A MODEL OF CONCEPTUAL COMPLEXITY

by

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ABSTRACT

Various theoretical and experimental works in the fields of conceptual complexity, information processing, electroencephalography, and brain trauma are reviewed. A model of conceptual complexity is then derived which utilizes some of the viewpoints and data found in these works, and also is mainly consistent with current knowledge about cognitive processes. A more detailed review of the conceptual complexity literature is then presented, along with an analysis of the implications of the present model with respect to that literature. Appendices contain other implications of the model in other fields, as well as an outline of a research program.
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This thesis is an attempt to construct a model of the information processing functions which are salient to a discussion of conceptual complexity, mainly using ideas developed by Schroder, Driver and Streufert (1967), Powers (1973) and Luria (1973). Although the model, of necessity, describes many of the functions normally dealt with in the fields of perception, memory, cognition and so forth, it is not intended to be a definitive theoretical exposition of any or all of these more limited areas. Rather, the model is meant to show that all of these processes must be accounted for in any model which deals with a more global aspect of brain functioning such as conceptual complexity. By implication, such an integrative viewpoint must also be taken in other areas such as attitude change or attitude measurement, some of which are briefly discussed in the Appendices. Although I have attempted to make this model consistent with current models in the more specialized fields of psychology, its emphasis on the processes necessary to describe conceptual complexity will occasionally put it in conflict with these more circumscribed theories. These processes are defined in terms of the input data they work with, the kinds of transformations or decisions made from those data, and the various kinds of outputs produced. Although the basic flow of processing in the model presented here is computer-like, the physiological structure underlying these processes is hypothesized to use an analogue, rather than a digital, process.

In general, the model describes processes, not content. This means that attitude change might, for example, be described in terms of the temporal sequence of rule and memory usage and the comparison decisions
necessary to produce such change, but very little will be said about the actual content of such rules and comparisons. Only broad generalizations can be made about such content, since in many kinds of processes it will be partly determined by the history and culture of the individual. In attitude change, for example, one person may mainly consult the opinion of experts, while another might pay the most careful attention to the presumed wishes of his family and ancestors. The process of information search occurs in both people, but the content of that search may be highly individualistic. It is, of course, difficult to distinguish between processes determined genetically and those determined environmentally; for the sake of simplicity, I will assume that the potential for the development of the processes described in this model is genetically present in all human beings, although specific environmental influences may accelerate, retard, or even prevent their appearance in certain situations.

The model will provide an outline of the processes present in the brain, a brief description of the neural wiring producing such processes, and an outline of possible equivalences between these processes and the physical organization of the brain. The purposes of such a model are four-fold: (1) to make more clear the relationships among, and the common features of, a number of diverse fields of psychology in order to facilitate the use of information from one field to another, (2) to provide insight into the processes underlying many content areas, (3) to develop new paradigms for the study of process structures, and (4) to give impetus to the development of other processing models at the same general level of analysis.
The following review of the most pertinent theories which led to the present model is not intended to be an exhaustive look at the work that has been done on information processing. Nor is it intended to be an especially critical review of this work. Rather, it is presented with the purpose of explaining briefly some of the concepts which will be incorporated into the model in the following sections, and indicating why I found them insufficient in themselves for the kind of model developed here. These theories do not represent major departures from the mainstream of thought in their areas but are presented as representative samples of current thinking which were most germane in the development of the present model.

William T. Powers

Powers (1973) has provided a hypothesis about the functional significance of several kinds of elementary neuron circuits found in the nervous system. In addition, he has conceptualized a hierarchy of control systems which are comprised of various of these elementary circuits, and which in turn comprise all the processing faculties of the brain. I will begin with a look at the elementary neuron circuits that Powers described.

In the Introduction, I mentioned that my model assumes analogue, rather than digital, computing elements. This idea is taken directly from Powers, who first explained precisely how such elements could operate. He first notes that a neuron seems to operate in a binary
mode in the sense that the neuron fires whenever an excitation threshold is exceeded, and the discharge shape, timing, and magnitude are always invariant under different excitations. However, this does not necessarily imply that the signal operated upon by the neuron consists of these binary impulses. Rather, many psychologically relevant perceptual phenomena have been shown to be correlated with the frequency of firing of a neuron. For example, the firing rate of a temperature sensor in a cat depends smoothly upon the temperature of that neuron (e.g., Dodt and Sotterman, 1952). Note that the exact dependency of firing rate to input stimulation is not important in this argument, so long as some regular dependency exists.

In the nervous system, signals, especially to muscles, are usually transmitted not just by single neurons, but by parallel bundles of redundant fibers. A good statistical average may then be made of the firing frequency of this bundle, making this signal a reliable one to use to carry information in the nervous system. The discrete binary impulses, on the other hand, are subject to vagaries in timing due to the individual nature of the neurons producing them and the varying lengths of the axons conducting them, which would make their use as the basic information unit impossible in the nervous system.

Therefore, Powers defines the neural current as "the number of impulses passing through a cross-section of all parallel redundant fibers in a given bundle per unit time" which is to be the basic information unit of the nervous system.

The next step is to show that neurons using this frequency information can perform the basic operations needed by a computing system. In
Figures 1 through 6, I will reproduce Powers' drawings of the connections needed to perform such operations with only the following general comments: first, that the law of conservation of energy (and current) does not apply since the required energy is supplied to the system along the whole length of the axon by the surrounding tissue allowing each of the branches in Figure 3, for example, to carry a neural current equal to I. This is unlike a made-made electrical circuit, where each branch would have to carry a current of $I/3$; second, that since a computer can and does perform all necessary operations using only adders and subtractors, presumably the nervous system could too.

The symbol $\oplus$ indicates an excitatory synapse, $\ominus$ indicates an inhibitory one. In all cases, it is the neural current which is being operated on, rather than each discrete impulse. Multiplication occurs when two impulses must arrive simultaneously in order for the cell to fire.

Powers notes that integrators and differentiators can also be simply constructed; I will omit these circuits from discussion since the foregoing is certainly sufficient to form a fairly efficient computing system.

The next important concept is that of negative feedback control. "Feedback" is a word which is often used very loosely to describe any kind of information returned from some process or event, but which does not necessarily have any effect on that process or event. As used here, feedback will always refer to negative feedback: that is, to information about a process or event which is passed back almost immediately to a control point in order to influence future actions in
Figure 1. A neuronal adder. The frequency $I_3$ equals the sum of the input frequencies $I_1$ and $I_2$ since both synapses are excitatory (Powers, 1973, p. 27.)
I, a neuronal subtractor. The frequency $I_3$ is approximately equal to the difference of the input frequencies $I_2$ and $I_1$, since one synapse is inhibitory (Powers, 1973, p. 28.)

Figure 2. A neuronal subtractor. The frequency $I_3$ is approximately equal to the difference of the input frequencies $I_2$ and $I_1$, since one synapse is inhibitory (Powers, 1973, p. 28.)
Figure 3. A neuronal amplifier. The input is divided into 3 branches, each of which carries a neural current of $I_1$. The output of the neuron is therefore three times $I_1$ (Powers, 1973, p. 29.)
Figure 4. A neuronal multiplier. This cell has an elevated firing threshold which requires two excitatory impulses to arrive simultaneously in order to initiate firing (Powers, 1973, p. 30.)
Figure 5.  a. An example of a first-order control system.

b. An equivalent flow diagram.

(Refer to Powers, 1973, p. 43 and p. 83.)
Figure 6. A behavioural control unit using memories of past perceptual signals (m) as reference signals (r).

(Powers, 1973, p. 221.)
that process or event in a mathematically determined manner such that errors are reduced; it will be the key concept in describing how motor behaviour is controlled. It is analogous to the term "feedback" used in servo-mechanism theory (e.g., D'Azzo and Houpis, 1966). The main elements of a negative feedback control unit (servomechanism) are shown in Figure 5.

Suppose the effector is a muscle. Then the feedback system works in the following way to create the proper muscle tension: the brain provides a neural current to energize the muscle, whose tension is a function of the magnitude of the neural current reaching it (Milner, 1970). The signal provided by the brain is called the reference signal, \( r \). The output of the muscle is its tension, \( o \). A special stretch receptor in the muscle tendon (the Golgi tendon receptor) generates a perceptual feedback signal, \( p \), whose magnitude (frequency) is directly related to the amount of muscle tension. This signal is sent back to the comparator (the spinal motor neuron), in such a way that it is subtracted from the reference signal. Thus only the error signal, \( e \), is really used to control the muscle tension.

Suppose that, due to some disturbance, the muscle has not contracted by the amount required by the reference signal. Then the feedback signal \( p \), which depends upon that contraction, will be rather smaller than it should be. Since \( p \) is subtracted from \( r \) at the motor neuron, the effect is to make the error signal, \( e \), a bit larger, increasing the muscle tension. Similarly, if the muscle should contract a bit too much, the effect of the subtraction \( r - p \) will be to reduce \( e \) somewhat, and therefore to reduce the muscle tension. The "negative"
part of "negative feedback control" refers to this subtraction: only if the feedback is negative will this control system work properly. Note that "error" in this case does not mean "mistake": the control system stabilizes to some steady state in which $e$ is some constant non-zero value. Only if the muscle is completely flaccid is $e = 0$.

Simplifying things somewhat, the steady-state conditions of the feedback loop are such that $e = r - p$, and $p = ke$, where $k$ is a constant known as the Loop Amplification Factor. The effect of varying $k$ is to regulate the sensitivity of the system: as $k$ increases, the system controls errors more accurately. Using Powers' example (p. 64), if $k = 10$ and a muscle system is disturbed by a force of 10 pounds, the muscle effort countering this disturbance will be 9.1 pounds. If $k = 100$, however, the countering effort will be 9.9 pounds. (Note that although the greater part of a disturbance may be countered automatically, only by changing $r$ will it be completely countered.)

Unfortunately, it is not possible to work through the effects of such a disturbance in a simple manner using the steady-state equations above because they do not take into account the time-dependencies existing in the system. Disturbances do not occur instantaneously, they occur over some finite period of time. Similarly, the neural currents $p$, $r$, and $e$ cannot change instantaneously, but rather vary according to the physical limitations of the system. The exact mathematical description of a feedback system depends on knowing the nature of such time-dependencies. In the case of inorganic systems such as those described by D'Azzo and Houpis (1966), these dependencies are determined by the physical laws pertaining to the operation of the
elements of those systems. Such a description is currently impossible for organic systems because we lack detailed knowledge of their method of operation.

We are now ready to discuss Powers' model of the organization of the human nervous system. He conceives of a hierarchy of nine behavioural control systems; each control level works to adjust its output functions (e.g., muscles in Figure 5) so that the perceptual signals reaching it are "correct", relative to the reference signals supplied to it by a higher-order control system. Each level of the hierarchy receives information of a certain kind, integrates that information in certain ways, and passes it upwards to the next highest level.

**Level One: Intensity**

The lowest level system controls and perceives intensity of neural current. The perceptions involved arise directly from sense receptors such as the Golgi tendon receptor; an example of a controlled quantity would be muscle tension. Powers identifies the physiological units for this level with the spinal motor loop for motor perception and control, and the retina for visual perception.

**Level Two: Sensation or Vector Control**

First order perceptual signals are combined by weighted summation circuits to produce a signal which can be thought of as an n-dimensional vector, where n is the number of first-order signals involved. This vector need not represent any "real-life" physical quantity, but Powers considers that it may do so in the case of kinesthetic control and visual perception: for example, some "vectors" may represent joint rotation angles. These vectors are the result of second order input
functions -- the units for weighted summation: they are analogous to the current produced by the Golgi tension receptors -- the first order input functions. For motor behaviour, Powers identifies these input functions with the sensory nuclei of the brain stem. Similarly, the second order output functions are identified with the motor nuclei of the brain stem.

Level Three: Configuration Control

The second-order systems produce perceptual signals which are passed to the cerebellum and thalamic areas. The integration of this vector information is considered to result in information about configurations: for example, kinesthetically it provides data on the position and orientation of the body; visually, it would provide data about object forms.

The preceding three levels are the easiest to conceptualize and the least open to argument. Powers considers the next two levels to be the final stages of perception and motor behaviour. The four levels after that deal with activities of the brain which deal with the processing of these perceptions.

Level Four: Control of Transitions

This level perceives and controls changes of perception, for example, visual motion or the change in tone of a musical note. It is very tentatively identified by Powers with the second somatic sensory area of the cerebral cortex.

Level Five: Control of Sequence

At this level the key variable is the temporal order of events. This level could, for example, be the one at which complex motor
sequences such as the motions necessary for writing are "remembered" and could reasonably be the level at which particular phoneme orders are recognized and given word meanings. Powers feels that there is some evidence (Bickford, Dodge, and Vilhein, 1960) that such a level may exist just below the precentral cortex.

Level Six: Control of Relationships

This level analyzes the conjunction of certain perceptions or events as being examples of some set or rule. These relationships may be logical (identifying both grass and trees as being plants), or illogical (identifying bad luck with the breaking of a mirror).

Level Seven: Control of Programs

At this level, lists of relationships, motor sequences, etc. are called up sequentially, but with choice points inserted in some places to allow various actions to occur depending upon the outcome of a previous decision, as in the ways we might search for a missing set of keys.

Level Eight: Control of Principles

This level employs heuristic principles to decide which set of programs might be appropriate to run in a given situation, as in a chess player's use of the heuristic "keep strength in the centre" to decide which of several possible gambits (programs) to employ. "Strength" is not a well-defined relationship; rather it is a principle embodied in several programs.

Level Nine: Control of Systems Concepts

Essentially, some sort of common pattern is recognized in different principles, and given an identity of its own. Such an idea as
"nationalism", for example, might be an example of an integration of various principles into a whole, which upon examination, may have little real-world existence. It is the way, perhaps, that each individual orders the "reality" of his world.

Another important concept is that of reorganization. The reorganization system's function is to randomly change already existing programs and hierarchies, or create new ones; without a reorganization system, there can be no learning of processes. Again, it is a negative feedback system in the sense that it works to minimize the difference between a set of reference signals and a set of perceptions. Powers considered these reference signals to be related to the intrinsic variables of the organism: that is, those genetically determined variables which affect the physiological survival of the organism, and which have genetically determined reference levels. The means by which such reorganization occurs is unknown at present, although Powers believes that it may operate, at least in part, by altering synaptic conductivities. Powers also believes that consciousness is perception and awareness resulting from the monitoring of p signals from various systems by the reorganization system since this fits the introspective sensation of "perceiving perception". Note that reorganization is really more descriptive of a brain process necessary for learning than of some physical organization to affect that process -- Powers recognizes that this process could be an integral part of the very systems it acts upon, or could be some manner of higher order control system.

Powers, and I, have left for the end the difficult question of
where those higher order reference signals originate. He feels that the most elegant and parsimonious approach is to envisage memory being in some way associated with each neural comparator. This memory consists of a number of addressable codes which refer to past perceptual signals, and those codes are probably comprised of chemical changes within the comparator system, perhaps in accordance with the RNA theory of Hyden (1969). When the appropriate address memory signal arrives at the memory unit, the corresponding code is "played back", causing a duplicate of some formerly experienced p signal to be generated as an r signal and transmitted to the comparator. Thus memory, too, is hierarchically organized, for each memory unit will code information that has been integrated in a manner appropriate to that level of processing. The output function of such a system, then, must consist of the mechanism to produce the address signals to be sent to the next lower level control system memories.

Last, notice in Figure 6 that the control system has switches associated with the perceptual tract and the memory tract. These allow for control (both switches vertical), passive observation (perceptual switch vertical, memory switch horizontal), automatic behaviour (perceptual switch horizontal, memory switch vertical), and imagination (both switches horizontal).

I have used selected portions of Powers' theory to explain in detail the operation of some parts of my model. By itself, however, it tends to leave some questions unanswered. What exactly does a "program" consist of? How do the various hierarchies operate when, for example, behaviour and cognition programs are running simultaneously?
How do short-term and long-term memory fit in? And how exactly might reorganization operate?

Aleksander R. Luria

A.R. Luria (1973) has developed a model of the relationship between the physical parts of the brain and their roles in brain functioning by studying patients who have suffered brain lesions. The classical approach has been to identify very specific processing functions with certain areas of the brain because lesions of those areas cause performance decrements of those functions (e.g., Kleist, 1934). Luria argues that this approach is subject to error for two reasons. First, lesions in many different areas may cause the same specific functional decrement (singing ability, for example, could be affected by lesions to either the auditory cortex or the sensorimotor area controlling the larynx); and second, a lesion in one place causes many specific decrements, only some of which are likely to be investigated by the experimenter (a blind person, for example, will have many performance decrements, such as walking, piano playing, etc.). This, in turn, implies that the brain is not organized into little boxes, each of which performs a certain specific function (such as addition, or recognition of melodies), but rather is organized into a complex functional system in which many areas play a role in any single kind of processing. The way to learn about this organization, he says, is to observe the common factors underlying the complete syndrome of problems arising from any given lesion.

At this point, it is interesting to note that some of the syndromes
he presents as examples demonstrating such common factors seem to be almost identical to some of the hierarchical levels proposed by Powers. For example: kinaesthetic apraxia (inability to place a limb in the correct position), corresponds to Level Three of Powers' scheme; spatial apraxia (inability to perform movements in the correct direction and orientation, although Luria sees it as inability to place the limbs in the correct position in space) corresponds to Level Four; kinetic apraxia (inability to perform smoothly coordinated motor movements) clearly corresponds to Level Five; and apraxia of goal-directed action (loss of purpose) would correspond to some of the yet higher levels. Luria, however, does not clearly present these as being functional processes (and certainly not hierarchical ones), but rather deals with such symptoms individually, as they occur in specific areas such as speech, letter recognition, and so forth.

Three points are to be noted in this: first, that independent evidence presented in support of a completely different theory is also not inconsistent with Powers' theory; second, that finding the "common factors" underlying lesion syndromes is clearly open to more subjectivity than we would like to see as Powers and Luria postulate different factors from essentially similar data; and third, that Luria appears to fall into exactly the trap he warns up to avoid -- that of interpreting lesion evidence in too narrow a way.

He does, however, consider a more general level of functional organization consisting of three parts: first, "a unit for regulating tone or waking" (mainly the reticular formation), second, "a unit for obtaining, processing, and storing information from the outside world"
(the lateral areas of the neocortex or the posterior convex surface
of each hemisphere including the occipital, temporal, and parietal
regions), and third, a unit for programming, regulating and verifying
mental activity (the frontal and prefrontal areas). In addition, each
of these units consists of three hierarchical cortical zones: first,
the primary projection areas, which exchanges information with the
periphery of the second; the secondary projection-association area,
which processes information or creates programs, and third, the ter-
tiary zone of overlapping, which integrates the operation of many dif-
ferent processing areas. All three principal brain units work inter-
dependently although all three sub-units of each need not be in opera-
tion at all times.

Luria goes on to describe in detail the specific effects that
lesions have on visual, auditory, speech, motor, memory, and intellec-
tual functioning, but the identification of these effects in terms of
their relation to his general model of processing is too vague to be
of use in understanding the brain's system. In effect, there are so
many sub-processes which must operate within one of his process cate-
gories that we are left in the dark as to how things work -- descri-
bining a brain function as one which "creates programs" is not very
helpful, we know that programs must be created, but we don't know how
or in what situations. Because of the vagueness of his process descrip-
tions, they will not be referred to often in the model I am presenting.
Rather, reference will be made to Luria's compendium of lesion syn-
dromes (which may be thought of as content descriptions) where they
bear directly on either Powers' model, as I have shown earlier, or on
the physiological features of my model.

There is one processing distinction which Luria makes, however, that is pertinent to the following model: that of successive versus simultaneous synthesis, terms similar in meaning to serial versus parallel processing. An overview and extension of this idea is found in a paper by Das, Kirby and Jarman (1975). Luria says that simultaneous synthesis, occurring the occipital-parietal region, is involved in three areas: direct spatial perception, creation of Gestalt images from consecutive presentation or parts of the image, and complex intellectual processes. Successive processing, occurring in the fronto-temporal regions, is used in analysis of speech, writing, music, etc.

Das et al. (1975) assume that direct perception and the creation of Gestalt images can be performed in either a simultaneous or a successive manner, depending on the exact nature of the problem and the individual's personal preference, which may be molded by social and genetic factors. They believe that complex intellectual behaviour is more flexible, using either or both kinds of processing in order to solve the problem most effectively. For example, they factor-analyzed the scores on a number of cognitive tests and found that two factors usually emerge, one corresponding to tasks performed in simultaneous fashion, the other to those performed in a successive manner. They also found that which kind of processing was used by an individual on a given task depended on several variables, including cultural background and educational experience. The distinction between simultaneous and successive processing will be taken up in the model presented here, but worded in a different, and more specific, manner.
Harold M. Schroder, Michael J. Driver and Siegfried Streufert

Schroder, Driver and Streufert (1967) provide an interesting analysis of memory and processing functions, in that it relates internal processes to relatively easily observable external behaviours. Schroder, Driver and Streufert, like myself, have attempted to develop a process, rather than a content, model but have tried to restrict themselves to dealing only with what we might call high-level "idea" processing; that is, they do not deal with the initial processing necessary for translating elementary perceptions into recognizable thoughts, with memory process or emotions, nor with motor behaviour. Rather, they theorize about the way in which "thoughts" (which they loosely categorize as attitudes, decisions and judgements) are related to one another in memory, and how various ideas are combined and integrated in decision-making.

They postulate two interdependent factors underlying such information processing: the number of dimensions along which an "idea" is conceptualized, and the kind of rules used to integrate those dimensions. An integration index can then be derived which measures the complexity of the integration rules which an individual uses in processing information about some idea. Because of the different circumstances under which the dimensions and rules pertaining to those different ideas are learned, this index is content-specific in that an individual is likely to process different ideas using rules differing in complexity. Some persons, however, will have higher average integration indices than others.

This index of conceptual complexity may be measured by means of
the Paragraph Completion Test, designed to determine the various dimensions that people use to characterize certain ideas, and the nature of the rules used to combine those dimensions. A very simple integration structure would be one which analyzes the dimensions according to a single fixed rule, without alternatives or conflict. A somewhat more complex structure would be able to organize the dimensions in at least two alternative ways, but would have no overall rule which relates those two alternate organizations; thus there is a choice in deciding what to think about an idea, but no sense of those choices being part of a larger idea.

A reasonably complex structure has, in addition to the features already discussed, some means of comparing different organization rules and integrating them into more general rules. If those rules, in turn, are subject to being interpreted as being part of an even more general rule that may be generalized to many situations in complex ways then a very high level of conceptual complexity has been attained. Clearly this could become an infinite regression of rule upon rule; in practice, the integration index is judged according to a fixed set of criteria as to the number and kind of integrations, and the underlying continuous nature of conceptual complexity is understood. The most important thing about these criteria if that they are, or should be, content-free; only the structure of rules is analyzed, not the content.

At this point it is useful to note the basic similarity between this model of conceptual complexity and Powers' more general model: both are hierarchical in nature and both postulate that various kinds of transformations and integrations are performed on information in
order to generate new meaning from it. Powers, however, most clearly describes this hierarchy for perceptual processes. He is self-admittedly vague in his description of his highest two levels, which deal with principles and systems concepts. Schroder et al. address themselves exclusively to these high levels of thought, postulating a similar kind of hierarchical organization for them. Unfortunately, they do not deal with this hierarchy in terms of either the control of mentation or its relationship to a general processing model, leaving its function somewhat obscure.

Although this is a useful approach to a difficult subject, some vexing problems remain. One is that the theory does not sufficiently differentiate between the process of categorizing information and that of making decisions using that information. Categorization (discrimination of the dimensions of a stimulus and determination of its associations) necessarily involves rules for determining which categories a certain stimulus fits into. Is this rule usage, then equivalent to "decision-making"? In this theory, the situation is unclear. Another problem is that rules must have content, at least at the level of processing that this theory deals with. It is easy to think of simple rules that have complex content; for example, "There are two sides to every question." Judging by structure, it is a clear case of an inflexible rule, and therefore it must be rated as conceptually simple. Judging by content, however, it is equally clearly a case of a rule allowing for at least two viewpoints and therefore it is moderately complex. Thus although the content of the subject under discussion should rightfully be ignored, the content of the rules used to process
ideas about that subject cannot be. Although Schroder et al. provide an ad hoc way of scoring such responses, they do not consider such problems in their theory. A third problem is that a person's behaviour may be at a different level of complexity from his information processing. The model presented here attempts to partly clear up some of these questions, and detailed discussion of them will be found in the following chapters.

E. Roy John

The neuropsychiatrist, E. Roy John (1976), has developed a model of brain processing which has several features in common with that of Powers, notably those of information level hierarchies, and an information flow diagram which could easily be interpreted in the context of reference signals, although John does not see it in quite such a mechanistic way.

The processing hierarchy defined by John is more philosophical, and far less mechanical, than that of Powers. In addition, the exact details of the processes involved, which are very explicitly stated by Powers for at least his first five levels, are left undefined by John, so the following brief discussion will only outline the general nature of the hierarchy.

His first information level is that of sensations, and is clearly identical to Powers' first level of intensity.

John's second level is that of perceptions, which give meaning to sensations in terms of sub-conscious memories of similar past experiences. This level, although combining levels two through five of Powers, differs
from Powers' perceptual levels in one major respect: Powers would argue that neuronal circuits for the creation of such perceptions become "wired-in" after some learning period, and would not involve the comparison of input perceptions with remembered ones.

John's third level is that of consciousness: here the various perceptions are unified with appropriate memories, emotions, drive levels, and programs into what John calls "a sequence of multivariate 'frames'". This would seem to be roughly analogous to Powers' levels six and seven, although the distinction between automatic processing and processing requiring reorganization (the critical key in Powers' definition of awareness) is not made.

John's fourth level defines subjective experience as being the various meanings which can be applied to the same perceptions in different circumstances, and consists of such things as thoughts, plans, emotions, shapes, and sounds. Since it mixes so many different kinds of "meaning", it is impossible to fit into Powers' scheme very well, where the differential processing of meaning could presumably be at almost any level except the first.

The fifth level in John's theory is the self, which consists of an accumulated memory of an individual's life history of subjective experiences. John's sixth level, self-awareness, is the real-time instantaneous perception of subjective experience in the light of memory of past experiences, and is not clearly differentiated from the level of subjective experience. Neither of these levels has a direct equivalent in Powers' process model, perhaps because they seem to deal more with content than with processing.
If we disregard the discrepancy between John's and Powers' description of when certain information integrations take place, and whether they are conscious processes or not, one part of the processing flow scheme appears very similar in the two models: John says that present perceptions are compared to memories of past sensations in order to build up the multivariate frame in which appropriate plans or programs are contained; Powers says that the reference signals controlling lower levels consist of the memories of past perceptual signals. They disagree mainly on whether memories are needed to build up "subjective experience" or "meaning" in ordinary situations.

John goes on to present a fascinating body of EEG data related to experiments in simple classical conditioning paradigms, discrimination paradigms, and perception paradigms. Although these data can be made to fit John's model, I believe that they fit more clearly into my extension of Powers' model, which has more potential for making specific physiological predictions. Discussion of these data will be found in Appendix B entitled "A Research Program."
A MODEL OF HUMAN INFORMATION PROCESSING

Basic Outline

The general nature of the model is shown in Figure 7. It depicts a processing system utilizing hierarchically-organized perceptual systems, motor output systems, programs, and long-term memory.

The portions depicted in blue represent information in various forms, items in red represent programs, and portions in black represent processing areas. Information from the environment is received through sense receptors, whose only output consists of stimulation intensity data. This information is passed upwards through interconnected networks of neurons which form the perceptual input functions, labelled (1) in Figure 7. These input functions consist of units made up of adders, subtractors, and so forth, as well as units acting as logical gates such as AND, NOR, etc. These integrated data are then available at the second level of processing, which may be thought of as an input buffer (2). Similar transformations provide higher level integrations of the data as they progress upwards through the system. Some portion of this information is available in short-term memory (3) which holds it for a few seconds without need for rehearsal.

Processing of the information in the buffers, or of information drawn from long term memory (4), is accomplished by running one or more programs (5), whose exact features depend upon the system (motor, memory, etc.) being operated upon. In general the function of a program is to provide the signals necessary for certain kinds of information comparisons to occur. Programs are hierarchically organized;
Figure 7. The general organization of the mind (refer to text for details.)
each section of a program deals with information at a specific level of analysis. The number of levels encompassed by different programs varies. Many programs can run simultaneously (simultaneous synthesis) unless some new programs must be created by a reorganization system, or some programs which have not been well learned are running. In either case, parts of the new or poorly-learned programs must run in a serial processor (6) which is closely related to STM (in Luria's terms, this is successive synthesis). Ordinarily, however, different programs run in various different areas of the brain, rather than all running in some central computing area.

Motor behaviour is organized and controlled hierarchically by comparison units (7) operating on the principle of negative feedback control. "Thinking", which involves memory manipulation programs, may not be so organized, depending on the nature of the program.

The kinds of data stored in LTM are information received from various buffers, programs, and "rules" -- that, rules for the construction of programs. These data are also present at various levels of integration, and data about similar events may be present in several areas of the brain, if those data have been stored during the running of different programs.

**Detailed Description**

**Sensory buffers and input functions**

The data at each level of analysis are present in the form of neural currents originating from input function networks. These input functions consist of organized units of neural computing units (adders,
AND-gates, etc., as discussed previously) and are functionally and physically separate for different perceptual modalities, at least at low levels.

The first order units are simply the various kinds of somatosensory receptors, such as those recognizing pressure, heat, red light, and so forth. The only information they transmit is about the intensity of stimulation — as the stimulation decreases, the neural current produced by the receptor decreases (see P. Milner, 1970, pp. 161-163, for some examples). Note that this represents information coded in an analogue manner.

These intensity data are combined in the second level systems to create new kinds of information. Powers believed that this information represents the orientation of the irritating stimulus, but other kinds of meaning may also be extracted at this stage. For example, work done on animals using microelectrode recording from individual nerve cells has shown that several kinds of processing are performed in the retina. Maturana, Lettvin, McCulloch, and Pitts (1960), found that frog retinas contain groups of cells for detecting boundaries between areas of brightness contrast, others for detecting small, dark objects, and still others for responding to moving edges. Weisel and Hubel (1966) found groups of cells in the lateral geniculates of monkeys which selectively responded only to spots of light, and others which only fired when stimulated by bars of light oriented in a particular direction.

Although similar studies are difficult to perform on human beings, these data suggest that a particular layer of the retina or of the brain could conceivably be responsible for detecting several features of the
input. What exactly, then, determines whether one input function is at a higher level than another?

The answer lies in the exact nature of the neural connections to those input functions. If the unit for detecting contours receives its input signals from the output of the orientation detectors, then it is a third level detector. If, on the other hand, it receives its input directly from the rods and cones, without any mediation from the orientation detectors, then it is a second level detector. Note that it is possible to do sophisticated pattern recognition (such as recognizing "things that are red, hollow, and asymmetrical") using only connections from the first order receptors. The number of interconnections necessary for such a task, however, would be immense; it is much less wasteful of neural space to recognize "red", "hollow", and "asymmetrical" at lower levels and use signals from those recognition units as the input to a higher level analyzer.

In effect, this means that we may make educated guesses as to what functions are served at various processing levels, but that we cannot determine these functions on logical grounds alone. Only an investigation of the neural circuits will tell us what kinds of data are processed at any given level, and the nature of this processing will undoubtedly be different in different sense modalities.

Note that the advantage of needing fewer connections when processing hierarchically is partially offset by needing more time to analyze higher order information, since the information must pass through more computing units. This timing difference could be detected if low order outputs were directly available to a program. If information
from a low-level system could be acted upon before it passed upwards to a higher-level system, then reaction times to low integration level stimuli (e.g., intensity) should be lower than reaction times to higher level stimuli (e.g., shapes). Work on the reaction time paradigm by Ward and Wexler (1976) and Neisser (1963) shows that such direct access is probably possible (this direct access is often termed "multiple readout"). The Ward and Wexler study also indicates that curved shapes may also be processed at the same level as straight lines. The hierarchy proposed by Powers seems mainly concerned with the processing of spatial information (orientation, movement, and so forth); this may well be true of the visual and kinesthetic systems. Other systems, however, undoubtedly perform their own specialized integrations. I make no predictions as to the exact nature of such integrations, nor as to how many levels of buffers there may be, although five perceptual levels would seem to be a reasonable minimum. The use of the term "buffer" implies at least short term storage of the information present at a given level of analysis. In Hunt's (1973) discussion, he writes that information in a given buffer is compared to stored LTM information; if a match is found a signal is passed upwards to the next level buffer. If such searches occurred at all buffer levels some storage of information would certainly be necessitated. What determines when a buffer changes its information if a match is not found is not adequately dealt with by Hunt. In the present model, temporal storage of information is not required for processing to occur at low levels. The term is retained since a given output device will continue sending a signal upwards so long as the appropriate input stimuli are present, rather than
just when the stimuli first appear (relying on higher levels to remember that those stimuli are present). In this limited sense only is there storage of information in the low level buffers.

In summary, the sensory buffers and input functions form a feature analysis system for the input from somatosensory receptors. Information present in the form of neural currents at each buffer represents the recognition of features appropriate to the level of integration of that buffer, and is available both for program processing at that level and further integration by a higher level system.

Comparison units for motor behaviour

As explained earlier, the comparison units utilize negative feedback to compare perceptual input signals to reference signals in order to control a set of output functions (see Figure 5). The output functions of one level generate the reference signals for the next lower level. The evidence presented by Powers for the existence of such control systems for generating motor behaviour is very convincing (e.g., Bickford et al., 1969; Hess, 1957; Ranson and Clark, 1947).

One of the features of such systems, however, is that they control variables which are smoothly continuous, such as limb position or speed of finger movement. Other systems that the brain must have, such as memory storage and search, logical thinking, and program control, seem less amenable to such hierarchical control networks. I believe this is because such systems either work in a more binary fashion than the motor system (as in selecting one program or another program, rather than controlling a smooth range of programs), or they operate at only one level of processing. How such systems might work will be discussed in more
Programs

Programs are ordered sets of instructions and choice points for organizing the computing units of the brain in such a way as to perform the required processing. They are hierarchically organized so that any given program may contain instructions for directing processing at a number of levels of integration, and may perform multiple operations at any one level. In addition, there may be several sub-programs available at any given level; a sub-program also consists of an ordered set of instructions and choice points, but is available as one of several options within the main program. Instructions for choosing which one is to run depend on the information input to a sub-program selection mechanism. A general program for opening a door, for example, will contain sub-programs for different muscle movements depending on whether the door is hinged, sliding, or revolving; this is an example of a fairly high-level program. The program responsible for controlling respiration operates at a lower level than the one for opening doors, and may not have any sub-programs.

Consider a program for directing a sequence of behaviours such as moving one's arm in small circles. This would require motor control for roughly the following control levels: motion (circles), configuration (arm straight), orientation (arm out to the side), and intensity (small angles). Remember that each control level generates the reference signals for the next lower level, and that Powers considers the reference signals to be address memory signals. I then identify programs to be ordered sets of memory address locations for generating
the correct kind and sequence of those reference signals, and ordered sets of computing address locations for organizing the logical units necessary to select sub-programs. Within a given program, those address locations are associatively linked and hierarchically ordered, from the most general addresses (those corresponding to the highest level systems) to the most specific ones (those corresponding to the lowest level systems). In addition, sub-programs are associatively linked to their main programs.

This will work if memory consists of past perceptual signals, as Powers suggests, and if it is organized hierarchically and is physically present at the control systems. This mechanism of memory storage provides a clue for the distinction between programs which seem to run automatically and simultaneously with other automatic programs (such as those controlling breathing, heart rate, etc.) and those which appear to run in successive steps and need more conscious mediation (such as learning to walk). If memories and their associated addresses may be stored at the site of integration then programs, which consist of similar addresses may also be stored there. I thus identify simultaneous and parallel processes as those which have run often enough that their address lists are stored at the site of their operation — i.e., they have been learned. Different programs for different muscle groups may then easily run at the same time without interference, because they are running in physically separate areas of the brain rather than in a central computing unit. If two programs use the same set of muscles, and therefore the same program locations, they cannot run simultaneously; but there is nothing to prevent the same physical location from being
the storage place for addresses coded to several different programs. Lifting one's arm, for example, is part of many different programs. Therefore, similar reference signal addresses will be stored at the same location for those programs, differing only in their associative link with higher level addresses. These links identify the programs of which each address is a part. The associative link, of course, must be some address code referring to the address of the next higher computing level of the program or perhaps to the highest, most general one.

The logical units for selecting sub-programs (choice points) are also set up at the site of the appropriate computing level. The decision-making part of the program which accomplishes this does not select the addresses of memorized reference signals. Rather it must somehow set up adders, AND-gates, and so forth from some stock of neural tissue which is not being used for perception or motor control, perhaps by altering synaptic thresholds or influence (positive or negative excitation) at those sites. Again, these circuits become permanent, and the sub-program selection becomes automatic, when that selection mechanism has been run many times.

Many kinds of programs besides motor programs may become automatic, of course. The analyzer responsible for constructing words from patterns of sounds, for example, runs automatically. Note that, although automatic, this is probably a sequential analyzer; this points out the fact that an automatic program can run in parallel with other programs, but the actual operation of that program may have to be sequential because of the nature of its task.
It should be noted that many reference signals, especially for behaviour, are undoubtedly supplied genetically (this is certainly a strong point in favour of memory being coded in RNA or in proteins, which are synthesized using RNA codes). When I speak about detecting error during the running of a program, it should be understood that one kind of error could be a result of deviation from those genetic references (Powers' "intrinsic error").

Memory

The identification of memory units with the units responsible for generating the reference signals at various levels of processing necessitates the hypothesis of a distributed, hierarchical type of long-term memory. Other workers have proposed similar models based mainly on the way in which language is analyzed (e.g., Hunt, 1971; Lindsay and Norman, 1972). The derivation of similar models from very different viewpoints would seem to be a strong point in favour of this general view of LTM.

A. Long-term memory

Hierarchical memory consists of two things: the content of the memory -- that is, the thing being remembered -- and a set of addresses for that memory. There are three basic kinds of content: information, programs, and rules for building programs. In addition, there are two basic kinds of addresses: one that is used by the brain to "replay" the memory when that address signal arrives at the memory storage unit, and one or more others to associate that memory with other memories at the same level at higher or lower stages of integration. If, as seems reasonable, memory is coded chemically, then the content and the
addresses are likely to be all stored together in one master chemical code. This is not essential to the present model, however.

The addresses which associate a memory with other memories at the same or different levels are initially constructed during the running of the program that led to the original set of perceptions. The number of branches of that program at various levels and between levels of analysis is reflected in the number of associative addresses of that memory. For example, think of the word "pedestrian". No doubt a number of associations spring to mind, related perhaps to walking, store fronts, and so on. Now imagine that you are driving a car, and think of "pedestrian" again. The associations this time are probably very different from those you first thought of, illustrating how memory associations may be linked to the programs which were running when those memories were stored.

The generation of address codes during program operation amounts to a kind of "content addressing", since different pieces of information having similar content will be processed by similar programs, or even within the same main program. Such content addressing is consistent with the theories of other workers (Norman, 1968; Shiffrin and Atkinson, 1969), but is discussed here with emphasis on the programs that produce it.

The last example clearly shows that memory, whether hierarchical in nature or not, does not contain one fixed set of associations for any given subject or idea. Rather, it shows that memory is redundantly stored in many physical locations in the brain since it is stored during the operation of different programs in different brain areas. Each of
these redundant "memories", however, are subtly different from each other in that their associations are different.

How then do the two views of "pedestrian" ever become recognized as being related to each other, given that it is impossible to drive and to sit reading a paper at the same time? Clearly, it would be difficult for the programs for those two actions to become associated, thus leading to a memory association.

The answer, I think, is that we must postulate the presence of some special programs in the memory process itself. First, for reasons which probably relate to evolutionary survival, automatic programs have evolved for checking incoming perceptions against already stored information to detect consistencies and inconsistencies between the two. This involves both LTM and STM. Exactly what consistencies are checked is a moot point, but it is reasonable that visual and auditory pattern matching would be among the first to be evolved. Note that two perceptions of the same event which have been formed during the operation of different programs will never be identical to one another, and so perfect matches will not be found. Yet some aspects of those perceptions will be similar, and remain relatively unchanged by the program associations -- such as the visual features of a pedestrian -- and so will be available for matching. Checking for "unusual" events would be another useful program. Second, conscious attention is sometimes directed towards two pieces of information, for any of a variety or reasons, and a deliberate attempt is made to see if any consistencies exist. Such conscious checks would most likely occur at high levels of processing, using sophisticated comparison rules. To decide
that "the moon is made of rock", and "the moon coalesced from a gas", are not inconsistent pieces of information required very complicated comparisons indeed for the man who first thought of the dust cloud theory of planetary formation. One very common reason for making such a conscious comparison is when the same name is associated with two hitherto separate pieces of data. This often gives rise to an "aha" response.

Since the language analyzer and the set of rules of scientific deduction are both programs, these last two examples can be seen as special cases of the general way in which memories are stored. Memories only become associated when they are related by some program.

Memory retrieval operates by means of a retrieval program which operates in an associative and constructive manner. Two main modes of operation are possible: automatic information search and non-automatic constructive search. Automatic information search may result when a person is asked a question related to data which has an associative address (or addresses) directly related to the question asked, as when a historian is asked "When did Julius Caesar reign?" A non-historian, if unable to access the same information directly, may then engage in the constructive task of retrieving this information by, for example, remembering when other rulers governed before and after Julius, and inferring the dates required. Some kinds of constructive sub-programs appear to work partially automatically, however, such as those which search out the correct associative addresses. Note that the reliance of memory search programs on associative addresses means that these programs are related to the input programs running when the information
was memorized. Although automatic and non-automatic search strategies are similar in nature to the episodic and semantic memories, respectively, described by Tulving (1972), two differences exist. First, non-automatic searches in the present model need not rely exclusively on semantic processes as in Tulving's model. Second, the result of an automatic search will reflect the encoding bias of the program which stored that information, but it will not be biased by the search itself; such bias is more likely in the non-automatic search -- a reverse of Tulving's prediction.

Forgetting may occur both in STM and LTM. Many researchers have developed models of forgetting involving decay and interference processes in STM, and storage and retrieval mechanisms in LTM (see Lindsay and Norman, 1972 for a review). In addition, I wish to propose that two other mechanisms may be responsible: either the original perception was not stored (at least at the level the person is trying to remember) or the information is not sufficiently differentiated in terms of the programs associated with it when it was stored. As an example of the first process, a person may remember that a square was presented tachistoscopically during an experiment several weeks previously, but be unable to remember its size, colour, or orientation. Only the relatively high level meaning -- square -- was stored. In many situations only the highest level perceptions may be stored. It is reasonable to suggest that attentional processes are important in the selection of perceptions to be stored, but no detailed model of attention will be described in this model. The second process probably operates in situations like the typical serial learning experiment. Words are
forgotten because the learning program in operation during the task contained no processes for distinguishing the various words from one another. If some words are different from the others (e.g., a different colour) they are remembered much better (see Kohler, 1940, for a review), since now different programs, having different associations, are used during the processing. Although this differentiation may appear to be a property of the stimulus, rather than the program used to process it, I believe that the work done by Luria (1969) with a mnemonicist shows that the converse is true. Luria found that the mnemonicist he studied typically memorized lists by creating very elaborate image associations between the items; these associations seem much more like programs for processing the items than properties of the items themselves. In general, of course, identifying forgetting with aspects of the programs processing the data is consistent with my theoretical linkage between programs and LTM.

B. Short term memory and the serial processor

The role of STM (a memory of limited capacity and duration; e.g., Miller, 1956; Peterson and Peterson, 1959) is not quite as clear as that of LTM, since the hierarchical nature of the buffers, programs, and LTM does not logically imply any particular structure for STM. Indeed, it would seem that an organism could survive without any STM processing whatever, merely coding all information into LTM.

Figure 7 shows STM as encompassing portions of some of the higher levels of the input buffers. How many buffers are available in STM, and how much of each buffer is available, is currently a subject of controversy. Whatever is the case, it is assumed here that this
information is available to the serial processor (SP). Programs which have not run often enough, or because they have just been created, run in a sequential manner. The basically serial nature of STM has been investigated mainly in the context of sentence analysis, by such researchers as Lindsay and Norman (1972). In my model it is assumed that sentence analysis has to be not only a serial program due to the nature of the task, but must run in the SP using information held in STM, because no one sentence is analyzed often enough for that analysis to become automatic (although sentences like "How are you?" may be exceptions).

One function of STM, then, can be to hold information long enough for special purpose programs such as the sentence analyzer to work on it. Another special program which seems to run in STM is selective attention. Although selective, or "channel", attention could be present in the input buffers, some workers believe that attention mechanisms work only in STM, meaning that STM encompasses all of a buffer (e.g., Shiffrin and Grantham, 1974; Shiffrin, Pisoni and Castaneda-Mendez, 1973).

The studies by Shiffrin et al. are worthy of further scrutiny, however. Both studies presented near-threshold signals masked by white noise. The subjects had to detect whether and where the signal was present. In the Shiffrin and Grantham study, a signal was presented to the subjects to either the eye, ear, or skin. In the simultaneous condition, any of the sensory modes could contain the signal within 500 msec of the subject's pressing a start button; in the successive condition, the signal would be present either visually in the
first 500 msec, auditorily in the second 500 msec, or tactilely in
the third 500 msec. A pre-STM attention effect was considered to be
the presence of a better hit rate in the successive condition than in
the simultaneous condition; such an effect was not found, and the
authors concluded that attention must operate in STM, rather than before
it. The second study was similar, except that signals were presented
to one or the other ear.

The assumption made by Shiffrin et al. is that the identification
process should be more accurate in the absence of any irrelevant infor-
mation, so that when attention is focused exclusively on a single
modality (by using pre-STM attention) the hit rate would be higher.
However, since STM was far from overloaded in this paradigm and the SP
was probably not involved, there seems to be no particular reason to
believe this. The signal recognition could well be part of an auto-
matic STM search search program for "unusual" events, the memory load
was not impaired. Indeed, Eijkman and Vendrik (1965) found precisely
this. There was no difference between attending to two modalities
(either of which could contain a signal) and attending to only one
(but without switching, as in the Shiffrin et al. studies).

This is not intended to resolve the question, as a great deal of
inconclusive work has been done on this topic. I merely wish to leave
open the possibility that STM only encompasses part of a buffer, i.e.,
that attention is a pre-STM effect, quite possibly performed by the SP.

The "multiple read-out" feature discussed earlier indicates that
it is possible for STM to operate in several buffer levels; but perhaps
it is only the SP which does so. The capacity of STM is usually con-
sidered to be about 5 to 9 "chunks" of information (e.g., Miller, 1956; Simon, 1975); in the present model it is hypothesized to be the number of addresses which may be held in STM. Thus a chunk is a general address for a piece of information, and contains the code for the program which analyzed that information, as explained earlier. A chunk can contain different amounts of information according to the program which coded it.

The serial processor is an area of brain tissue which can be set up to run novel programs to analyze the information in STM. Besides being limited by STM capacity in the amount of information it can handle, it is also presumably limited in the number of program steps it can perform in parallel, perhaps to as few as one step. Since no one seems to have tested STM during the running of more than one program, as opposed to running different programs sequentially, however, the exact nature of the SP and its relationship to STM is quite vague.

It is even possible that several STM's or SP's are available in different areas of the brain. The split-brain work by Sperry (1964), for example, could be interpreted as evidence for STM associated with both visual and motor areas. Since a program consists of addresses, however, and since STM can only hold about 5-9 addresses, I suggest that the number of novel program steps which can be generated at any one time is also 5-9. Some of them are presumably executed by the SP, while the others are held by STM. The higher level program (address) for generating these steps, however, may need to be stored as well, thus further reducing the STM capacity.
The reorganization system

The reorganization system is responsible for the creation of new programs. These new programs may direct perception, behaviour, or information comparisons, and could, of course, later become automatic. Since novel programs are being run, the reorganization system must run these programs in the SP. This implies that only part of a new program can be learned at a time, which is certainly consistent with common knowledge. The SP must create these programs according to some set of rules of its own.

Reorganization occurs when an error signal from some program or sub-program exceeds some critical amount, and there are no more programs available under the general address at which the error occurred. Since programs are ordered sequences of addresses, self-generated reorganization must be the generation of different address orders, and/or the generation of address lists from some content area previously unassociated with the problem at hand. The first corresponds to "trying things a different way around"; the second to "trying something completely new". These new addresses may be generated either randomly or through the use of some program formulation rules. These rules, naturally, are like higher-level programs, the only difference being that they do not run automatically. Reorganization may also occur if one can learn the new program by watching the behaviour of others, or by being explicitly told the correct program; these ways, however, must necessarily generate only high-level reorganization. Lower-level changes must be effected by the individual (for example, we may be told the principles of driving a car, but we must practice
Reorganization will end when the error signal drops below the critical value, $E$. The value of $E$ will be different in different content areas, and in different individuals.

Reorganization is clearly the key to learning, but its mechanism is the most unclear of anything in this model. Children certainly find learning a new program to be very rewarding (e.g., Bower, 1974), but adults appear to find it more difficult and aversive, perhaps because more systems become interrelated, and changing one implies a need to change many others as well.

**Information Usage**

**Perception**

Perception programs control the operation of the input functions in the buffers. These input functions abstract "meaning" from lower order signals from the somatosensory system. Most of these programs are "hard-wired", especially at the lower levels. That is, they are genetically predetermined and highly resistant to change, although they may need certain environmental conditions in order to develop properly. The organization of visual perception in detecting contours, movement, and colour mixes, for example, appears to be virtually identical in all individuals if one disregards acuity. Some higher level integrations, such as perceiving perspective appear to be either learned or dependent on exposure to the correct environmental conditions to bring out the hard-wired capability (see Deregowski, 1972, for a review). It does not appear that we can easily modify the action of perceptual programs at low levels, but that may be because we seldom
need to do so. In unusual situations, such as when wearing prism goggles which invert the visual field, it appears that a slow, incomplete, modification of these processes does occur (e.g., Kohler, 1962). When such modification becomes automatic, it must be because the input functions have been reorganized.

At higher levels, more programs and integrations are possible. We may see a picture as a random pattern of dots until we are told that it really represents a picture of a tree — and a tree appears. At first, of course, this may be a memory process such as template matching (see Neisser, 1967, for a review), but it can easily become an automatic process if we see similar pictures again and again. The change to automatic integration implies a direct modification of the high level perceptual program.

As discussed earlier, the way in which information associations are formed is determined by the program running at the time. In all but the most unusual situations, these associations are relatively high level ones in the perceptual system.

Motor behaviour

A sub-program at a given level of motor control will use perceptual and memory information at that same level of analysis both for the control operation and for making decisions about program switching. That information, however, will consist of data which have become associated with the program then running, and hence the details they contain will tend to be those relevant to the program. Other details will tend to be ignored and lost. In addition, the relevance of this detail to any other program will tend to be missed since it will not
necessarily produce error in the motor output. For example, the sub-
programs associated with the perception of a pedestrian to a driver do
not involve paying attention to the pedestrian's facial expression.
The driver might then easily miss the pedestrian's expression of alarm
as he watches the driver run a red light. That same expression would
not go unnoticed to someone speaking to the pedestrian, since facial
expressions are data associated with the program of "conversation".
The actual feedback mechanism of behaviour is considered to be as
discussed by Powers.

**Thinking and decision-making**

Thinking and decision-making are defined as the process and output
of conscious memory control programs running in the STM and SP for
retrieving and comparing information, respectively. The program choice
points which select between sub-programs are not considered in this
discussion because the choices are performed automatically and uncon-
sciously. "Consciousness" is then defined as being those processes
performed in the SP. "Awareness" constitutes the information moment-
tarily in STM. Since the SP is only part of STM, this implies that
awareness completely subsumes, but is not limited to, consciousness.

Using these definitions while assuming that attention is a post-
STM process creates a problem when trying to answer questions like,"Why am I not always aware of my feet, but I am when I think about
them?" If awareness consists of everything in STM, and STM contains
all the information in all of the buffers, or at least in those re-
ceiving somatosensory information, then we should be "aware" of our
feet all the time. Several resolutions are possible. Attention may
be a pre-STM effect, perhaps partly directed by the SP, different modalities may be directed preferentially into STM (for example, I seem to be more easily and more continually aware of my entire visual field than of my auditory field); or there may be STM's of different capacities for different kinds of information.

The definitions above are, of course, rather arbitrary; but it seems useful to distinguish between types of processes and of information which are somewhat different in our introspective awareness, and which, therefore, may also be created by different processes. Powers (1973), for example, also makes this distinction, holding awareness to be the reception of high-level perceptual signals, and consciousness to be the monitoring of those signals by the reorganization system. Hunt (1971), however, does not make this distinction, considering attention and consciousness to be those processes which are being performed by a Central Processing Unit (CPU), and identifying the CPU closely with language analysis. However, these differences in viewpoint about consciousness and awareness are slight, and perhaps of only minor importance, except in how they relate to STM.

At what processing level do thinking and decision-making occur? Philosophically, they seem higher than perception, motor control, or memory storage; but they may not be higher in terms of physical organization. It is difficult to conceptualize either of them as negative-feedback control units, except in that they will both occur as a result of error signals originating when memory search programs detect inconsistencies, or when a decision is called for. Identifying thinking with processing done by a language analyzer seems too simple: for
example, people solve some kinds of visual problems by moving images around in their imaginations. It seems more reasonable to consider the language analyzer as an area separate from STM and the SP, which may be used in certain conscious processes. Thus, although the language processor may well use STM and the SP, it is not identical to either of them. Indeed, Hunt says that some rules available in language analysis may not be available in certain other problem-solving tasks.

Our definitions of consciousness and awareness certainly imply that the information these functions use may be at different levels. Perhaps it is easiest to conceptualize their processes as being at different levels as well, with the exception that the reorganization system must be at a higher level than anything it reorganizes. Powers' definitions of eighth and ninth level systems (control of principles and control of system concepts, respectively) sound like functions which would control our thinking, but perhaps they merely represent different kinds of programs available for conscious processes.
CONCEPTUAL COMPLEXITY

The above model is useful in breaking down conceptual complexity into more specific processing components than has been done before. Rather than seeing complexity in terms of only discriminative and/or integrative components, I propose that at least four semi-independent components are involved in processing complexity. These components are categorization, decision-making, rule, and behavioural complexity.

These four components relate to various stages in the processing system. First, the automatic analysis of information in the input buffers provides both discrimination and integration of information, resulting in the data used by various programs. This automatic analysis may differ in the number of dimensions discriminated and the number of constructs generated, resulting in varying degrees of categorization complexity. Second, perceived data and data retrieved from LTM are used to select a program that is appropriate to the perceived situation. The selection flexibility and the complexity of the program and the information it uses determine decision-making complexity. Third, whereas categorization and decision-making run relatively automatically, various situations will elicit the use of memory processes to create new programs and/or constructs, requiring rule usage in the SP. Rule complexity refers to the structure and content of such processes. Finally, we may consider that in situations where behaviours are elicited, those behaviours may vary in flexibility and complexity, resulting in behavioural complexity.
These four components of complexity relate to the processes described in the model of the brain system and are most easily thought of in terms of structure rather than content. However, as discussed in the introductory remarks about conceptual complexity, confusion may arise when a subject's response exhibits different amounts of complexity depending on whether the structure or the content of the response is considered. There is no simple way around this difficulty; however, a hypothesis will be made below as to the ontogenetic development of such responses.

**Detailed Model**

**Categorization complexity** of a given subject topic would include:

1. The number of different pieces of information available about the subject in all memory areas.
2. The number of different chunks associated with roughly equivalent pieces of information. This number will be positively correlated with the number of sub-programs relevant to that piece of information within any given program.
3. The number of "constructs" linked together. Constructs may be thought of as being general addresses associated with different programs; the number of linked constructs reflects the number of programs with which the topic has become associated. This linkage implies that those programs have also become associated with each other.
4. The complexity of the processing necessary to produce that chunk of information. This relates to the content of the information and
of the processing that produced it. For example, chunking binary digits by translating them into decimal numbers involves less complex (or at least, less complicated) processing than, say, taking the binary digits to be Morse code (dots and dashes for ones and zeros), translating them into letters, and then constructing acronyms from those letters. With long practice, an individual might perform the greater part of either chunking method in an automatic manner.

Categorization complexity would tend to be elicited by questions such as "What do you know about _____?"

Rule complexity relates to the complexity of memory processes which may be used on information and constructs stored in LTM. The purpose of these processes is to detect consistencies and inconsistencies between different constructs, as mentioned earlier. It would depend on:

(1) The tolerance for error in the memory search programs: more connections will be made as the critical tolerance decreases. In searching for a consistency between the statements "The moon is made of rock", and "the moon coalesced from a gas", a person having a large error tolerance may not do any memory searches or attempt to create any new rules; a person having small error tolerance may spend a lifetime perfecting rules which interrelate large amounts of information and many programs. Note that in any individual rule complexity may be high in some content areas and low in others.

(2) The number of available rules for comparing constructs and the number of associations between them.
(3) The content complexity of the rule, in terms of the complexity of processing which was necessary to generate that rule. Reducing inconsistency in the previous example by saying "Planets were formed from gaseous nebula" shows higher content complexity than does reducing inconsistency by saying "So what, I don't care", although in both cases the processing is simple, once the rule is learned.

(4) The complexity of categorization, in that the potential for rule complexity increases as the complexity of information those rules act upon increases.

Rule complexity may be elicited by questions such as "How do _____ and _____ relate to one another?" Note two content areas must be specified, not one as in categorization complexity. Clearly categorization and rule complexity are similar, the difference being that categorization complexity is determined by the kind and number of programs running during the learning of the information while rule complexity is a function of the memory processes which combine information already present in LTM; categorization processes run automatically, while rule processes run in the SP. Rule complexity is more content-independent and less related to the circumstances under which the information was learned than is categorization complexity.

Decision-making complexity relates to the operation of programs on information in a specific environmental situation, rather than in a more abstract memory process. It is dependent upon:

(1) The amount of information used and the categorization complexity of that information.
(2) The number of programs which could be used to process the information. This will range from low (only the one program immediately associated with that precise environmental condition) to medium (several associated programs are available because of moderately high categorization complexity) to high (several previously unrelated programs are used as they become associated through rule usage).

(3) The flexibility used in choosing the program or rules to use. An individual may have many programs available but may use only the simplest ones most of the time.

(4) The complexity of the program structure as indicated by the number of choice points it contains.

(5) The number of situation-specific outputs possible in the decision process.

Decision-making complexity will tend to be elicited in specific problem tasks, such as "If _____ were the case, what would you do about it?"

Behavioural complexity will depend on:

(1) The number of available behavioural outputs. A person may have highly complex processing in a given situation, leading to several available decisions about what he should do, but only be able to do one of them (the perceptive, but shy, person would be a good example of this).

(2) The tolerance for error, especially at high level analysis. As error tolerance decreases, the person tends to be forced to employ various other behaviours, more perfectly suited to various situations.
Hypotheses

The preceding model describes several semi-independent features of the processing system. Two main points should be noted about such a system in reference to a discussion of conceptual complexity or, indeed, any other relatively "high-level" psychological concept. First, that it is difficult to describe the origins of any psychologically interesting behaviour without examining the functions of the several interacting features which were instrumental in producing that behaviour.

Very few of the outputs that psychologists measure can reasonably be thought of as being the result of only one independent, homogeneous process. Rather, it is necessary to try to determine exactly which processes are involved in the situation, and to theorize on that basis. This point is expanded upon in Appendix A, Attitude Measurement. Second, note that the processes described by the model are both considerably different from each other (implying some independence of functioning and complexity) and semi-independent within themselves across different program areas.

As a result, we may hypothesize that an individual may have different processing complexity not just in different content areas (as Schroder et al., 1967, have suggested), but also in different process areas. A judge who considers many conflicting and complicated aspects of a case, but who always decides in the end that the accused person must be guilty might be said to use a relatively complex categorization process but a relatively simple decision process. The flexibility and appropriateness of the judge's sentence could be seen as reflecting the complexity of a different decision process as well as that of a
behavioural output. Similarly, a superstitious person may evolve a complex rule system for explaining the interrelations between various events without necessarily employing complex processing in other areas. We might expect, however, that such an individual would tend to have relatively complex decision-making and behavioural processes if he or she decided to act in ways which minimized the unpleasant consequences of breaking "bad luck" superstitions.

It is a matter for empirical investigation to determine the degree of correspondence between the various complexities of structure in the four areas of processing mentioned above. However, since the complexity found in any given area is at least indirectly related to error tolerance, we might expect a small positive correlation between the complexities of different areas if this tolerance is constant in different areas. Remember that error is detected in some manner in a neuron comparison unit; to the degree that such comparison units are similar across processes we may expect error tolerances in those processes to be related.

The purpose of further dividing conceptual complexity in this way, of course, is to attempt to improve the predictive validity and descriptive usefulness of complexity when used in conjunction with measures of behaviour or mental processes. To the extent that this model accurately describes cognitive functions, and that suitable measurement devices may be found for them, it is hypothesized that the set of four measures will prove more predictively and descriptively useful than any single measure of complexity. It should be emphasized here, however, that the postulated program-dependent nature of complexity means that complexity is not such a global attribute of mental processes as is
often implicitly assumed. That is the validity of any measurement of the complexity of the four cognitive functions will depend on how similar the content area tapped during the measurement is to the content area which the researcher wishes to describe or predict.

The ontogenetic development of the various processes occurring in these areas has, of course, long been studied in many different areas of psychology. However, part of the model presented here describes the development of automatic processes from non-automatic ones, which will lead to changes of function not only within a given process, but also in the transfer of function from one process to another. In particular, there will be a gradual shift of function over time from relatively non-automatic processing to relatively automatic processing as a particular function is repeated. Some functions which originally had to be run as rule manipulations in the SP will later become automatic decision functions; decision functions may eventually be incorporated into categorization processes. For example, a rule structure consisting of "hot things cause pain if touched" and "pain is to be avoided", will soon be incorporated into the more automatic decision program "if it's hot, don't touch it". This decision might later be incorporated into the categorization "hot-bad" associated with those situations in which the original program was true. In this latter situation, the decision rules may be superceded or left more simple and fewer in number, with a concomittant increase in the complexity of categorization complexity.

Such a reduction in high-level complexity accompanied by an increase in low-level complexity is almost certainly only true for
adults. Clearly rules are built up by processes tending to increase complexity at high levels using information found at low levels of processing. Thus these processes might be seen as being in opposition to those described above which tend to decrease high level complexity. When relatively large amounts of new, unintegrated data is being encountered (as is the case with children), such a combination of processes will overall tend to increase high level complexity. At some point, however, most incoming information will be dealt with automatically and so the result of these processes will be to decrease high level complexity. The adult in a "rut" will tend to use automatic programs far more often than rules. Thus any procedure which measures rule usage will find such usage to follow an inverted U-shaped curve over the course of an individual's life. To the extent that a person's life situation keeps introducing new experiences to be integrated into a cognitive scheme, this rule usage curve will tend to peak at later ages.

Relationship to Conceptual Complexity Literature

It is difficult to relate this model to specific research in the field of conceptual complexity because most of that work has been done using either tasks involving discriminative (categorization) complexity as developed by Kelly (1955) and Bieri (1955, 1961), or tasks involving integrative complexity as modeled by Schroder et al. (1967) and Harvey, Hunt and Schroder (1961). Although studies using either of these approaches often prove predictively useful in specific situations, there has been little attention paid to the relationship between the
two models, and no attempts have been made to integrate these forms of complexity into a general model of brain activity. In addition, many workers only consider complexity with respect to social stimuli, considerably reducing the certainty with which we can extrapolate their findings into general processing activities.

The studies that consider several areas of complexity simultaneously have been done quite recently and are not yet very sophisticated. MacNeil (1974) notes that workers in the complexity field have not usually tried to combine integrative and discriminative complexity ideas into an overall theory, and have also not made much headway in identifying the rules used in integrative complexity. In particular, he notes that concept attainment rules have not been found to have very much in common with integrative complexity rules. He proposes a descriptive model which synthesizes the two complexity approaches in relation to the Neisser and Weene (1962) rules for concept attainment. Although he presents no experimental evidence, it is clear that he intends to use a concept attainment paradigm as a tool to discover the relationship between integrative and discriminative processing.

Epting and Wilkins (1974) present measures of the intercorrelations between two measures of discriminative complexity, two measures of integrative complexity, and a measure of discrepant information integration in a person-perception task. None of the correlations exceed .31, and six of the ten correlations are below .11; Epting and Williams suggest that this reflects the possibility that each measure is evaluating a different cognitive process. However, the low correlation of .25 between the Schroder et al. measure (1967) and the person-perception
integration measure (Kaplan and Crockett, 1967) tends to weaken one's confidence in their results in that the two measures use almost identical procedures for assigning ratings of complexity. Only the form of the data used is different in that the Schroder et al. measure uses responses to incomplete sentence stems and the Kaplan and Crockett method uses descriptions of a person; it seems most unlikely that this should be of any significance.

Scott (1969) similarly found that various other measures of cognitive functioning within a metric multidimensional model of cognitive space tended to show only limited consistency across content areas within a given process area, and limited consistency across process areas within a given content area. His measures of processing included several not considered here, such as articulation, affective consistency, and centrality; his measures of dimensionality and integration, however, were not highly correlated with each other. A similar study was done by Kuusinen and Nystedt (1975), who used various factor analytic methods to study the relationship between Bieri self-constructs and three measures of integration as defined by Vannoy (1965); these measures were also taken when constructs were supplied to the subjects. They found low convergent validity between the various cognitive measures and also found that the type of construct used affected the intercorrelations of the measures.

The above-mentioned studies show a recent trend towards considering the relationship between discriminative and integrative processing in a more quantitative manner than has been done previously. They support in a general way the hypotheses that these process areas may be
independent in terms of complexity and that complexity may be quite different in different content areas.

The hypothesis that the error tolerance associated with a given content and program area may change given various work of Press, Crockett, and Delia (1975) and Earle (1970). In these studies character evaluations and cue learning, respectively, became more complex when the subjects were placed in situations which encouraged such processing. In both studies, however, only subjects who were conceptually complex with respect to the task at hand showed such an increase; there was no change for non-complex subjects.

Tests

The two main hypotheses of the model are that the structure of cognitive processes may be described in terms of four semi-independent areas of functioning, and that some combination of these four areas will prove to be more predictively and descriptively useful than any single measure of complexity. The ability to test such hypotheses, of course, is limited by the ability to accurately measure the complexity of the four process areas. Given measures of these processes, any experiment which essentially duplicates a single cognitive process experiment but with measurements of all four process areas will at least show if these measures are heuristically useful. Showing the "true" relationship of these measures to the actual cognitive processes is much more involved: see Appendix B for a fuller description of how this might be done. Since any testing of this model depends on the development of such measurement techniques, this section will describe
some ways in which these measures could be developed. The outline of possible measures will loosely follow the points outlined under Detailed Model, above.

Categorization Complexity

(1) The number of pieces of information available about a given topic will to some degree reflect the different ways in which that topic may be categorized. It might be measured by means of a world-knowledge questionnaire about the given content area. However, as such a questionnaire would probably inevitably tap into various memory processes, its reliability would be open to question. The number of self-generated constructs elicited from a Bieri-type construct role task would also tend to reflect the amount of information present about the topic, and might be less subject to the above criticism.

(2) The number of constructs linked to a given topic might be measured by asking for constructs associated with an experimenter-supplied construct. These elicited constructs would then be used in a role construct task and the number which were independent at some criterion level would reflect the construct linkages for that topic.

(3) The content complexity of a given construct or chunk of information must be measured in a relatively subjective manner. However, some of the ideas of Schroder et al. (1967) with respect to the simultaneous use of several points of view about a topic as reflecting complexity might prove useful here. First, does a given self-generated construct explicitly or implicitly assume the conjunction of opposing views? If so, that construct would be considered to
have a more complex content that one that presented a single viewpoint. The construct "contradictory" would be an example of one having some complexity of content. Note that Schroder et al. would disagree with this if the construct were used in a simple fashion. Second, are two or more self-generated constructs potentially conflicting? If so, then presumably some complex processing must have been responsible for such a situation and we may consider this type of categorization to have relatively high content complexity. Using both the constructs "warm" and "forbidding" about the same person would be an example of such a situation. A third way of measuring this might be to give experimenter-generated associations to them. Given that the subject uses the stimulus constructs in an independent manner, the number of identical associated to the conflicting stimulus constructs will reflect the degree of content complexity.

Rule complexity

(1) The tolerance for error in the memory search programs cannot be measured directly unless some physiological way can be found to do so. However, it might be measured indirectly by presenting the subject with a situation which contains ambiguities and potential conflicts (perhaps in a standard person-perception task) and using the number of conflicts and ambiguities which the subject notices as a measure of this facet of rule complexity.

(2) The number of available rules for comparing constructs would be reflected by the number of conflicts and similarities noticed in an ambiguous person-perception task. Alternately, in a paragraph
completions task (Schroder et al., 1967) this measure would be reflected by the number of content areas mentioned by the subject, without regard for the decisions reached.

(3) The content complexity of the rule will be reflected in the number of disparate content areas which are related by the rule. As in categorization complexity, it may be possible to elicit rules about potentially conflicting areas and noting how many are similar, or by judging whether the rule implicitly or explicitly related dissimilar content areas.

Decision-making complexity

(1) The amount of information used will be reflected in the number of content areas sampled for data before a decision is reached. Although this is similar in nature to point (3) of rule complexity, here it would be measured in the context of a specific decision situation rather than in a descriptive situation as for rule complexity.

(2) The number of programs available and the flexibility of using those programs could be measured in a hypothesis-testing or concept-formation situation by noting the number of hypotheses employed and the time taken to try a new hypothesis when the experimental contingencies for "correct" responses are changed. Complexity will be associated with trying more hypotheses and changing hypotheses more quickly. Alternately, the facet of decision complexity might be measured in a paragraph completion task how many different decision are referred to, without regard for which decision the subject actually employs with respect to the specific
situation dealt with in that paragraph.

(3) The content complexity of the program would be related to the number of choice points referred to and could be measured as such in a paragraph completion task. It would also be reflected in the implicit or explicit use of conflicting information, but the automatic nature of programs may make this difficult to measure except as a function of conscious rule processing.

(4) The number of situation-specific outputs (either decisions or behaviours) possible could be measured by explicitly asking the subject to list all of the decisions which he feels would be reasonable in the experimental context, without regard for which one is considered to be superior.

**Behavioural complexity**

(1) Given that a subject has previously indicated that a number of situation-specific behaviours are possible in a given context, a field study of the number of behaviours actually employed in that situation would be a measure of behavioural complexity. This is, of course, rather clumsy, but any attempt to measure this aspect of complexity in any non-behavioural manner must inevitably measure the other aspects of complexity to some degree, confounding the measure.

(2) The flexibility of behaviours again may only be properly measured in a field study of behaviours under changing situations. This may be possible when relatively simple, especially non-social, behaviours are being considered, but would probably be impossible to control in more complex situations.
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APPENDIX A

Other Implications

Automatic Hierarchical Programs and Normal Processing

Programs will run automatically so long as the error signals generated by them are not too large. If the critical error level is exceeded, program change or reorganization results. Note that higher level control systems need to react more slowly than low level ones in order to remain stable (if high-level systems acted faster than low-level ones, the high-level systems would act before the low-level ones has a chance to correct any errors they detected, introducing new errors into all the systems; a steady state would be very difficult to achieve). Correspondingly, we would expect the critical error tolerance to be larger in the higher order systems. This, in turn, implies that running high level automatic programs is "the path of least resistance," since it results in the least probability of having to alter programming.

Using high level programming means using programs to deal with highly integrated material. This high integration level of information while running automatic perceptual programs, however, implies a loss of detail and of specificity, if we assume that lower level programs are only run when the higher level error tolerance is exceeded.

This may, perhaps, sound contradictory, as we are used to associating "highly integrated" with a richness of processing and large amounts of information. In fact, although a general information address is created through detailed input comparison programs, that detail is submerged in lower level information buffers; we can think
of the detail as being in "categories", and the higher level address as being a "supercategory". Processing is easiest when very general programs process the information found in these supercategories.

Of course, doing the easiest thing possible is not necessarily what the individual wants to do; many theorists believe that people seek to maintain some optimum, non-zero, level of arousal (e.g., Yerkes and Dobson, 1908; Schroder et al., 1967). In the present model, the level of arousal may be equated with total amount of error present in various systems which is greater than the error tolerance for those systems. Playing tennis, for example, may produce arousal in several ways: if we are losing when we wish to win, if we are trying to move faster than we are used to or our conditioning permits, if we are trying always to hit the ball a certain way but sometimes miss, and so forth. Reducing error in any of these systems (by beating poor players, be getting physically fit, or by improving co-ordination) reduces arousal, and may result in our changing some program to increase its error (for example, looking for more skilled competitors).

From casual observation, however, it appears that we prefer to contain this arousal to only a few areas, while striving for tranquility in others. People don't seem to maintain a great deal of arousal in every activity, but rather in just a few, usually consciously chosen ones. In the majority of everyday behaviours, such as driving, eating, walking, and so forth, many people appear to prefer acting relatively automatically, and with little arousal. This small amount of arousal could, of course, be considered optimal in those situations. For some individuals this automatic activity may carry over into such areas as
casual social interactions, reading, studying, and many forms of decision-making. How much processing is done automatically, and in what areas, could best be studied in the context of individual differences.

**Brain Plasticity and Specificity**

If the brain has been damaged, but not too severely and not in both hemispheres, a program function which originally was lost will gradually reappear in some other area of the brain, either in a nearby area or in the equivalent area of the opposing hemisphere (Rose, 1975). The reappearance of the function must be due to the action of the reorganization system. Since the function only reappears if the damage is not too widespread, one of two things is implied. Either the rules used for generating new programs are stored in physical locations near, or identical with, those of the programs they create (with apparently some redundancy across hemispheres), or the brain's specificity is due to the fact that the necessary program interconnections are partially hard-wired, and other areas of the brain simply don't have the necessary physical connections.

The model predicts that loss of memory due to injury would not be as severe as loss of program function, since roughly equivalent memories would be present in different areas of the brain, having been stored during the running of different programs. In the event of memory loss, careful questioning under different circumstances (corresponding to different programs) might show that the memory is still present but has lost some of its associations. I don't know if anyone has found this kind of associative memory loss.
Attitudes Measurement

The measurement of attitudes has always presented severe problems to psychologists. This theory helps clarify the reasons for, if not the solutions to, those problems in two main areas: program specificity of attitudes, and content/process measurement distinctions.

First, the theory implies that measurement of an attitude in the laboratory, for example, is only going to be useful if we wish to study other attitudes about, or behaviours in, the laboratory. Remember that associations (either of information or of programs) are built up during the running of programs, so that an attitude used in one situation need not be very consistent with the attitude about the same topic when used in a different situation. We may love pedestrians when we are walking and hate them when we are driving. The traditional approach to this problem has been to assume that there is some kind of global consistent attitude for any given subject matter, and that situation-specific anomalies are relatively unimportant (e.g., Allport, 1937). The present theory suggests that, in fact, the global attitude is the anomaly, and the specific attitudes are the important ones, since the latter determine what information is processed at any given time. Measuring global attitudes is confounded by the nature of an individual's memory programs: the more consistency they create, either in the normal course of events or during the attitude measurement, the more meaning a global attitude may have. However, a global attitude constructed during the measurement process does not necessarily have any relevance to the person, who may forget it immediately afterwards, and revert to situation-specific ones.
Second, various kinds of measurement instruments elicit different kinds of data depending on which area of processing they tap. In ways roughly analogous to those described above under "Conceptual Complexity", different kinds of questions may measure the content of the memory store, or the programs which are used to process that content, or the kinds of behaviour used, all of which will tend to be situation-specific. Careless questions which tap several situational contexts may elicit constructed, more global attitudes through forcing rule usage by the subject.

The above discussion implies that more care must be taken in designing the format of questionnaires to ensure that the appropriate kind of data is being solicited, and that those questionnaires should relate as clearly as possible to the situation of interest. I leave the implementation of these suggestions as an exercise for the alert reader.

**Behaviour and Attitude Change**

Many researchers have found that attitudes and behaviour may be changed relatively independently of one another (see e.g., Bem, 1972, for a review). The present theory is entirely consistent with those results, in that informational attitude changes (rather than evaluative or emotional ones) are the result of higher level processing than are behaviour changes. Changing the behaviour involves changing its reference signals. Since these signals are supplied by a program independent of the memory program that searches for informational consistency, there is no reason why changing a behaviour should necessarily change
the corresponding attitude. Similarly, changing the content of an attitude involves using a memory program; the changed attitude will then be associated with that program and not with the behavioural or decision-making program.

We would expect, though, that persons showing high rule complexity would tend to have higher positive correlations between changes in behaviour and attitude, since their memory search programs would be less likely to tolerate errors in consistency. It is conceivable that persons showing high decision-making complexity would show lower correlation between behaviour and attitude, since there would be more program-specific attitudes for available use and the effort of making them all consistent would be too high.
Overview

There are two basic approaches to be taken in doing research on cognitive models. The first, and most commonly used, is to deduce the operation of the brain from the analysis of a person's behaviour while he performs a task which is supposed to discriminate between various kinds of processing. Memory process, for example, may be studied by using various serial learning paradigms, or serial synthesis by employing arithmetic problems formulated in different ways. The interpretation of data from such studies is made difficult because there is no way of directly verifying that the task only activates those brain processes which the experimenter hopes to activate. The memory load imposed by an arithmetic problem, for example, may be considerable for someone who has not done such problems for many years; this may confound the results if the experimenter does not consider the role of memory in deriving the experimental hypothesis.

The second way is to study brain activity directly. The direct study of brain functions has most often been done using lesion and ablation techniques. In these studies, a portion of an animal brain is lesioned, and the investigator seeks to determine what kinds of performance decrements result. Paradigms involving biochemical assays of brain tissue are also used, either after the injection of drugs into the brain, or in conjunction with lesion studies. More recently, EEG work has become more popular, especially with the discovery of the
Contingent Negative Variation (CNV), and with the use of computer averaging to study the evoked potential (EP).

The interpretation of such studies has generally proved to be difficult. Criticisms of paradigms involving searching for performance deficits after causing some brain areas to cease working (either permanently, as with lesions, or temporarily, as with drugs) have been made frequently (e.g., Gregory, 1961; Luria, 1973) and center around three main points.

First, the performance decrement resulting from a given lesion is often only indirectly caused by that lesion, as in the famous example of hearing ability in rats apparently being an inverse function of the number of limbs still attached to the rat (Cohen, 1971). This may be termed a problem of specific function. The severity of this problem increases as a function of how many systems are interconnected and interdependent.

The second problem is that of localization: some functions seem to be confined to one small, relatively well-defined area of the brain, the most famous example being the motor areas mapped by Penfield and Roberts (1959). Others seem to be distributed through the entire cortex and defy attempts to localize them. In Lashley's famous learning study (1950) the decrement in maze performance of rats was related to the amount of cortex removed after learning the maze; no one area contained the memory. In addition, lesions in one area of the brain may cause neurons to degenerate in other areas.

The third problem is that of precision: precise lesion, chemical
and electrical studies often may be performed only on animals, and the results of such studies, even on man's closer relations such as monkeys, often do not apply to human beings. In addition, human lesions are often caused by accidents, and tend to be so large as to involve many brain structures.

Without denying the usefulness of decrement paradigms, the problems of precision and specific function would indicate that procedures involving non-brain-damaged humans engaged in carefully constructed tasks could be useful if some non-surgical means were available of measuring physiological brain activity; at present only the EEG meets this requirement. In addition, the tasks must be such that their relationship to some theoretical model of information processing is unambiguous: the specific function problem is worsened when it is unclear what processing functions the task studied involves. For example, an associative learning task may or may not require a subject to categorize information in a novel way, and may or may not impose overloading of STM processes, depending on the nature of the stimulus materials and the way in which they are presented. The specific function problem then, may be seen as not just applying to performance decrement techniques, but rather as being a problem in any paradigm. Only a task or stimulus which has been formulated using a clear theory of information processing can produce interpretable experimental results, either about the effects of that task or stimulus, or about the validity of the theory.

The above-mentioned problems mean that an analysis of the results of physiological studies will provide only rather obscure clues as to the physical organization of brain functions. Nevertheless, some of the
data are helpful in at least delineating general areas in which some processing occurs.

I propose that a combination of direct and indirect methods may provide a more rigorous means of studying cognitive processes, since the data from one method of study can be used to help verify the assumptions of the other. In outline, such a research program would progress roughly as follows: (1) Tasks of the most simple kinds will be formulated so that they are as "pure" examples as possible of tasks activating the various brain functions proposed by this model. For example, a simple perceptual task could be devised which imposes no load on LTM, the SP, the reorganizer, or program selection. (2) The physiological activities accompanying such tasks will be measured, and consistent activity patterns for tasks involving a given cognitive process will be taken as signifying the operation of that process. (3) These process patterns may then be studied when tasks activating more than one brain function are used. In this way the interactions (if any) between process patterns will be found and temporal sequences of activation may be investigated.

Having a cross-validated set of tasks and process patterns, any task may now be evaluated in terms of what processes it activates. Also, cognitive models may be tested by looking for the activation of particular sequences of process patterns, or by noting inconsistencies in those already developed, indicating a problem in the model currently being used. Although this method still does not provide a direct, completely verifiable technique for measuring brain functioning, it allows more cross-validation of results than is presently available and
should simplify both the development of cognitive models and the construction of tasks and stimulus materials.

The alert reader will have noticed one major difficulty in pursuing such a research program: what are the "physiological activities" which are to be measured? I believe that EEG processes are the activities most closely related to the ongoing activity of the brain, and presently may be studied by analyzing the CNV and EP or by calculating the power spectrum of the EEG frequencies. Although it has been found that certain kinds of EP accompany decision making (see following references), there are still reasons for believing that the EEG is only indirectly related to processing. Petit mal epileptic attacks, for example, produce grossly abnormal EEGs, yet the attack may be completely unnoticed by the patient (Johnson, Davidoff, and Mann, 1962) who may show only relatively minor performance decrements which are not perfectly in phase with the EEG irregularities (Nursky and Van Buren, 1965).

Nevertheless, the EEG still seems to be the technique with the most direct relevance to information processing. Other measures which have also been found to be related to processing, such as eyeblink rate (Holland and Tarlow, 1972), number of eye fixations (Loftus, 1972), heartrate decrement (Blatt, 1961), and skin resistance (Harding, Stevens, and Marston, 1973), could also be used in conjunction with the EEG, but generally their discriminative abilities are too small and their time scales too long to be worthy of much hope.

The next two sections will present a brief review of the physiological evidence about the functions of various brain areas and a
brief description of some techniques which could be used in the research program outlined above.

Physiology

The areas in which input buffering takes place are fairly well known to be the retina, lateral geniculate and the occipital cortex for vision (e.g., see Luria, 1967; Marg, Adams, and Rutkin, 1968); the various areas of the temporal lobe, especially the transverse gryi of Heschel, as well as some processing by the cochlea and basilar membrane, for hearing (see P. Milner, 1970 or Luria, 1967 for reviews); and the parietal area for sensory-motor processing (e.g., Penfield and Jasper, 1954; Penfield and Roberts, 1959; Luria, 1967). Luria (1967) considers that everything in at least the second unit of the brain (that for processing and storing information) is arranged hierarchically (p. 69). Although he makes the same claim for the unit that regulates tone and the unit that programs mental activity, he seems to treat only the second unit as hierarchical in the sense of information integration, rather than in the more limited sense of information flow.

The control units for directing motor behaviour at the third level in Powers' scheme seem to be found in the cerebellum (Rose, 1975; Powers, 1973), and those for controlling the fourth order may lie in the second somatic area of the sensory cortex (Powers, 1973, based on Penfield and Roberts, 1959). Second-order systems are identified by Powers with the motor nuclei of the brain stem, and first-order systems are controlled by the spinal motor neurons.

The physical locations of the reorganization system, the serial
processor, and memory (both STM and LTM, and of both information and programs) are far more difficult to pinpoint. Part of this difficulty is certainly due to the problems of interpretation discussed above, but part is also due to the structure of the brain. In terms of this model, the precise localization of memories by Penfield and Roberts, for example, would be due to their somehow activating the general address for those specific memories which would be stored in specific locations. The elusiveness of the engram in Lashley's 1950 study, on the other hand, is due to the fact that a given memory may be stored in many areas and associated with many programs. Thus electrical stimulation of the brain in two areas may produce two memories, each of which contains the memory of a maze, for example. The memory of the maze remains approximately the same, but the associations differ. Lashley's study then implies that, for rats, programs related to searching out food are richly associated, so much so that maze learning becomes associated with other programs and memories across the entire cortex.

Long-term memories of automatic programs and information are thus stored in many areas of the cortex; it appears, however, that certain areas of the brain have specialized their function, although at present it is unclear whether that specialization involves program operation, memory storage, or both. The most obvious specialization is that of laterality: the left hemisphere in right-handed people usually contains areas associated with verbal and sequential abilities, especially in the temporal lobe, while the right hemisphere seems more associated with spatial and simultaneous ones, again mainly in the temporal lobe (e.g., Galin and Ornstein, 1972) but also in the
parietal region (Luria, 1967); in addition, emotions seem associated
with the right hemisphere (e.g., Schwartz, Davidson, Maer, and
Bromfield, 1974). Even this simple dichotomization is probably an
oversimplification, however; P. Milner (1970) notes that the split-
brain experiments done by Sperry and Gazzaniga (1967) imply that the
right hemisphere produces various verbal deficits (e.g., Luria, 1967),
while right hemisphere injuries do not. Such diffusion of function
may in the future be found to apply to spatial and simultaneous func-
tions as well.

It also appears that STM is present in different areas of the
brain. According to Luria (1967), no one area of the brain gives rise
to decrements in STM when lesioned; rather, a modality-specific
memory decrement will appear in the area associated with the processing
of that modality. A lesion in the left temporal lobe, for example,
interferes with immediate audio-verbal memory. Relatively little is
known about such memory deficits, especially in the right hemisphere,
but Luria hypothesizes that there are many modality-specific memories.
This would imply the existence of many STMs.

It appears that one region responsible for the transference of
memory from STM to LTM is the hippocampus, lying in the medial
temporal lobe (see Milner, 1970 and Luria, 1967 for reviews of this
literature). Patients with hippocampal damage may have unimpaired
STM, but be unable to retain new information for more than a few
minutes. Even though certain skills learned in motor and perceptual
learning tasks may be retained, the patient is usually unaware of
having done those tasks before (B. Milner, 1962). In terms of my
model, these data suggest that what is impaired is the consolidation in LTM of conscious memories from the SP, and that perhaps memories not acted upon by the SP can be at least partially retained. This is consistent with my earlier hypothesis that the SP and STM may only hold part of the data in the higher level buffers. These consolidation problems are considered by several researchers to be related to interference with the STM memory by irrelevant stimuli since the information in STM is immediately lost if the patient is distracted (see Luria, 1967, for example).

Note that the SP would certainly be involved in any attentional mechanisms. We might consider two possibilities for the relationship between STM and the SP: (1) That the information in the SP is part of the information in STM, but is distinguished by being "attended to", probably as a result of some kind of action by the limbic system and reticular formation (which are associated with medial temporal lobe structures); and thus the SP and STM are different aspects of the same structure; (2) That attentional mechanisms direct information back and forth between STM and the SP, which are different structures. In either case, it appears that consolidation of memories can occur from both STM and the SP into LTM.

Damage to the frontal lobes of humans produces behaviour which is stereotyped, unplanned, and rather unmodifiable. Simple behaviours, however, can be performed by such patients, verbal abilities seem unimpaired, their I.Q.'s are normal, and STM for verbal and visual material shows no deficit (see P. Milner, 1970 and Luria, 1967 for examples). Generally, the patients seem unable to change their
behaviour when it is inappropriate to the situation, and are unaware of committing any errors. This is in spite of the fact that they can repeat verbal instructions about what they should be doing, even while they are actually doing something else. This dissociation of verbal from motor responses leads Luria to conclude that lesions of the anterior frontal lobes cause a disturbance of the regulatory function of speech, as well as generally producing an inability to notice errors related to plans and intentions. In addition, the construction of hypotheses about the meaning of pictures seems to be impossible for such patients. The eye movements used to scan pictures in order to determine various kinds of information are grossly impaired, leading Luria (1967) to conclude that the patients are unable to formulate any clear plan for performing the visual search.

These results seem to correspond to what might be expected if there were lesions of the SP and reorganization system. Both are involved in the recognition of error in order to switch programs and construct new ones. It appears that only relatively high level errors go unrecognized, however, for previously learned programs run unimpaired; it is the selection of an appropriate program to use in a novel situation that becomes inappropriate. In terms of this model, however, lesioning of the SP should result in no learning at all, at least at higher levels. This hypothesis does not appear to be true. Simple tasks can be learned as long as they do not conflict with some "set" that the patient already has; but once learned they are very resistant to change even when they become inappropriate. These results are further complicated by the fact that patients having unilateral lesions
of the frontal lobes usually show these effects, while patients with orbital lesions do not, or show diminished effects. The specific role of the frontal area is thus in considerable doubt, and awaits future study.

Techniques

For the research program outlined earlier to be feasible, it must be shown that the EEG can produce data that can be related to processing events. Such data include the evoked potential (EP), contingent negative variation (CNV), and EEG frequency analysis.

The EP has been shown by several workers to have a late positive component (known as P300) related to information processing, in that the P300 is present when uncertainty is being resolved (Sutton, Tueting, Zubin, and John, 1975), when novel stimuli are presented (Ritter, Vaughan, and Costa, 1968), or when stimuli are "task relevant" (Donchin and Cohen, 1967). Some workers (Karline, 1970; Naatanen, 1970) feel that the amplitude of the P300 represents the state of preparedness of the subject, and is therefore related to attentional processes. However, the work of Rohrbaugh, Donchin, and Eriksen (1974) seems to show that it is in fact related to decision making, at least for visual imagery tasks and for P300 measured at the vertex and occiput. This is consistent with the research of Ritter, Simpson, and Vaughan (1972). Unfortunately, in the work of Rohrbaugh, et al. and Ritter et al. the motor response required of the subject often occurred before the onset of the P300, which would seem to obviate the possibility of P300 being related to decision-making. In terms of the
present model, however, decision-making components of the EP should not be present at all at the vertex and occiput and might rather relate to some post-decision image formation or verification process.

As mentioned in the Introduction, E.R. John and his associates have also performed many experiments involving the EP in both cats and humans. Their results indicate that the EP displayed in different areas of the brain related to the meaning of the test stimulus displayed. Since different areas of the brain process different kinds of information, the relationship of the EP to the test stimulus varied depending on where the EP was recorded. For example, John and Grinberg-Zylberbaum (cited in John, 1976) found that a vertical line used as a stimulus would produce different EPs in the parietal and temporal regions depending on whether it was interpreted as the number "one" or the letter "ell", but that the EP was identical in both cases when recorded from the occipital area where primary visual perception processes occur. Similarly, when the two stimulus "A" and "a" were presented, different EPs were found in the occipital region but not in the temporal or parietal regions. These data show that EPs are at least potentially discriminating in terms of the meaning of the stimuli processed in a given area of the brain. The question of exactly what these EPs represent is a difficult one to answer. John believes that they represent the activation of specific memories; in my model they could represent the output from the automatic visual processing system, which does not require any reference or memory signals. In situations that require decisions and motor output, however, as in the discrimination learning experiments performed with cats (John, Shimokochin, and
Bartlett, 1969) it has been found that the EP produced during the cat's response corresponds to the one which is present when the correct stimulus has been presented. The same EP is present if the incorrect stimulus or some other stimulus were presented on that trial (i.e., if the cat made a mistake). This could result from either incorrect perception or incorrect decision-making, and hence the generation of the incorrect motor reference signal. Unfortunately, it is unclear from these data which has occurred. Nevertheless, the EP is again implicated in processing and decision-making.

The CNV paradigm consists, in its simplest form, of measuring EEG while a subject waits to make some motor response (like pushing a button) in response to a stimulus after having been warned a few seconds previously that the stimulus was about to appear. In this situation a slow, negative potential shift of the EEG baseline is observed. The shape of the CNV has been found to be correlated with the kind of information processing being performed. The CNV is often thought of as an accompaniment to expectancy (e.g., Walter, Cooper, Aldridge, McCallum, and Winter, 1964); Weinberg, Michealewski, and Koopman (1976) have postulated that its amplitude is positively related to time estimation and negatively related to the information processing load occurring during the response discrimination. In addition, it is interesting to note that Weinberg and Papakostopoulos (1975) have found that the shape and amplitude of the CNV recorded from the frontal lobe are different from those recorded from the vertex, central, and parietal regions, which all show much more similarity to each other. If the frontal lobes are the site of
"higher" processes involving the SP, we might expect the CNV magnitude to be smaller there than at other sites in the light of the Weinberg et al. (1976) results since the processing there is less automatic, and produces greater load — and, in fact, this is what Weinberg and Papakostopoulos observed. Thus, although the typical CNV paradigm does not investigate the roles of different brain areas in various kinds of processing, it would seem that the CNV could be useful in such investigations to indicate the presence of expectancy, time estimation, and information load.

The frequency analysis of EEG data has also shown that various kinds of processing are accompanied by distinctive changes in the power spectrum of the EEG. Doyle, Ornstein and Galin (1974), for example, performed Fourier analyses on the EEGs produced during tasks such as writing a letter, constructing a design from Kohs blocks, and doing arithmetic. They found reliable differences in EEG lateral asymmetry during the performance of different tasks, especially in the alpha band, but also in the beta bands, and occasionally in the theta band. In a different vein, Martindale and Hines (1975) have found that persons differing in creativity, as measured by the Remote Associates Test (Mednik and Mednik, 1967) and the Alternate Uses Test (Christensen, Guilford, Merrifield, and Wilson, 1960) differ in the amount of alpha activity generated during different kinds of cognitive tasks. The authors postulate that this is due to differential ability to activate various kinds of cortical processes, either selectively or globally.
These kinds of data from frequency analysis, the CNV and the EP suggest that a research strategy of the kind proposed here could produce data which would show reliable associations between the type of task employed and the kind of EEG activation produced, probably through a combination of all three techniques. In addition, the time sequence of EP or CNV activation across the cortex could provide valuable clues as to the operation of various brain functions. Decision-making, for example, must take place after primary perceptual processing in a discrimination learning paradigm and so we would expect the electrophysiological correlates of these processes to happen in a similar time sequence. Preliminary data indicate that such time sequencing of the EP is present (Gary E. Schwartz, personal communication, 1975). Finally, we might hope that in the future better means will be found to measure the brain activity, perhaps incorporating a mathematical analysis of the activity produced at an array of several hundred electrodes. Such an array may be able to three-dimensionally reproduce the activity of the mind, akin to the way that holographic images are reproduced from a two-dimensional visual array.