, after amygdectomy the effectiveness of food as a reward is diminished. Ordinarily a change in the amount of reward given, changes its effectiveness. After amygdectomy, changes in amount have much less effect than they do when control subjects are used (Schwartzbaum, 1960).

The disturbances in feeding after amygdectomy were shown to be due to connections with the satiety mechanism centered in the ventromedial region of the hypothalamus. For instance, a precise relationship was established between the amount of carbachol injected into the amygdala and amount of feeding (or drinking) once these behaviors had been initiated (Russell,

Singer, Flanagan, Stone, & Russell, 1968). Injections into the ventromedial hypothalamic region simply terminate feeding.

Modulation of a stop process was also shown responsible for changes in fighting behavior. Fall in a dominance hierarchy after amygdectomy, when it occurred, was related to the amount of aggressive interaction between the dominant and submissive animals of the group. After amygdectomy such interactions were overly prolonged leading to a reorganization of the dominance hierarchy. It was as if the amygdectomized monkeys approached each interaction as novel. Prior experience, which modulated the behavior of the control subjects, seemed to have little influence after amygdectomy. This finding characterizes many of the experimental results to be described shortly.

Analyses of the effects of amygdectomy and electrical stimulations of the amygdala on avoidance (fleeing) behavior brought a similar conclusion. Escape behavior is unaffected and sensitivity to shock is not diminished (Bagshaw & Pribram, 1968). Nor is there a change in the generalization gradient to aversive stimulation (Hearst & Pribram, 1964a, 1964b). What appears to be affected primarily is the memory aspect of avoidance — the expectation based on familiarity with the situation that aversive stimulation will occur. Such expectations are ordinarily referred to as fears that constrain behavior.

The theme recurs when the effects of amygdectomy on sexual behavior are analyzed. The hypersexuality produced by the resections is found to be due to an increased territory and range of situations over which the behavior is manifest: Ordinarily cats perceive unfamiliar territory as inappropriate for such behavior (see Pribram, 1960, for review). Sexual behavior is limited to familiar situations and situations become familiar as a consequence of rewarding sexual encounters.

The importance of the amygdala in more generally determining the spatial and temporal boundaries of an experience or a behavioral routine — in short, an episode — is attested by the results of another set of experiments. Kesner and DiMattia (1987) presented a series of cues to animals to allow them to become familiar and then paired the initial, intermediate, and final cues of the series with novel cues in a discrimination. When similar tasks are administered to humans, they recall the initial and final cues of the series more readily than they recall the intermediate ones. These are termed the primacy and recency effects. Unoperated monkeys showed both effects in Kessler's experiments. However, after amygdectomy, monkeys failed to show either a recency or a primacy effect. If the series is taken to be an episode, the effects of amygdectomy can be considered to impair the demarcation of an episode. As described in the second half of this essay, after resections of the far frontal cortex, ordering within an episode becomes deficient.

### 2.3. FAMILIARIZATION: EPISODE AS CONTEXT

In this and the next section the evidence is reviewed to show that behavioral habituation serves as an indicator of familiarity and that habituation occurs as a result of visceromotoric activity. What is oriented to, the novel, depends on the familiar which serves as the context within which an event becomes appreciated as novel.

Habituation is fragile. The process is readily disrupted by head injury or distraction. Some of the factors governing distractibility such as pro- and retroactive interference are well known. Amygdalectomy and resections of forebrain systems related to the amygdala have been shown to increase susceptibility to distraction (Douglas & Pribram, 1969; Grueninger & Pribram, 1969). More on this shortly.

It is, of course, clear from a host of other studies relating brain and behavior reviewed elsewhere (Pribram, 1991), that not all memory storage processes critically depend on the occurrence of visceromotoric responses. The learning of motor skills, perceptual categorizing, and rote memorization, are examples where the memory storage mechanism operates on the basis of simple repetition. Still, it is equally clear that there are occasions when memory storage is dependent on a "booster" that places a value on the experience and thus leads to a *feeling* of familiarity. It is this booster process in which the amygdala is involved (Pribram, Douglas, & Pribram, 1969).

Familiarity is a feeling regarding a valued experience. In the clinic, patients who have a lesion in the region of the amygdala (and the adjacent horn of the hippocampus) describe experiences that are called *jamais vu* and *déjà vu* — the patient enters a place such as his living room and experience a "jamais vu," a feeling of "never having seen," of complete unfamiliarity. Others come into a place they have never been and feel that they have "already seen," are already, *déjà*, completely familiar with it.

In the laboratory, familiarity has been shown to be related to reinforcement history. Monkeys were trained to select one of two cues on the basis of a 70% reinforcement schedule: that is, selection of one cue was rewarded on 70% of the trials; selection of the other cue was rewarded on 30% of the trials. Then the cue that had been most rewarded was paired with a novel cue. Control monkeys selected the previously rewarded cue. Monkeys who had their amygdalas removed selected the novel cue. Familiarization by virtue of previous reinforcing experience had little effect on monkeys who lacked the amygdala (Douglas & Pribram, 1966). These monkeys were performing in a "jamais vu mode."

#### 2.4. VALUATION: VISCEROMOTORIC PROCESSING

An extensive series of experiments was then undertaken to discover what might be the physiological basis for this deficiency in the familiarization process. The problem was found to center on the fact that ordinarily a novel or a reinforcing event produces a visceromotoric reaction: A galvanic skin response due to a slight increase in sweating, a brief increase in heart rate, a change in respiratory rate, are some of the readily measurable effects. After amygdalectomy the visceromotoric reactions to novel or reinforcing events fail to occur (Bagshaw & Benzie, 1968; Bagshaw & Coppock, 1968; Bagshaw, Kimble, & Pribram, 1965; Kimble, Bagshaw, & Pribram, 1965; Koepke & Pribram, 1967a, 1967b; Pribram, Reitz, McNeil, & Spevack, 1979).

These visceromotoric responses are, in fact, elicited by electrical excitation of the amygdala and the related limbic cortex of the medial portions of the frontal lobe, anterior insula, and temporal pole (Kaada, Pribram, & Epstein, 1949; reviewed by Pribram, 1961). Changes in blood pressure, heart and respiratory rate, gut and pupillary responses, as well as gross eye, head,

and body responses are elicited. An entire mediobasal, essentially visceromotor, motor system involving the anterior portions of the limbic forebrain has been delineated. As in the case of the classical precentral somatic motor system (see review by Pribram, 1991, Lecture 6) the mediobasal motor process operates by way of a circuit that alters receptors, for example, for adrenaline (McGaugh, 1966), from which signals for processing originate.

In summary, the familiarization process is initiated and terminated by an orienting reaction, a stop to prior ongoing processing, an interrupt that begins and ends a behavioral episode. The episode is thus a demarcated period of stability within which the visceromotor effects and hedonic attributes — that is, pain and comfort (see review in Pribram, 1991, Lecture 8) of stimuli are processed. This allows valuation of the episode in terms of its relevance to the organism.

### 3. THE FORMAL DEFINITION OF EPISODE AS CONTEXT

Familiar episodes provide the context for further processing. Given a formalism describing the neural process coordinate with the perception of images and object-forms (Yasue, Jibu, & Pribram, 1991, Appendices A & B), such a formalism for "context" can be developed. This formalism delineates the conditions under which a system of eigenvectors in Hilbert space forms a complete normalized orthogonal system (CNOS), a mathematical description of a processing context.

With this goal in mind, an abstract geometric formulation of neurodynamics starting from a neural wave function was developed in detail in Yasue et al. (1991). This neural wave function is a complex-valued function of time  $t$  and position  $x$  in the dendritic network  $M$ . The dendritic network  $M$  is thought of as a geometric object, that is, a two dimensional compact manifold. Such an object will fall into the composition of well-known geometry of a Hilbert space.

In many other neural network models (e.g., Anderson & Murphy, 1986; Carpenter & Grossberg, 1987; Kohonen, 1984), states of the system are described as finite-dimensional vectors, that is, quantities with a finite number of attributes. A Hilbert space, which is an infinite dimensional vector space with certain additional properties (see, e.g., Halmos, 1957), is a convenient approximation to a finite-dimensional vector space, and is applied frequently to understanding wave phenomena in physics.

For each instant  $t$ , the neural wave function is such a complex-valued function  $\psi_t = \psi_t(x) = \psi(x, t)$  that the absolute square  $|\psi_t|^2$  describes the polarization density and so the integral

$$\int_M |\psi_t(x)|^2 dx \quad (1)$$

remains finite. Here,  $dx$  denotes the invariant volume element of the manifold  $M$ . We say in this case that  $\psi_t$  is square integrable on  $M$  for each  $t$ . Let us consider a set of all the square integrable complex-valued functions on the dendritic network  $M$ . We denote it by  $L^2(M)$  or simply  $H$ . From a mathematical point of view, this set of functions manifests a very intuitive geometric structure.

We suppose each element of  $H$  a vector. There, the constant multiplication of  $a\psi$  of a complex number  $a$  and a vector  $\psi$  is defined to be a vector in  $H$  corresponding to a function  $a\psi = (a\psi)(x) = a\psi(x)$ . The vector sum  $\psi + \varphi$  of two vectors  $\psi$  and  $\varphi$  is defined to be a vector in  $H$  corresponding to a function  $\psi + \varphi = (\psi + \varphi)(x) = \psi(x) + \varphi(x)$ .

Orthogonality of two vectors in  $H$  can be introduced by defining the inner product of two vectors. The inner product of any two vectors  $\psi$  and  $\varphi$  in  $H$  is denoted by  $\langle \psi, \varphi \rangle$  and its value is given by the integral

$$\langle \psi, \varphi \rangle = \int_M \overline{\psi(x)} \varphi(x) dx \quad (2),$$

where  $\overline{\psi(x)}$  means to take the complex conjugate. Then  $\psi$  and  $\varphi$  are said to be orthogonal with each other if their inner product vanishes, that is,

$$\langle \psi, \varphi \rangle = 0$$

The inner product may be used to measure the length of a vector. Namely, the length of a vector  $\psi$  in  $H$  is given by a real number

$$\|\psi\| = \sqrt{\langle \psi, \psi \rangle}$$

which will be called a norm of  $\psi$ . This means that the inner product of  $\psi$  with itself becomes naturally a square of its length.

Having introduced the notions of vector calculus and norm (i.e., length), we can now measure the distance between two vectors in  $H$ . Let  $\psi$  and  $\varphi$  be any two vectors in  $H$ . Then the vector calculus claims their difference  $\psi - \varphi$  to be another vector in  $H$ . This vector  $\psi - \varphi$  indeed represents a balance between  $\psi$  and  $\varphi$ . It is therefore natural to call the length  $\|\psi - \varphi\|$  of this balance vector  $\psi - \varphi$  a distance between two vectors  $\psi$  and  $\varphi$ . We denote it by  $d(\psi, \varphi)$ . The length of a vector is nothing else but a distance from it to a basis vector  $O$ . This basis vector  $O$  is called a zero vector, and stands for a unique vector in  $H$  with vanishing length. As a function on the dendritic network  $M$ , the zero vector  $O$  in  $H$  corresponds to a constant function with constant value equals to zero.

The totality of all the square integrable complex-valued functions on  $M$  thus manifests a geometric structure in which vector calculus with inner product is allowed. Such a geometry is called a Hilbert space geometry in mathematics. It is in this sense, that the set  $H$  may be called a Hilbert space.

#### 4. A SYSTEM OF EIGENVECTORS

The neural wave function  $\psi_t = \psi_t(x) = \psi(x, t)$  for each instant  $t$  may be considered as a vector  $\psi_t$  in the Hilbert space of square integrable functions  $H = L^2(M)$ . As time  $t$  passes, an

equation of the same form as the wave equation in quantum theory evolves from fundamental neurodynamic considerations as described by (a):

$$\frac{\partial \rho}{\partial t} = -v \operatorname{div}(\rho \nabla S) \quad (3),$$

which indicates how the system and control variable couple with each other and (b): the second order partial differential operator, a Laplacian which is nonlinear in the variables  $\rho$  and  $\theta$ .

$$-\frac{\partial S}{\partial t} = \frac{1}{2} |v|^2 + U_{*x} - U_{op} - \frac{v}{4} \Delta \log \rho \quad (4).$$

From these fundamental equations a neural wave equation, a variant of the Schroedinger equation, is readily derived:

$$i v \frac{\partial \psi}{\partial t} = \left( -\frac{v^2}{2} \Delta + U_{*x} \right) \psi \quad (5).$$

In other words, the time-dependent vector  $\psi_t$  draws a curve in the Hilbert space  $H$ . This curve may be denoted by  $\{\psi_t \mid 0 \leq t < \infty\}$ .

We are thus working in a geometric framework of Hilbert space  $H$ . It seems convenient therefore to rewrite the neural wave equation symbolically as an evolution equation in  $H$ . First, let us see the right-hand side of the neural wave equation (3). The Laplacian is a second order linear partial differential operation, and multiplication by a given function  $U_{*x}$  is a linear operation. Therefore, we are allowed to think of the object

$$K = -\frac{v^2}{2} \Delta + U_{*x}$$

as a linear operator that transforms a vector  $\psi_t$  in the Hilbert space  $H$  to another vector  $K\psi_t$  in  $H$ . The term *linear* means that the operation by  $K$  to any vector preserves vector calculus. Namely, we have identities

$$\begin{aligned} K(\psi + \varphi) &= K\psi + K\varphi \\ K(a\psi) &= a(K\psi) \end{aligned}$$

where  $a$  is a constant, and  $\psi$  and  $\varphi$  are two vectors in  $H$ . We call this linear operator  $K$  a neural wave generator, and rewrite the neural wave equation (5) as

$$iv \frac{d}{dt} \psi_t = K \psi_t \quad (7)$$

In general, the neural wave equation (5) defines an initial value problem. Given the initial neural wave function  $\psi_0$ , it determines the neural wave function  $\psi_t$  for all time after. Correspondingly, Eq. (5) may be understood to determine the vector  $\psi_t$  for all time after given the initial vector  $\psi_0$  in  $H$ .

Let  $t > 0$  be a small time interval. Then

$$\psi_{\Delta t} - \psi_0 = \frac{d}{dt} \psi_t \Big|_{t=0} \Delta t$$

and by Eq. (7) we derive

$$\begin{aligned} \psi_{\Delta t} &= \psi_0 - \frac{i}{v} K \psi_0 \Delta t \\ &= \left( 1 - \frac{i}{v} K \Delta t \right) \psi_0 \end{aligned}$$

Successively, we have

$$\begin{aligned} \psi_{2\Delta t} &= \left( 1 - \frac{i}{v} K \Delta t \right) \psi_{\Delta t} \\ &= \left( 1 - \frac{i}{v} K \Delta t \right)^2 \psi_0 \\ \psi_{3\Delta t} &= \left( 1 - \frac{i}{v} K \Delta t \right) \psi_{2\Delta t} \\ &= \left( 1 - \frac{i}{v} K \Delta t \right)^3 \psi_0 \end{aligned}$$

and so on. For arbitrary  $t$ , we have an identity

$$\begin{aligned} \psi_t &= \psi_{N\Delta t} \\ &= \left( 1 - \frac{i}{v} K \frac{t}{N} \right)^N \psi_0 \end{aligned}$$

valid for any integer  $N$ . The approximate equality here becomes an exact equality as  $N$  passes to infinity. Namely, we obtain

$$\psi_t = \lim_{N \rightarrow \infty} \left( 1 - \frac{i}{v} K \frac{t}{N} \right)^N \psi_0$$

This fact can be understood at least intuitively by the identity

$$\begin{aligned} & \lim_{N \rightarrow \infty} \left( 1 - \frac{i}{v} K \frac{t}{N} \right)^N \\ &= \lim_{N \rightarrow \infty} \left\{ \exp \left( - \frac{i}{v} K \frac{t}{N} \right) \right\}^N \\ &= \lim_{N \rightarrow \infty} \exp \left( - \frac{i}{v} K t \right) \\ &= \exp \left( - \frac{i}{v} K t \right). \end{aligned}$$

This symbolic exponential function has the proper meaning of linear operator acting on the Hilbert space  $H$ . It is called a *unitary operator* since the transformed vector has the same norm (i.e., length) as the original one.

A solution of the evolution equation (7) can be found by applying the unitary operator  $\exp \left( - \frac{i}{v} K t \right)$  to the initial vector  $\psi_0$  in  $H$ . The curve  $\{\psi_t \mid 0 \leq t < \infty\}$  representing the time evolution of the neural wave function due to the neural wave equation (5) is given by

$$\left\{ \exp \left( - \frac{i}{v} K t \right) \psi_0 \mid 0 \leq t < \infty \right\}$$

Although the rewritten neural wave equation (7) is considered as an initial value problem, it can be reduced to a time independent eigenvalue problem. We look for a special solution of Eq. (7) in a form

$$\psi_t = \varphi f(t)$$

where  $\varphi$  is a certain vector in the Hilbert space  $H$  and  $f(t)$  is a complex-valued function of time  $t$ . Then, Eq. (7) can be separated into the following two equations

$$i v \frac{df(t)}{dt} = \lambda f(t) \quad (8)$$

$$K\varphi = \lambda\varphi \quad (9).$$

The former is a simple linear differential equation that admits a special solution.

$$f(t) = e^{i\lambda/vt}$$

where  $\lambda$  is a constant to be determined by the latter equation (9). This constant plays a role of joint coupling the former and latter equations, and called a constant of separation. The latter equation (9) is considered as a typical eigenvalue problem for the linear operator  $K$  in the Hilbert space  $H$ . A vector  $\psi$  in  $H$  is said to be a solution if there exists a certain constant  $\lambda$  with which it satisfies Eq. (9). The vector  $\varphi$  is called an *eigenvector*, and constant  $\lambda$  is called an *eigenvalue* of the linear operator  $K$ . The linear operator

$$K = -\frac{v^2}{2}\Delta + U_{ax}$$

is known to admit infinitely many solutions of the eigenvalue problem (7) for a wider class of given function  $U_{ax}$  (Kato 1966).

Let  $\{\varphi_n\}_{n=1}^{\infty}$  be the solutions of Eq. (9) with eigenvalues  $\{\lambda_n\}_{n=1}^{\infty}$ , namely, each vector  $\varphi_n$  in the Hilbert space  $H$  satisfies a linear equation

$$K\varphi_n = \lambda_n\varphi_n$$

Without loss of generality, every eigenvector  $\varphi_n$  can be assumed normalized so that  $\|\varphi_n\| = 1$ . Even if this is not the case, each eigenvector  $\varphi_n$  may be normalized by dividing it by its norm. Suppose each eigenvalue  $\lambda_n$  differs from others. In this case, the eigenvalues of  $K$  are said to be nondegenerate. We assume this in what follows for keeping mathematical simplicity. Furthermore, the identity

$$\begin{aligned} \lambda_n \langle \varphi_{m,n} \rangle &= \langle \varphi_{m,n}, K\varphi_n \rangle \\ &= \int_M \overline{\varphi_{m,n}(x)} \left( -\frac{v^2}{2}\Delta + U_{ax} \right) \varphi_n(x) dx \\ &= \int_M \left\{ \left( -\frac{v^2}{2}\Delta + U_{ax} \right) \varphi_{m,n}(x) \right\} \varphi_n(x) dx \\ &= \langle K\varphi_{m,n}, \varphi_n \rangle \\ &= \lambda_n \langle \varphi_{m,n}, \varphi_n \rangle \end{aligned}$$

claims that

$$\langle \varphi_m, \varphi_n \rangle = 0$$

if  $m \neq n$ . This means that the system of eigenvectors  $\{\varphi_n\}_{n=1}^{\infty}$  forms a *complete normalized orthogonal system (CNOS)* in the Hilbert space  $H$ , and may be considered to define a specific coordinate basis of  $H$ . In other words, any vector  $\psi$  in the Hilbert space  $H$  can be measured by the eigenvectors  $\varphi_n$  of the neural wave generator  $K$ , obtaining

$$\begin{aligned} \psi &= \sum_{n=1}^{\infty} \alpha_n \varphi_n \\ &= \sum_{n=1}^{\infty} \langle \varphi_n, \psi \rangle \varphi_n \end{aligned}$$

##### 5. ESTABLISHING EQUI-VALENCE: A CONTEXT TRANSFER MATRIX

When monkeys are trained to select the larger of two circles and then tested to see whether they will select the larger of two squares, unoperated controls select the larger of the squares with no hesitation. After amygdectomy, transferring the selection to the new pair is severely impaired: Larger is no longer perceived as an independent dimension common to the pair of circles and the pair of squares (Bagshaw & Pribram, 1968). This change in perception is not due to any change in the monkeys' ability to discriminate between cues or between reinforcing events: *generalization gradients remain unaltered by amygdectomy in both a food reinforcement and a footshock deterrence procedure* (Hearst & Pribram, 1964a, 1964b). The effect of resection is that larger fails to be perceived as equi-valent, of equal value for the purposes at hand.

The disruption of valuation was demonstrated in another similar experiment. In this experiment the monkeys were trained to select the lighter of two grey square panels embedded in a medium grey background. On test trials, panels of different shades of grey were substituted but the monkeys were still to choose the lighter shade. Control monkeys did just this. The amygdectomized monkeys, however, hesitated and then selected either of the new panels on a random basis. They perceived the situation as novel, which it was, but failed to perceive it on the basis of the history of reinforcement that placed a value on the relation "lighter of two shades." It is this relation that made the original and substitute panels of equal value, i.e., equi-valent (Schwartzbaum & Pribram, 1960).

Coming back to the general case of dendritic network  $M$  and the Hilbert space  $H = L^2(M)$ , there may exist many different CNOSs. This means that a vector  $\psi$  in  $H$  (representing a processed sensory input) may have many different coordinate representations. Let  $\{\varphi_i\}_{i=1}^{\infty}$  and  $\{\xi_j\}_{j=1}^{\infty}$  be two different CNOSs in the Hilbert space  $H$ . Then the vector can be decomposed in both CNOSs  $\{\varphi_i\}_{i=1}^{\infty}$  and  $\{\xi_j\}_{j=1}^{\infty}$ , obtaining

$$\psi = \sum_{i=1}^{\infty} \langle \psi, \varphi_i \rangle \varphi_i \quad (10),$$

and

$$\psi = \sum_{j=1}^{\infty} \langle \psi, \xi_j \rangle \xi_j \quad (11).$$

The same vector (i.e., neural wave function)  $\psi$  can be measured by coordinates ( $\langle \psi, \varphi_1 \rangle$ ,  $\langle \psi, \varphi_2 \rangle$ , . . .) on the one hand, and ( $\langle \psi, \xi_1 \rangle$ ,  $\langle \psi, \xi_2 \rangle$ , . . .) on the other. Each CNOS becomes an infinite dimensional orthogonal coordinate system to measure every vector in the Hilbert space H. *The input has become familiarized.*

It is convenient to introduce an intuitive notion of infinite dimensional column vector. If we measure the whole Hilbert space H by the CNOS  $\{\varphi_i\}_{i=1}^{\infty}$ , each vector  $\psi$  in H may be viewed as a column vector

$$\begin{pmatrix} \langle \psi, \varphi_1 \rangle \\ \langle \psi, \varphi_2 \rangle \\ \langle \psi, \varphi_3 \rangle \\ \vdots \\ \vdots \end{pmatrix} \quad (12).$$

We may equally measure the whole H by the other CNOS  $\{\xi_j\}_{j=1}^{\infty}$ , and in this case  $\psi$  can be seen as

$$\begin{pmatrix} \langle \psi, \xi_1 \rangle \\ \langle \psi, \xi_2 \rangle \\ \langle \psi, \xi_3 \rangle \\ \vdots \\ \vdots \end{pmatrix} \quad (13).$$

Both column vectors represent the same vector  $\psi$  in the Hilbert space H, and so they must be interconnected with each other. Let us decompose a basis vector  $\xi_j$  in the CNOS  $\{\varphi_i\}_{i=1}^{\infty}$ ,

$$\xi_j = \sum_{i=1}^{\infty} \langle \xi_j, \varphi_i \rangle \varphi_i$$

Then, we compute an inner product between  $\psi$  and  $\xi_j$  obtaining

$$\langle \psi, \xi_j \rangle = \sum_{i=1}^{\infty} \langle \xi_j, \varphi_i \rangle \langle \psi, \varphi_i \rangle \quad (14).$$

This identity shows how the column vectors (12) and (13) are connected with each other. Eq. (14) may be rewritten in an intuitive notion of matrix multiplication. Namely, we have an identity

$$\begin{pmatrix} \langle \psi, \xi_1 \rangle \\ \langle \psi, \xi_2 \rangle \\ \langle \psi, \xi_3 \rangle \\ \vdots \end{pmatrix} = \begin{pmatrix} \langle \xi_1, \varphi_1 \rangle & \langle \xi_1, \varphi_2 \rangle & \dots \\ \langle \xi_2, \varphi_1 \rangle & \langle \xi_2, \varphi_2 \rangle & \dots \\ \vdots & \vdots & \dots \\ \vdots & \vdots & \dots \end{pmatrix} \begin{pmatrix} \langle \psi, \varphi_1 \rangle \\ \langle \psi, \varphi_2 \rangle \\ \langle \psi, \varphi_3 \rangle \\ \vdots \end{pmatrix} \quad (15).$$

There, an infinite dimensional matrix with the  $j$ - $i$  component given by the inner product  $\langle \xi_j, \varphi_i \rangle$  plays an important role. It will be called a *transfer* matrix from the CNOS  $\{\varphi_i\}_{i=1}^{\infty}$  to the other CNOS  $\{\xi_j\}_{j=1}^{\infty}$ .

## 6. STABILITIES FAR FROM EQUILIBRIUM

An ensemble of CNOS becomes stabilized by virtue of the transfer functions entailed in familiarization. Under conditions in which probabilities play a minor role (such as the recurrent regularities that often characterize physiological states as, for example, those determining hunger and thirst) the stabilities define steady states of equilibrium. When, however, probabilities play a significant role, stabilities occur far from equilibrium and are thus subject to destabilizing influences.

The thermodynamic considerations put forward by Prigogine (1980) regarding stabilities far from equilibrium provide for the formation of such constraints in the form of *attractors* toward which the process tends. Thus the episode, characterized by its temporary stability far from equilibrium, can contain attractors which operate as consequential events. In experimental psychology terms, the attractor is an event which is constructed by cross multiplication among ensembles of CNOS.

Ordinarily habituation of the visceromotoric components of an orienting reaction occurs within 3 to 10 repetitions of the orienting stimulus. The orienting, distracting stimulus has perturbed a stable organization of redundancies (an organization sometimes referred to as an apperceptive mass), which rapidly restabilizes. After restabilization, there continue to be mild

cyclic fluctuations of these components with irregular periods measured in minutes. Originally, we thought these stabilities described states of equilibrium (Piaget, 1970; Pribram, 1958, 1969). The advent of Prigogine's descriptions of stabilities far from equilibrium offered a much richer model: Perturbations of equilibrium states could only lead to a return to equilibrium; perturbations of states far from equilibrium would lead to bifurcations (the shaping of new "hills" or "wells") and provide the potential for achieving novel attractors and therefore new states of stability (McGuinness, Pribram, & Pirmazar, 1990).

The results of the experiments performed in my laboratory, which delineated the effects of amygdectomy and resections made in related systems, can therefore be conceived as failure to attain temporary stabilities in processing (Pribram 1969, 1980; Pribram et al., 1979). The failure to stabilize was shown to be related to an inability to properly process the structure of redundancy (Pribram 1969, 1987; Pribram, Lim, Poppen & Bagshaw, 1966; Pribram & Tubbs, 1967).

Often the neuropsychological system is actually operating close to equilibrium and perturbation is handled by a return to equilibrium: the distraction of an orienting reaction is either ignored or incorporated into the ongoing process through repetition and familiarization. However if the perturbation is great, a reaction we ordinarily call emotionally upsetting can result in turbulence and a new stability has to be achieved. When, as in the models described here, the process is conceived to be composed of continuous functions, for example, as neurodynamic manifolds described by the Lie algebra, vortices can develop in the turbulent systems. Thus, an often realized possibility is to be "hung up" in the turbulence. But, because this is a chaotic state far from equilibrium, one can deliberately seek constraints in order to anticipate such a change of state and maintain stability.

As noted earlier, destabilization poses the risk that the organism becomes "hung up" in chaotic turbulence. However, in his book *Design for a Brain* (1960), Ashby described an interesting and powerful method for controlling destabilization. His method leads to "catastrophic" and therefore unpredictable restabilizations ("step functions"). In his model, stability was achieved by adding to the computation, numbers taken from a list of random numbers. A similar procedure was found necessary to keep a Hopfield learning network from premature stabilization by falling into a well — an attractor — above optimization. Adding randomness, "noise" provides maximum possibility (potentiality) for new organizations to develop. As in Prigogine's model one cannot predict just how the system will restabilize because of the randomness injected into the turbulent system. Effective processing is achieved by a heuristic in which the addition of noise is important to preclude premature closure onto a spurious attractor.

The current section discusses the manner in which stabilities far from equilibrium can become perturbed and how destabilization can be controlled and thus provide the ground for innovation.

To this end, let us consider a highly idealized dendrite network, which on the basis of familiarization has become stabilized and isolated electrochemically from other dendrite networks in the system. The dendritic microprocesses of the distribution of the density of the ionic bioplasma as it affects fundamental oscillations of membrane potentials in this isolated dendritic

network  $M$  can be described by the neural wave equation (5). The neural wave equation (5) may be written as

$$i v \frac{d}{dt} \psi_t = K \psi_t \quad (16)$$

within the realm of Hilbert space geometry. By reducing this equation to a time-independent eigenvalue problem (9), we have found infinitely many stationary solutions of the neural wave equation. They are nothing but the eigenvectors  $\{\varphi_n\}_{n=1}^{\infty}$  of the neural wave generator  $K$ . In other words, for each eigenvector  $\varphi_n$  and eigenvalue  $\lambda_n$ , a neural wave function

$$\psi(x, t) = \varphi_n(x) e^{i \lambda_n t / v} \quad (17)$$

solves the neural wave equation (5). As we have seen, the absolute square of a neural wave function represents the density distribution of the ionic bioplasma that manifests the global dynamics of dendritic microprocesses. Thus, each eigenvector  $\varphi_n$  may be understood as a mathematical representative of the typical global dynamics of a dendritic microprocess given by a density distribution of the ionic bioplasma

$$\rho = |\varphi_n|^2 = |\varphi_n(x)|^2 = \rho_n(x) \quad (18).$$

Those ionic bioplasma density distributions  $\rho_n$  that do not change as the time  $t$  passes, manifest temporarily stationary dendritic microprocesses. This means that each eigenvector  $\varphi_n$  represents a set of stable dendritic microprocesses. The fundamental oscillations of dendritic membrane polarizations are synchronized within the dendritic network, and no effective currents of changes in the distribution of the density of the ionic bioplasma exist. In other words, the distribution of ionic bioplasma in the dendritic network is in a temporarily stable state of the dendritic network. The stationary state is stable in the sense that it remains unchanged as long as the dendritic network remains isolated. It is worthwhile to notice here that no other vectors in the Hilbert space different from the eigenvectors  $\varphi_n$  can define the stable dendritic microprocesses.

As detailed earlier, the fact that the isolated dendritic network manifests selectively stable dendritic microprocesses represented by eigenvectors  $\varphi_n$  provides us with the neuronal basis for familiarization. The isolated dendritic network resonates only with selectively limited processes associated with the stationary states  $\varphi_n$ . These tuned resonances are represented by the stationary "familiarized" states of the dendritic network,

$$\varphi_1, \varphi_2, \dots, \varphi_n, \dots.$$

Other types of resonance given by a vector  $\varphi$  different from the stationary states  $\varphi_n$ 's cannot be realized, as they deform immediately into one of the stationary states by the dispersion effect.

The isolated dendritic network is capable of an infinite variety of stable dendritic microprocesses associated with the familiarized states  $\varphi^n$ , because the neural wave equation (3) admits infinitely many stationary solutions  $\varphi^n$ .

## 7. INNOVATION

What happens to sensory stimuli to which the organism has become habituated? Do they fail to influence perception and behavior? Many observations and experiments indicate that habituated sensory events, called *S delta* in operant behaviorism and *negative instances* in mathematical psychology, continue to shape the course of learning and, in general, to act as a contextual guide to behavior.

In the process of achieving sensory discriminations, behavior toward the nonreinforced aspects of situation becomes extinguished in steps (see, e.g., review by Pribram, 1986) as these aspects become habituated. Should the situation change, as when another aspect is reinforced, these cues are again noticed (spontaneous recovery). In fact they have been influential throughout the procedure serving as context, the familiar "ground" within which a "figural" content becomes processed.

Whenever a situation changes, an orienting reaction occurs, previously habituated perceptions become dishabituated (Sokolov, 1963). The orienting reaction signals the perception of novelty, the perceived change in the situation. Perceived change can be generated internally — as when an organism becomes hungry. In such instances, "novel events" — restaurant signs begin to populate the landscape — valuing what had become irrelevant. Effort is expended, attention is "paid," and the familiar is experienced innovatively.

There is a great deal of confusion regarding the perception of novelty. In scientific circles, much of this confusion stems from the confounding of novelty with information. Shannon and Weaver (1949) introduced measures on information in terms of bits that reduce the amount of uncertainty in communication. Berlyne (1969) and others then suggested that bits of information and novel events were equivalently arousing, calling them collative variables. However, as is detailed shortly, novelty in the sense used here, neither increases nor reduces the amount of uncertainty; rather novelty is due to a rearrangement of what is familiar, that is, a change in the structure of redundancy. The skill in writing a novel resides not in providing information in the sense of reducing the amount of uncertainty in communication. Rather, the skill lies in portraying familiar events in novel ways, that is in new combinations. If the structure of a novel depended on providing information, *Reader's Digest* would not be in business. Nor is there a reduction in the amount of communicable uncertainty involved in the composition or production of a great piece of music. It is the arrangement and rearrangement of a theme that challenges composer and conductor; the manner in which to structure repetition: "Repetition, ah, there's the rub," exclaimed Leonard Bernstein in his comparison of musical composition to natural language (1976).

A definitive experiment that draws the distinction between a) novelty defined as a change in the structure of redundancy, and b) measures of information (in Shannon's sense) was performed by Smets (1973). Smets used some of the same indicators of arousal as those used in our monkey experiments. He presented human subjects with a panel upon which he flashed

displays equated for complexity (difficulty in discrimination), differing either in the number of alternatives (bits) or in the arrangement of analyzable attributes, alternatives (orientations of lines) of a pattern. *Very little visceromotoric activity was induced by varying the number of alternatives; by contrast changes in arrangement evoked pronounced reactions.*

Innovation depends on an initial step, a process by which the familiar drops into background as current events arouse and habituate. But these earlier events remain available for renewed processing should demand arise. The floor, walls, and doors of a classroom are familiar objects; we are not aware of them. We walk through the door when class is over, failing to notice what we are perceiving while engaged in a discussion following the lecture. But, should an earthquake rearrange things, we become instantly aware of events such as swaying floor and walls and head deliberately for the safety provided by the door's frame.

In the laboratory the process of familiarization is called habituation or, when discrimination is involved extinction, and is demonstrated by a discrimination reversal procedure. Monkeys are trained to select one of two cues by consistently rewarding only one of the cues. After criterion performance (90% or better on 100 consecutive trials) is reached, the reward is shifted to the other cue. Ordinarily monkeys, after a few trials, stop selecting the now nonrewarded cue and proceed to select the now rewarded one. The shift in behavior accelerates as the reversal is repeated. Response to the currently nonrewarded cue has been extinguished, but is rapidly reinstated once the situation demands it (Douglas & Pribram, 1969).

Hippocampectomy (i.e., removal of the entire hippocampal gyrus: hippocampus, and its surrounding subiculum and entorhinal cortex) radically alters this course of behavioral events. The hippocampus, a phylogenetically ancient cortex, is the other major anatomical structure lying within the medial portion of the temporal lobe. As might be expected, extinction (conceived as an extension of habituation) of the response to the now nonreinforced cue remains intact after hippocampectomy.

Not only do the hippocampectomized monkeys show normal extinction, the slope of acquisition of the currently appropriate response does not differ from that of the control monkeys. What does occur is a long series of trials, which intervene between extinction and acquisition, during which the monkeys select cues at random. They receive a reward approximately 50% of the time, which is sufficient to keep them working (Pribram, Douglas, & Pribram, 1969). There is no obvious event that pulls them out of this "period of stationarity"; quite suddenly the hippocampectomized monkeys resume the acquisition of more rewarding behavior. What goes on during the period of stationarity and what prolongs this period for monkeys who have had their hippocampal gyrus resected?

There are currently no techniques for directly assessing what goes on during the period of stationarity. It is clear, however, that rearrangement of the association between cue and reward has occurred and that this rearrangement must be perceived before it can be acted upon. Rearranging must be processed efficiently and appears to take effort (Pribram, 1986b, 1991; Pribram & McGuinness, 1975). A model follows which shows how rearrangement, changing the structure of redundancy, can give rise to novel associations, that is, consequential events.

## 8. WEAK INTERACTIONS AS POTENTIAL PERTURBATIONS

Each dendritic network of the system is, of course, actually not isolated but connected with other ones. To make the familiarization process of the dendritic network more realistic, we introduce weak dendritic interactions with other networks. This induces multiple transitions between different states of familiarity. Existence of the weak dendritic interaction makes the lifetime of a stability finite. Thus, the dendritic microprocess fluctuates among the temporarily stable states  $\varphi^n$  due to dendritic system weak interactions.

This fact may be well illustrated by means of perturbation theory. Suppose that the dendritic network in question remains isolated until a certain instant, say  $t^0$ , and a weak dendritic interaction is turned on at  $t^0$ . Time evolution of the dendritic microprocesses is described by the revised neural wave equation (16). However, the neural wave generator  $K$  in the right hand side has different forms before and after the onset of a weak dendritic interaction. Let  $U = U(t)$  be the additional quasistatic energy due to the weak dendritic interaction. The value of  $U$  is relatively small compared with the external static energy  $U_{ex}$ . Then, the neural wave equation (16) has the form

$$i\nu \frac{d}{dt} \psi_t = K \psi_t, \quad (19)$$

for  $t < t_0$ , and

$$i\nu \frac{d}{dt} \psi_t = (K + U(t)) \psi_t, \quad (20)$$

for  $t > t_0$ . We call Eq. (19) a non-perturbed neural wave equation and Eq. (20) a perturbed one. We consider onset of a weak dendritic interaction as a perturbation of the neural wave equation.

Suppose that the dendritic microprocess is in one of the isolated, familiarized states, say  $\varphi_m$ , before the onset of perturbation. Then, Eq. (19) claims

$$\psi_t = \varphi_m e^{-i\lambda_m/\nu t}$$

for  $t < t_0$ . This suggests that the perturbed neural wave equation (18) may be solved with respect to the initial condition

$$\psi_{t_0} = \varphi_m e^{-i\lambda_m/\nu t_0}$$

The perturbed neural wave equation (20) may be solved by the following mathematical procedure.

Let  $\psi_p$  be the solution of Eq. (20). We introduce a time-dependent vector  $\Psi$  in the Hilbert space  $H$  by

$$\psi_t = \exp\left(\frac{i}{v} Kt\right) \psi_{t_0} \quad (21).$$

Then, it solves a reduced perturbed neural wave equation

$$i v \frac{d}{dt} \psi_t = \hat{U}_t \psi_t \quad (22)$$

where

$$\hat{U}_t = \exp\left(\frac{i}{v} Kt\right) U(t) \exp\left(-\frac{i}{v} Kt\right) \quad (23)$$

is a time-dependent operator in  $H$ . The initial condition for  $\psi_{t_0}$  yields the initial condition

$$\psi_{t_0} = \varphi_m$$

for  $\psi_t$ . Equation (22) can be solved immediately by the perturbation series

$$\psi_t = \left[ 1 + \left(\frac{1}{i v}\right) \int_{t_0}^t \hat{U}_s ds + \left(\frac{1}{i v}\right)^2 \int_{t_0}^t \int_{t_0}^s \hat{U}_s ds \hat{U}_u du + \dots \right] \varphi_m \quad (24).$$

Because the perturbation  $U$  is small, the perturbation series (24) can be well approximated by the first two terms, obtaining

$$\psi_t = \left[ 1 + \left(\frac{1}{i v} \int_{t_0}^t \hat{U}_s ds\right) \right] \varphi_m \quad (25).$$

Finally, Eqs. (21) and (25) give a first order approximation to the solution  $\psi_t$  of the perturbed neural wave equation (20),

$$\begin{aligned} \psi_t &= \exp\left(-\frac{i}{v} Kt\right) \varphi_m \\ &+ \exp\left(-\frac{i}{v} Kt\right) \left(\frac{1}{i v}\right) \int_{t_0}^t \hat{U}_s ds \varphi_m \\ &= e^{-i/v Kt} \varphi_m \\ &+ \exp\left(-\frac{i}{v} Kt\right) \left(\frac{1}{i v}\right) \int_{t_0}^t \hat{U}_s ds \varphi_m \end{aligned}$$

It is convenient to measure the vector  $\psi_t$  in the Hilbert space  $H$  by means of the specific CNOS  $\{\varphi_n\}_{n=1}^{\infty}$  because the perturbation  $U$  is so small that  $\psi_t$  may not deviate much from the initial state  $\varphi_m$ . Let

$$\psi_t = \sum_{n=1}^{\infty} \alpha_n \varphi_n$$

be the coordinate expansion of  $\psi_t$  in terms of the CNOS  $\{\varphi_n\}_{n=1}^{\infty}$ . Here, the coordinates  $\alpha_n$  are given by the inner product

$$\begin{aligned} \alpha_n &= \langle \varphi_n, \psi_t \rangle \\ &= e^{-i/\nu \lambda_n t} \langle \varphi_n, \varphi_m \rangle \\ &\quad + \left( \frac{1}{i\nu} \right) \int_{t_0}^t \langle e^{i/\nu K s} \varphi_n, \dot{U}_s \varphi_m \rangle ds \\ &= e^{-i/\nu \lambda_n t} \delta_{nm} \\ &\quad + \left( \frac{1}{i\nu} \right) e^{-i/\nu \lambda_n t} \int_{t_0}^t \langle \varphi_n, e^{i/\nu K s} U(s) e^{-i/\nu K s} \varphi_m \rangle ds \\ &= e^{-i/\nu \lambda_n t} \delta_{nm} \\ &\quad + \left( \frac{1}{i\nu} \right) e^{-i/\nu \lambda_n t} \int_{t_0}^t e^{i/\nu (\lambda_n - \lambda_m) s} \langle \varphi_n, U(s) \varphi_m \rangle ds \end{aligned}$$

Namely, we have

$$\alpha_n = \left( \frac{1}{i\nu} \right) e^{-i/\nu \lambda_n t} \int_{t_0}^t e^{i/\nu (\lambda_n - \lambda_m) s} \langle \varphi_n, U(s) \varphi_m \rangle ds$$

for  $n \neq m$  and

$$\alpha_m = \left( 1 + \frac{1}{i\nu} \int_{t_0}^t \langle \varphi_m, U(s) \varphi_m \rangle ds \right) e^{-i/\nu \lambda_m t}$$

Thus the onset of perturbation causes the change of coordinates from

$$\begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ e^{-i/\nu \lambda_m} \\ 0 \\ \vdots \\ 0 \end{pmatrix} \quad (26)$$

to

$$\begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_m \\ \vdots \end{pmatrix} \quad (27).$$

In other words, the onset of perturbation forces the vector  $\psi_t$  to deviate from the initial stable, familiarized state  $\varphi_m$  so that it has nonvanishing components along other familiarized states  $\varphi_n$ .

### 9. NOVEL ASSOCIATIONS: THE ORIGIN OF CONSEQUENTIAL EVENTS

Here, we need a consistent interpretation of the dendritic microprocess associated with the vector  $\psi_t$  in  $H$ , and coin a new mathematical formulation of association. When the vector  $\psi_t$  has the coordinate representation (26) with respect to the CNOS  $\{\varphi_n\}_{n=1}^m$  the dendritic microprocess described by  $\psi_m$  remains identical with that of a specific state  $\varphi_m$ . If there is no perturbation, that dendritic network remains isolated and keeps the initial familiarized state  $\psi_m$ . Perturbation modifies the vector  $\psi_t$  so that its coordinate representation becomes (27).

Let us compute the length of vector  $\psi_t$  in terms of the coordinates (27). As the states  $\varphi_n$  form a CNOS in the Hilbert space, we have

$$|\psi_t|^2 = \sum_{n=1}^m |\alpha_n|^2$$

Before the onset of perturbation,  $\alpha_n = 0$  except for  $n = m$ , and this can be written as

$$\begin{aligned} |\psi_t|^2 &= |\alpha_m|^2 \\ &= |e^{-i/\nu \lambda_m}|^2 \\ &= 1 \end{aligned}$$

After the onset, we have

$$|\psi_t|^2 = \left| 1 + \frac{1}{i\nu} \int_{t_0}^t \langle \varphi_m, U(s) \varphi_m \rangle ds \right|^2 + \sum_{n \neq m} \left| \left( \frac{1}{i\nu} \right) \int_{t_0}^t e^{i/\nu(\lambda_n - \lambda_m)s} \langle \varphi_n, U(s) \varphi_m \rangle ds \right|^2$$

It is worthwhile to notice here that the perturbation acts on the vector  $\psi_0$  so that it is no longer parallel to the eigenvector  $\varphi_m$ . It comes to point along many other independent directions of eigenvectors  $\varphi_n$ . For any  $t > t_0$  and  $n \neq m$ ,

$$|\alpha_n|^2 = \left( \frac{1}{\nu} \right)^2 \left| \int_{t_0}^t e^{i/\nu(\lambda_n - \lambda_m)s} \langle \varphi_n, U(s) \varphi_m \rangle ds \right|^2$$

gives a relative proportion of the vector  $\psi_t$  to point along the  $n^{\text{th}}$  eigenvector  $\varphi_n$ . As the  $n^{\text{th}}$  eigenvector  $\varphi_n$  is a stable dendritic microprocess, the dendritic microprocess specified by the vector  $\psi_0$  realizes those of the other state  $\varphi_n$  with relative proportion  $|\alpha_n|^2$ . Thus, the perturbation causes the neural wave function  $\psi_t$  to represent typical dendritic microprocesses that resemble those of state  $\varphi_n$  with relative proportion  $|\alpha_n|^2$ . Such a neural wave function represents a novel event in which the several independent states are associated on the basis of frequencies given by their relative proportion.

## 10. THE FAR FRONTAL CORTEX AND NARRATIVE STRUCTURE

### 10.1. AN EXECUTIVE PROCESSOR

In a continually changing situation where episodic demarcation becomes difficult or when transfer among contexts is blocked other resources must be mobilized. Such situations demand executive intervention if action is to be consequential. This part of the essay addresses the issue of an executive processor, a brain system that directs and allocates the resources of the rest of the brain. Ordinarily, input from sensory or internal receptors preempts allocation (for discussion see, e.g., Miller, Galanter, & Pribram, 1960) by creating a "temporary dominant focus" of activation within one or another brain system (for review, see Pribram, 1971, pp. 78-80). However when extra demands are placed on the routine operations of allocation, coherences among proprieties and priorities must be organized, and practical inference initiated. Proprieties must structure competences, priorities must be ordered and practicalities assessed.

### 10.2. PROPRIETIES, PRIORITIES AND PRACTICALITIES

The far frontal cortex is surrounded by systems that, when electrically excited, produce movement and visceromotoric effects. On the lateral surface of the frontal lobe lies the

classical precentral motor cortex (for review see Bucy, 1944; Pribram, 1991, Lecture 6). As noted, on the mediobasal surface of the lobe lie the more recently discovered "limbic" motor areas of the orbital, medial frontal and cingulate cortex (Kaada et al., 1949; Pribram, 1961). It is therefore likely that the functions of the far frontal cortex are, in some basic sense, related to these somatomotor and visceromotor effects.

At the same time, the far frontal cortex derives an input from the medial portion of the thalamus, the n. medialis dorsalis. This part of the diencephalon shares with those from anterior and midline nuclei (the origins of the input to the limbic cortex) an organization different from that of the projections from the ventrolateral group of nuclei to the cortex of the convexity of the hemisphere. (See Chow & Pribram, 1956; Pribram, 1991 for review).

The close anatomical relationship of the far frontal cortex to the limbic medial forebrain is also shown by comparative anatomical data. In cats and other nonprimates, the gyrus proreus is the homologue of the far frontal cortex of primates. This gyrus receives its projection from the midline magnocellular portion of the n. medialis dorsalis. This projection covers a good share of the anterior portion of the medial frontal cortex; gyrus proreus on the lateral surface is limited to a narrow sliver. There appears to have been a rotation of the medial frontal cortex laterally (just as there appears to have occurred a rotation medially of the occipital cortex — especially between monkey and man) during the evolution of primates.

From these physiological and anatomical considerations it appears likely that the far frontal cortex is concerned with relating the motor functions of the limbic to those of the dorsolateral convexity. This relationship has been expressed by Deecke, Kornhuber, Long, & Schreiber (1985) in terms of the what, when, and how of action.

Deecke et al. (1985) concluded an extensive review of their studies using electrical recordings made in humans that: The orbital cortex becomes involved when the question is what to do; the lateral cortex becomes active when the question is how something is to be done and the dorsal portions of the lobe mediate when to do it. According to the anatomical connections of the far-frontal portions of lobe, described below, "what" can be translated into propriety; "how" into practicality and "when" into priority.

On an anatomical basis, the far frontal systems have been shown to comprise three major divisions (see Pribram, 1987, 1990 for review): One, an orbital, is derived from the same phylogenetic pool as, and is reciprocally connected with, the amygdala (and other parts of the basal ganglia such as the n. accumbens, which have been shown to be involved in limbic processing). As might be predicted from the role of the amygdala in familiarizing, in *déjà* and *jamais vu* phenomena, this orbital system augments and enhances sensitivities as to what to do, to propriety based on episodic processing (see below).

The second, a dorsal system, is derived from the same root as, and has connections with, the hippocampal system which includes the limbic medial frontal-cingulate cortex. As might be expected from the involvement of the hippocampus in recombinant processing — in innovation — the dorsal far frontal system controls flexibility in when actions are to be engaged, in ordering priorities to ensure effective action.

The third, a laterally located system has strong reciprocal connections with the posterior cerebral convexity. It is this system that involves the far frontal cortex in a variety of sensory-

motor modalities when sensory input from the consequences of action incompletely specifies the situation. In such situations practical inference becomes necessary.

### 10.3. ORGANIZING COHERENCE

In addition to its demarcation by successive orienting reactions, a defining attribute of an episode is that what is being processed coheres — processing must deal with covariation in terms of familiarity, equi-valence and novelty. Covariation can lead to interference, thus resulting in the inability to order the processing of events. Recall that primacy and recency effects were impaired after amygdala and hippocampal damage. With far frontal damage, monkeys show impairment in processing the latter part of the middle of a series. This impairment is attributed to increased pro- and retroactive interference among items in the series (Malmö & Amsel, 1948).

The impairment is also shown by patients with damage to their frontal cortex. These patients fail to remember the place in a sequence in which an item occurs: The patients lose the ability to "temporally tag" events, that is, to place them within the episode. With such patients, Milner (1974, see also Petrides & Milner, 1982) performed a series of experiments demonstrating how the processing impairment affects the middle portions of an episode. In her studies, it is *relative recency*, the *serial position* of covarying experiences, that becomes muddled. Other patients with fronto-limbic damage are described by Kinsbourne and Wood (1975). In keeping with the proposals put forward in this essay, they interpret the impairment in processing serial position as due to a derangement of the context that structures an episode.

Fuster (1988) conceptualized the far frontal processing of context in terms of cross temporal contingencies. Relative recency, for instance, implies that a temporal context exists within which recencies can be relative to one another. However, as indicated by experimental results in which spatial context is manipulated, as in variants of object constancy tasks (Anderson, Hunt, VanderStoep & Pribram, 1976) the contextual influence can be spatiotemporal as well as temporotemporal. In fact, in other experiments (Brody & Pribram, 1978; Pribram, Spinelli, & Kamback, 1967) data were obtained indicating far frontal involvement whenever processing is influenced by two or more distinct sets of covarying contextual contingencies, even when both are spatial.

The computation of this covariation demands that cross temporal, spatiotemporal, and cross spatial contingencies be processed. In classical and operant conditioning, the consequences of behavior are contiguous in time and place with the stimulus conditions that initiate the behavior. Contiguity determines the episode or conditioning "trial." When contiguity is loosened, stimulation that intervenes between initiation and consequence has the potential to distract and thus to prevent the processing of covariation. Processing is destabilized. Perturbation is controlled only if a stable state, established coherence, instructs and directs the process.

### 10.4. KRONOS, KAIROS, AND PROPRIETY

Covariation has posed special difficulties with respect to an understanding of time. Covariation must always occur within a defined episode: variation within a context. Our common

conception of clock time, based on successions of object-forms in space-time, specifies coherent (correlated) successions within a defined epoch of spacetime and was called "Kronos" by the classical Greeks. However, they recognized another form of time, "Kairos," which concerns the experiencing of an appropriate moment, a decisive moment that may be characterized by an event and its feeling of timelessness or timefullness. The subjective aspects of Kairos were described by Bergson (1922/1965) in terms of *duré* — an experienced duration that is not readily measured in chronological time. In his doctoral dissertation, Ornstein reviewed his own and others' experiments on *The Experience of Duration* (which in its published version was changed by sales minded editors to *The Experience of Time*, 1969).

An analogy attributed to William James was recently developed in a seminar presented to our brain research group by Fred Abraham. The analogy suggests that time is like a string of beads. Kronos, that is, Einsteinian space-time is measured by the *length* of the string. Kairos, as shown by Ornstein, is experienced as a function of the *density* with which the beads (events, episodes) are strung.

But there is yet another, additional, manner of experiencing time: the *order* in which the beads are strung. It is the serial position of events experienced within the context of coherent episodes that gives form to a story, a narrative. The extent and duration of a coherent state in the face of distracting perturbations is ordinarily discussed in terms of limits on processing span.

#### 10.5. MODIFICATION OF PROCESSING SPAN: COMPETENCE NOT CAPACITY

The issue of limited span is usually discussed in terms of a fixed channel capacity. But as reviewed by Pribram and McGuinness (1975, 1982), a considerable volume of work has shown that the central processing span is not fixed. Thus Miller (1956), Garner (1962), and Simon (1974, 1986), among others, have clearly shown that information-processing span can be enhanced by reorganization such as that provided by "chunking." In fact, Broadbent (see review, 1974) showed that with regard to cognitive operations such as attention, limited span is not so much a function of the final common path as it is a function of the central processing mechanisms in the brain.

These data have led to conceptualizing limitations in processing span as limitations in flexible channel competences rather than in channel capacities (Pribram, 1986b; Pribram & McGuinness, 1975), a view also expressed by Maffei (1985). Chunking has been shown, using the asymmetric delayed alternation procedure, to be influenced by resections of the far frontal cortex (Pribram, Plotkin, Anderson & Leong, 1977; Pribram & Tubbs, 1967). In the current section, data are presented demonstrating that electrical excitation of the frontal cortex changes receptive field properties of neurons in the sensory channels of the primary visual cortex. These changes are directly related to the ability to parse or chunk the input. Thus the conception of a limited capacity depending on some fixed channel "exoskeleton" becomes untenable. An increase in processing capability, in competence (in the sense of a deep structure as developed by Chomsky, 1965), becomes possible by way of challenges to a flexible "endoskeleton" of the channel.

Processing span is thus sensitive to structuring as by chunking, a top-down cognitive process. The continuously updated channel structures provide for flexibility in processing with

the accumulation of experience, memory-based influences organize the channel structure according to what is momentarily appropriate.

The particular experiments that demonstrate the neurophysiology of top-down processing, processing that implements changes in channel structure, were performed on the receptive field organization of single neurons in the lateral geniculate nucleus of cats and monkeys (Lassonde, Ptito, & Pribram, 1981; Spinelli & Pribram, 1967). Receptive fields were mapped by displaying a small moving dot on a contrasting background. The location and motion of the dot were computer-controlled. Thus the computer could sum (in a matrix of bins representing the range over which the dot was moved) the number of impulses generated by the neuron whose receptive field was being mapped. This was done for each position of the dot because the computer "knew" where the dot was located.

The maps obtained for the lateral geniculate nucleus are usually called Mexican hat functions. The brim of the hat represents the spontaneous background of impulse activity of the neuron. The crown of the hat represents the excitation of the cell by the dot of light shown to the animal when the cell is located at the center of the visual field. Where the crown meets the brim there is a depression indicating that the output of the cell has been inhibited.

The center-surround organization, first described at the optic nerve level by Kuffler (1953) is a cross section of the hat parallel to the brim. The inhibitory surround has been shown (e.g., Creutzfeldt, Kuhnt, & Benevento, 1974, for cortical cells) to be due to hyperpolarizing activity in a lateral network of "local circuit neurons" (Rakic, 1976), which do not generate nerve impulses.

It is this inhibitory surround that can be augmented or diminished by electrical excitation of other parts of the forebrain. Stimulation of the far frontal cortex diminishes the inhibitory surround; stimulation of the posterior intrinsic (association) cortex, specifically in this case, the inferotemporal portion of this cortex produces an augmentation of the inhibitory surround.

Dendritic fields overlap to a considerable extent. Thus when the excitatory portion of the receptive fields become enlarged, the dendritic fields essentially merge into a more or less continuous functional field. By contrast, when the excitatory portion of the receptive fields shrinks, each neuron becomes functionally isolated from its neighbor.

This modifiability of the primary visual system in the direction of greater separation or greater confluence among channels was supported by testing the effects of the same electrical stimulations on the recovery cycles of the system as recorded with small macroelectrodes: Far frontal stimulations produce a slowing of recovery, whereas posterior stimulations result in a more rapid recovery as compared with an unstimulated baseline. Slow recovery indicates that the system is acting in unison; rapid recovery that the system is "multiplexed" — that its channels are separated.

#### 10.6. PROCESSING PRIORITY: SERIAL POSITION EFFECTS

The results of these experiments can be interpreted to indicate that far frontal brain stimulation drives the visual system toward a continuous mode of operation while posterior stimulation drives the system toward a discrete mode. A convolution-correlation model is therefore more appropriate when the focus of brain activity shifts toward the frontal lobes. A

matrix model is more appropriate when the focus of brain activity lies more posteriorly. To test this interpretation we need to relate the known behavioral functions of the frontal and posterior portions of the brain to the known advantages of the two types of models.

Convolution-correlation mathematics have been used to model sensory-motor and perceptual-motor learning and skills. Thus Licklider (1951), Uttal (1975), and Reichardt (1978) developed temporal and spatial autocorrelation models to account for their results of experiments on perceptual performances. Cooper (1984) and Kohonen (1972, 1977) used a similar model to describe a variety of properties both perceptual and cognitive. Thus, for example, Cooper developed a model based on the effects of monocular deprivation on the responsiveness of neurons in the visual cortex and made successful predictions of outcomes of experiments inspired by the model. As reviewed elsewhere, our own efforts (Pribram & Carlton, 1986) have used this type of model to tease apart imaging as a function of convolving the various stages of processing in the primary visual system, from object perception, which depends on correlations among patterns in which centers of symmetry are determined by operations performed in the superior colliculus and the visuomotor system.

None of these perceptual and motor skills depend on functions that can be ascribed to the far frontal part of the brain. Nor are they related to the inferotemporal cortex and the posterior intrinsic "association" systems of which the inferotemporal cortex is a part. What is suggested by these successful models is that the convolution-correlation approach is the more appropriate for describing sensory-motor skills leaving the matrix model as more appropriate for cognitive operations such as comprehension (See Pribram, 1991, Lecture 7).

But certain aspects of cognitive processing are better described by a convolutional-correlational approach. The thesis to be presented proposes that such processing entails the computing of inner products of sensory input vectors to establish a coherent context, a processing episode.

Murdock (1979, 1982, 1983, 1985; Murdock & Lewandowsky, 1986) has reviewed the evidence that distinguishes convolution and matrix theories of associative memory. He pointed out that whereas the matrix model (as developed by Anderson, 1970, and Pike, 1984) has the advantage of simplicity in obtaining explicit expressions and to some extent in storage capacity, the convolution-correlation model is more powerful in other respects such as the handling of serial position effects, effects that entail far frontal lobe function.

The convolutional and matrix models differ in that in the convolutional model critical operations are performed on the inner products of its vectors, whereas in the matrix models such operations utilize the outer products of vectors. Murdock (1985) described the difference as follows:

The basic issue seems to be as follows. I would suggest that an association can be represented as a convolution, information is stored in a common memory vector, and correlation is the retrieval operation. Pike would suggest that an association is the outer product of two vectors, information is stored in a memory matrix or set of matrices, and vector-matrix premultiplication and postmultiplication is the retrieval operation. (p. 132)

Thus the convolutional approach "is not quite ready to be abandoned in favor of a matrix system" (Murdock, 1985, p. 132). But as processing prototypes characterizes the functions of systems of the posterior cerebral convexity (see e.g., Warrington & McCarthy, 1983) the matrix model also is not to be abandoned. This model is clearly viable in the hands of Anderson and his colleagues when applied to learning and performance of discrimination-type tasks (see Anderson, Silverstein, Ritz, & Jones, 1977, for review). Whenever classification is involved, storage as outer products of vectors and retrieval by postmultiplication appears to be more appropriate than storage by association in a common vector produced by convolving inner products.

This line of reasoning leads to the suggestion that reference — that is, in humans, semantic — processing is best represented by a matrix model and that the convolution-correlation model be reserved for episodic processing (see Tulving, 1972, 1985 for review). It is therefore important to find out if indeed the convolution-correlation model more effectively models all aspects of episodic processing.

As noted, a central characteristic of episodic and event processing is its preservation of some sort of place keeping and time tagging: that is, in the perception of serial position within the total processing span. Murdock & Lewandowsky (1986) presented a detailed review of models constructed to account for serial position effects and the evidence upon which they are based. Interference, trace decay, distinctiveness, end-anchoring, dual trace (item and order), and organizational (chunking) factors were assigned critical roles in model building and the convolutional model efficiently handles them all.

How can such models developed to account for remembering serial position effects in the recall of lists of items be relevant to understanding how the brain processes episodic controls? The key to understanding lies in the results of analysis of performance of the delayed response task. Recall that in this task a reward or token is hidden in a particular location chosen from others similar in appearance while the animal is watching — a screen is then interposed between the location and the animal for a short (e.g., 5 seconds) period and then removed, allowing the animal to have access to the reward. After resection of the far frontal cortex, monkeys lose the ability to perform this task. Pro- and retroactive interference effects have been demonstrated to play a role in this impairment (Malmo, 1942; Pribram, 1958; Pribram, Plotkin, Anderson, & Leong, 1977; Stamm & Rosen, 1972; reviewed by Pribram, 1987).

This impairment is almost entirely due to the fact that monkeys with such lesions fail to properly process the initial part of the trial, the hiding of the reward before the screen is interposed. It is the perceptual processing part of the task that is most susceptible to interference, not the memory trace of the initial perceptual experience. Furthermore, items that are identical produce interference in models dependent on trace decay; but as identical items do not interfere with recall of serial position, trace decay cannot account for difficulties experienced after far frontal lobe damage. When items are similar, however, demands on ordering escalate as expected when the convolution-correlation model is used.

To summarize: The effects of (a) amygdectomy on primacy and recency, (b) the effects of hippocampectomy on primacy, and (c) the effects of far frontal lobe resections on intralist interference (relative recency) stem from inadequate processing at the time of initial exposure to

the list of items, the establishment of an episode, the context that stabilizes further processing, and not to effects on the trace of the sensory input. We have all experienced a related phenomenon when we attempt to recite a poem or rehearse a melody: should we be interrupted or fail, for the moment, to be able to continue the recitation or rehearsal we often find it necessary to begin again at the beginning of the entire poem or piece, or at least at the beginning of a major section.

Murdock noted that convolutional and matrix models describe what must be processed but do not address how processing proceeds. There is a class of models, however, that do describe "how" in terms of parallel-distributed processes. The next section reviews the evidence for, and describes extensions of, the convolutional model that indicates how processing proceeds.

### 10.7. PROCESSING (PRACTICAL) INFERENCE

Scientists interested in perception have been especially intrigued by illusions and pictures in which figures are to some extent hidden by the context in which they appear. Such interest exists because perception is ordinarily experienced as "direct"; thus perceptual processes are difficult to study because, under normal circumstances, they are unavailable to conscious awareness. This is not so when the perceiver is challenged by an ambiguous input.

These perceptual ambiguities are the figural counterparts of the contextually covariant processes discussed so far: injury to the far frontal cortex (and not the systems of the posterior cerebral convexity) dramatically influences the rate of reversal of such figures as Necker cubes, and faces/vases (see e.g., Teuber, 1964). When the injury is severe, reversals may not be experienced at all.

In hidden and reversible figures, ground and potential figures vie for dominance. Figure and ground must be separated out from the ambiguous sensory input. The rate of reversals in reversible figure experiments speeds as the perceiver becomes aware of both figures and this rate can be influenced to some degree by intending to reverse. Rock (1983) has noted that reversals continue after each of the figures has been clearly perceived — indicating that the input continues to provide a processing challenge.

This challenge is met much as the other challenges to order that have been described here: centrally controlled changes are produced in the microprocesses occurring in the input channels. These changes can be conceived to operate much as does a zoom lens. When extended into the telephoto range, good separation between figure and ground occurs. A telephotograph has a very narrow depth of field and enhanced resolution. The same effect is obtained with a large surface hologram; by contrast, cutting such a surface into small areas reduces resolution but enhances depth of field. In the brain, large surface integration of a distributed process is achieved when the boundaries between overlapping receptive fields are attenuated, when the convolutional mode of processing is in force. The evidence presented above indicates that such a mode is placed in operation by virtue of the activities of the frontolimbic forebrain.

Smolensky (1986) extended the convolutional model to cover inference. Smolensky's is a dynamical "harmony" theory in many respects similar to the holonomic brain theory pursued in Pribram (1991). However, instead of relying on Gabor transforms, the transition from harmonic (such as Fourier) analysis to measures on the amount of information being processed

is done in terms of electrical circuits (with two resistors in series) that compose a "knowledge atom". The resultant measure on information is statistical.

Optimization is achieved in harmonium by simulated annealing, or, lowering the "computational temperature." This means that randomness of the initial state is "cooled" out: Inference is assumed to be stochastic. By this procedure a completely coherent interpretation can be constructed from an ambiguous input. Similarly, the harmonium model can answer ill-posed problems, those whose answers are replete with interference effects, just as it can answer well-posed problems: "There will be more than one state of highest harmony and the model will choose one of them. It does not stop dead due to insufficient information. Not 'any answer' will do [however]. Harmonium finds the best possible answers to ill posed problems on the basis of rules that have solved well posed problems" (Smolensky, 1986, p. 252).

One such ill-posed problem is the illusion called the *Aubert phenomenon*, a shift in the subjective vertical when a person's body is tilted in the dark. Mittelstaedt (1987) studied the shift of the subjective vertical with great care and has developed a processing model to account for this shift, a model in tune with both the harmony model and the holonomic brain theory. As such, the Mittelstaedt model serves as a precise illustration of this class of models for the resolution of ill-posed problems: When the ordinary context provided by an illuminated situation is absent, internally generated rules provided by previous established contexts attempt to substitute.

Mittelstaedt found "that the apparent orientation of the visual world to the vertical and that of one's own body to the vertical result from two separate computations" (p. 65). The vertical of the visual world, is the resultant of a gravity vector produced by an input from the saccules of the inner ear, and an "idiotropic" vector. Contrary to expectation, this idiotropic vector is not determined by current proprioceptive inputs that influence postural control. What then might be the origin of the idiotropic vector?

Insight into the origin of the idiotropic vector comes from an analysis of the Aubert phenomenon. Aubert (1861) noted that an objectively vertical line of light in an otherwise dark room appeared tilted to 45° when observed with his body tilted to a 90° angle. When the room was lit so that he could see it with all its window frames, walls, and furniture, the line snapped into its true position. When the light was switched off again, the line slowly returned to its apparent — nonobjective — vertical position, that is, it was again seen as 45° rotated from objective verticality.

The frames provided by windows, walls, and so forth, influence to a variable degree the perception of the subjective vertical (see e.g., Stark & Bridgeman, 1983; Witkin & Asch, 1948). Mittelstaedt's experiments show that these frames and the idiotropic vector superimpose to form a new resultant. This resultant is computed by cross multiplication between "circular Fourier components selected from a central nervous system representation of the retinal pattern" and "a central nervous component generator, which is controlled by internal feedback" from the resultant of the cross multiplications.

Neurophysiologically, the extraction of the Fourier components is envisaged by Mittelstaedt to devolve on the orientation selective neurons of the primary visual cortex. "Let the output of all those [neurons] whose preferred orientation falls into the same sector be summed." If a field of parallel lines is used as a panorama, the output of each of the sectorial

assemblies can be computed in terms of their Fourier coefficients. By introducing a weighting function, unequal cell densities within sectors and unequal mean amplitudes of the cells' tuning functions can readily be compensated.

In order for Mittelstaedt's model to work, before weighting, "a layer of polarity detectors would be required, that is, cells which peak just once within a full turn of the panorama." Such cells of course do exist: They are cells with receptive fields selective of directionality and orientation as well as the Fourier components specified by spatial and temporal frequency (Pribram, Lassonde, & Ptito, 1981; See review by DeValois & DeValois, 1988).

The Aubert phenomenon is dramatically altered in patients with frontal lesions (Teuber & Mishkin, 1954). This indicates that the far frontal cortex is critically involved in computing the idiotropic vector. In fact, a reasonable speculation would hold that the idiotropic vector is supplied whenever the input from receptors is insufficient to completely specify perceptual context. In such cases, the perceptual system is challenged rather than determined. Percepts gradually drift (e.g., to new orientations) and appear to be no longer "directly" perceived. According to the Mittelstaedt model, in such cases the reciprocal feedback between cross multiplication of the Fourier components representing the sensory input with the central nervous system generator is largely determined by the output from that generator and to a lesser degree by sensory input.

In any generalization of the model to other situations in which the input is ambiguous, conflicting, or demanding of serial position effects, in other words, when the input poses problems that are poorly specified, the output from the central nervous system generator is critical. Due to the storage properties of the frontolimbic systems, the central generator becomes shaped by experience. The process "does not stop dead due to insufficient information." Rather, the process proceeds by constant interaction of the centrally generated component with the results of cross-multiplication of the input vectors, a process that attempts to specify prototypical objects and events. Interaction adds a centrally generated component to enrich each prototype within its boundaries. Inference makes use of this richness, the rules, structures of redundancy, that have been developed on the basis of experience where the input has more completely specified the product of cross multiplication and central generator. The total inference process thus leads to conceiving the best possible fit between prior experience and current input.

## 11. NEURODYNAMICS AND INFERENCE

The insights gained from Murdoch's, Smolensky's, and Mittelstaedt's models of the inference process can be expressed in terms of neurodynamics as developed in the holonomic brain theory. We noted that external stimuli affect the internal states of dendritic microprocess so that the state vector satisfies the neural wave equation. Time evolution of the state vector is,

then, given by a unitary flow in  $H$  generated by a unitary operator  $\exp\left(-\frac{i}{\hbar} K t\right)$ . For each external stimulus, the neural wave generator  $K$  is specified and so is the unitary operator. Then specific state vectors that are invariant under the unitary flow with generator  $K$  play important roles to represent stable states of each external stimulus. They can be called "memory" states and specified mathematically as eigenvectors of the operator  $K$ . The well-known mathematical

fact that those eigenvectors form a CNOS in the Hilbert space  $H$  may provide us with a mechanism of *multiple* associations between memory and a specific currently activated process.

### 11.1. BIAS

We consider the simplest case of a process made up of two dendritic networks, unit A and unit B. Unit A is directly connected to a certain sense organ via nerve fibers and synapses so that it receives a neural signal generated by the effect of the surroundings of the sense organ. As we saw in the preceding sections, the dendritic network manifests limited and temporarily stable dendritic microprocesses. They are represented by stationary neural wave functions, that is, stable states in the Hilbert space  $H$  of the unit A. Thus a stable stationary state of the unit A becomes perturbed by the neural stimulus from the sense organ. The perturbation, as we have seen, can trigger a reorganization of the previously stable state.

Suppose that the unit A is excited by a stimulus from a sense organ, causing the dendritic microprocesses of the unit A to resonate. This produces the stationary state of the Hilbert space  $H_A$ . If the unit A becomes isolated, it resonates in this fashion "forever." However, because unit A is connected not only with the sense organ but also with unit B, there is a possibility for mutual interaction. Existence of the influence from the unit B makes the lifetime of the resonating stationary state  $u_A$  of the unit A shorter.

When unit A is driven both by outputs from the sense organ and from unit B, the output of the unit B plays the role of biasing unit A. The dendritic network of A then resonates to the output of the sense organ with a bias from B. Consequently, the state vector of the unit A becomes a stationary state  $u_A$  which is perturbed by the output of the sense organ as biased by the state of the unit B. In other words, the perception of the output of the sense organ depends on the process carried by a state vector  $u_B$  of the unit B.

Units A and B can each be considered as an isolated dendritic network as long as the sense organ does not send another input to unit A. This means that the state vectors  $u_A$  and  $u_B$  of the units A and B are kept unchanged until next series of inputs is generated by the sense organ. Therefore, the synaptic connections between the units A and B become especially tuned to this pair of state vectors  $u_A$  and  $u_B$ . We call this specific synaptic weighting between the units A and B a neural channel  $u_A \otimes u_B$ . This highly tuned neural channel  $u_A \otimes u_B$  can remain effective even when the next series of outputs of the sense organ again perturbs the state vectors  $u_A$  and  $u_B$ . This is the origin of inference. Once a temporary stability becomes established by means of a neural channel  $u_A \otimes u_B$ , it now acts as the bias contributed by unit B. Thus, the next series of perturbations from the sense organ become biased by the channels established by preceding perturbations. This simple "inference machine" based on dendritic networks A and B provides us with an interesting mathematical model of a more realistic inference process.

Suppose we have a finite number of neural channels between the unit A and B of certain learning processes. We denote them by  $(u_A^1 \otimes u_B^1)$ ,  $(u_A^2 \otimes u_B^2)$ , ...,  $(u_A^M \otimes u_B^M)$  for  $M > 0$ , where  $u_A^k$ 's and  $u_B^j$ 's are stationary states of the units A and B, respectively. Each neural channel composes a familiar perception. This strength of susceptibility of each neural channel represents the effectivity of the familiar. Thus, the totality of neural channels between the units A and B specifies the knowledge already obtained. In such a situation, if there happens to be

the same output of the sense organ as one of the preceding ones, the bias output of the unit B through the corresponding channel, say  $u_A^k \times u_B^j$ , enforces the units A and B to resonate to the stationary states  $u_A^k$  and  $u_B^j$ , respectively.

On the other hand, suppose we have a previously unexperienced output from the sense organ. The neural channels representing previously experienced perceptions then heavily bias units A and B, and making them keenly sensitive to the stationary states  $u_A^k$ 's and  $u_B^j$ 's, respectively. We investigate this process from the point of view of the Hilbert space geometry.

First, we notice that the finite number of stationary states  $\{u_A^k\}_{k=1}^M$  span a finite dimensional subspace of the Hilbert space  $H_A$ . Similarly,  $\{u_B^j\}_{j=1}^M$  span also a finite dimensional subspace of  $H_B$ . We denote those subspaces by  $M_A$  and  $M_B$ , respectively. Then, the state vector  $\psi_A$  in the Hilbert space  $H_A$  can be decomposed into a form

$$\begin{aligned}\psi_A &= \sum_{i=1}^{\infty} \alpha_i u_A^i \\ &= \sum_{i=1}^M \alpha_i u_A^i + \sum_{i=M+1}^{\infty} \alpha_i u_A^i \\ &\equiv \psi'_A + \psi''_A\end{aligned}$$

Here,  $\psi'_A$  and  $\psi''_A$  are components of the state vector  $\psi_A$  lying in and orthogonal to the finite dimensional subspace  $M_A$ . The neural channels between the units A and B biases the unit A so that the component  $\psi'_A$  in  $M_A$  is easily accomplished but the other one  $\psi''_A$  orthogonal to  $M_A$  is not. This is because of the absence of neural channels biasing the state vectors  $u_A^i$  for  $i > M$ .

Consequently, this inference process makes the system A and B resonate to the stationary states  $\{u_A^k\}_{k=1}^M$  and  $\{u_B^j\}_{j=1}^M$  with probability  $|\alpha_k|^2$  for  $k = 1, 2, \dots, M$ . In other words, the temporary stability in the units A and B of the novel input from the sense organ becomes related to the finite number of stationary states which represent prior experiences. Such a relation to prior experience then drives the neural channel.

## 11.2. INFERENCE AS THE METHOD OF LEAST SQUARES

It seems surprising that the present mathematical model of the inference process realizes a mechanism of inference similar to that known as method of least-squares in probability theory.

Notice that the state vector  $\psi'_A$  is the best estimate of the state vector  $\psi_A$  in a sense that  $\psi'_A$  is closest to  $\psi_A$  within the learned "knowledge" described by the finite dimensional subspace  $M_A$ . In the terminology of statistical modeling, the finite dimensional subspace  $M_A$  is an estimation

space and its orthogonal complement is an error space. The orthogonal projections  $\psi'_A$  of the state vector  $\psi_A$  onto the estimation space  $M_A$  is nothing but a least squares estimator.

Such an inference process takes place when a novel input from the sense organ modifies the state vector of the unit A. However, if this novel input continues for a longer period, the bias effect of the neural channels of the familiarized outputs becomes less dominant and a new neural channel will be made which reflects the orthogonal component  $\psi''_A$ . Then, this unfamiliar input from the sense organ comes to be stored in the new neural channel between units A and B. The inference process thus has a procedure for enlarging the scope of inference.

## 12. TOWARD A MODEL OF NARRATIVE PROCESSING

Whenever values are to be assigned to a process in a quantitative fashion, two attributes must be present: a reference and a unit of incrementation (Pribram, 1960, Sommerhoff, 1974; von Neumann & Morgenstern, 1953). For instance, if we wish to describe the amount of heat in terms of temperature, we need a reference such as that provided by phase changes of water (the freezing and boiling points at appropriate atmospheric pressure), and also a unit of incrementation such as the degree Celsius that divides the range between the freezing and boiling points into 100 equal units (centigrades). For the model of narrative proposed here, an episode within which familiarity is achieved can serve as the reference. The reference is demarcated by a destabilizing interrupt of prior ongoing processing (an orienting reaction) and ends with the next interrupt, which initiates a different processing episode. As reviewed, there is considerable evidence that the amygdala system is integral to this type of processing.

The manner in which the stabilities far from equilibrium are constituted after a destabilizing input has occurred was detailed earlier in the chapter. There, restabilization was achieved by the addition of random "noise". However, another alternative is provided by frontal lobe control over the process: a catastrophic reaction may be circumvented. Control is exercised by using equivocation, the sum of noise and redundancy. This option is provided by redundancies that enhance coherence and therefore constitute "structured" entropy, that is, potential information (Gatlin, 1972; Shannon & Weaver, 1949). The system of eigenvectors in Hilbert space describes the neural nature of this entropic structure.

Under this option, practical inference is exercised to achieve and maintain control over the process. Appropriate orderings of priorities among events, i.e., attractors, is achieved.

The unit of incrementation — the outcome, the event — is computed by cross multiplication of episodes (contexts, ensembles of CNOSs) by the achievement of equi-valence. In terms of neurodynamics, channels made up of a system of eigenvectors describing isovalent junctional polarizations would appear considerably different under the condition "mail a letter" from that mapped under the condition "hungry." Different configurations of values would display different hills and valleys on the polarization contour map. A simpler example would be attending to the color or form of a scene: The pattern of isovalent contours produced by receptive fields responding to color and the pattern of such contours responding to form would be different, much as when one asks all those in a classroom to briefly raise their hands if they are wearing a red sweater and then asking those who are wearing glasses to raise their hands.

Thus, the units of incrementation -- the valuations (weightings) of events -- must be measured in terms of the "distances" between hills — attractors — formed by isovalent contours in each system of eigenvectors. The minimum entropy (Gabor's quantum of information — see Pribram, 1991, Lecture 2) for the bandwidth defined by the isovalent contours serves as the unit of measure on these distances. This results in an entropic domain where the distance between (or density of) attractors delineated by isovalent contours is set in terms of the distances between the minimum uncertainty (wells) attainable in each channel.

Hinton and Sejnowski (1986) developed a "hill climbing learning routine" that moves an element in a stepwise manner over such a contoured terrain. Processing proceeds perpendicular to the contours. In their model, "climbing" is actually down the mountain and is accomplished by random steps to the bottom of the mountain, to a well, when the "elasticity" of the process contracts the "line of climb" into the shortest path. This "moment of truth" may well describe the attainment of familiarity, the consolidation of an episode in memory (McGaugh, 1966; McGaugh & Hertz, 1972).

Hinton and Sejnowski's model can be usefully modified with respect to learning to discriminate alternatives as reviewed in Pribram, 1991, Lecture 7. The process is described as a matter of sharpening generalization gradients until separation between domains is achieved. The "moment of truth" is when the separation occurs. Hill "climbing" is replaced by a stepwise "steepening" of each gradient - by actually changing the shape of each hill, the generalization gradient, until each domain is clearly distinguished and specified.

In Lecture 5 of *Brain and Perception* (1991) it was shown that in the case object-form constancy, specifying the object-form specifies its object centered space and vice-versa. In a similar fashion, specifying separate domains specifies separate events. Thus, in classifying an object-form as a triangle or as a chair, we specify both the domains of triangles or chairs and the events (outcomes) of perceiving a specific triangle or chair. The question remains as to what mathematical group structure most accurately describes such specifications.

When the sensory systems are stimulated by object-forms that can unambiguously be processed as triangles or chairs, only the temporal lobe systems, (posterior inferotemporal cortex and hippocampus — see *Brain and Perception*, Lectures 7 and 9) need be involved. When, however, sensory input fails to completely specify the event and its domain, the systems of the frontal lobe become involved as has been reviewed here. In such instances coherent proprieties, priorities and practicalities become assigned on the basis of inference, that is, on the basis of prior experience. Prior experience, memory, becomes not just a remembrance of the past but a re-remembering of a plausible (coherent) future. A story is constructed, a narrative is born: Once upon a time — and so they lived happily ever after.

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