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Identification of components of episodic learning : the CEL process model of early learning and memory

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Identification of Components of Episodic Learning: The CEL process model of early learning and memory

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The CEL Process Model of Early Learning and Memory

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ABSTRACT

This paper presents a process model of the acquisition and operation of early predictive behavior in young children, i.e., children's ability to accurately anticipate recurring sequences of events. The principal question that the model addresses is: how do children acquire predictive behavior from experience? The model presented here, called CEL (Components of Episodic Learning) provides an effective procedure for performing this acquisition process, and has been used as the basis for a prototype computer system running at the UCI Artificial Intelligence Project. The CEL model conforms to the constraints provided by relevant results in psychology and neurobiology; some observed stages of early child learning are explained in terms of the model, and theoretical lesions to specific parts of the model are used to predict particular behavioral deficits that correspond well to documented deficits associated with lesions to the hippocampus of human patients.

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1.0 INTRODUCTION TO THE PROBLEM

Consider the following three observations by Piaget (1952) of his daughter Jacqueline, first at birth, then at age 4 months 27 days, and finally at age 9 months 16 days:

[Observation 1]:

> From birth sucking-like movements may be observed: impulsive movement and protrusion of the lips accompanied by protrusion of the tongue.... As soon as the hands rub the lips, the sucking reflex is released (Piaget 1952, p.25).

[Observation 2]:

> Jacqueline, at 0;4(27) and the days following, opens her mouth as soon as she is shown the bottle. She only began [bottle] feeding at 0;4(12) [i.e., fifteen days earlier] (p.60).

[Observation 3]:

> At 0;9(16) ... she likes the grape juice in a glass, but not the soup in a bowl. She watches her mother's activity. When the spoon comes out of the glass she opens her mouth wide, whereas when it comes from the bowl, her mouth remains closed. (p.249)

These and scores of similar observations (e.g., Kessen 1967, Papousek 1967, Sameroff 1971, Seligman 1970, etc.) support the notion that a child progresses through distinguishable stages of ability, beginning with innate or hereditary reactive abilities and eventually acquiring predictive and discriminatory abilities.

In Observation 1, Jacqueline opens her mouth in _reaction_ to its being touched; that is, she opens it when she senses a touch on it, but does not respond to any other cues, e.g., visual, aural, etc., that she is about to be fed. By the time of Observation 2, she is able to _predict_ when her mouth is about to be touched, and she opens her mouth reliably in those circumstances which, she has learned, lead to her being fed. In Observation 3, Jacqueline is able to discriminate among different feeding episodes, depending on visual (and other) cues. Based on her discriminatory prediction, she implements what appears to be a plan of action, according to her goals: she opens her mouth for the (predicted) arrival of a desirable state (the taste of food she likes) and she shuts it to prevent a predicted undesirable state (taste of food she doesn't like).

This paper presents a theory of how a child is able to progress from initial reactive abilities, through predictive abilities, to discriminatory abilities. In particular, what is presented is a detailed analysis of the process components underlying this progression, from the initial limited abilities Jacqueline exhibits in early feeding episodes to the relatively powerful predictive and discriminatory abilities she eventually acquires. This analysis has resulted in a new memory model called CEL (Components of Episodic Learning), which consists of a set of mechanisms, or operators, that operate on memory structures we term episodic schemas. Taken together, the operators and episodic memory structures of the CEL model provide an effective procedure for both the acquisition and the operation of early predictive and discriminatory behavior.

Parts of the CEL model have been implemented in a prototype computer learning system called CEL-0. CEL-0 receives typed-in afferent sensory input (e.g. having its mouth touched, sensing a particular taste) and produces both typed-out mental operations (e.g., storing or retrieving a particular episode) and efferent motor actions (e.g., opening its mouth, moving its eyes). As the program operates, it progresses through identifiable stages, initially exhibiting only reactive behavior, then exhibiting predictive behavior, and finally exhibiting simple discriminatory behavior.

Much work has been done in the fields of psychology and psychobiology to account for aspects of observed early learning in children. These two fields have traditionally been separated by their respective methodologies, i.e., experimental work in psychology tends to focus on observable behaviors, manipulating infant sensory and motor behaviors and attempting to find capacities, limitations, individual differences and developmental stages in infants' learning abilities (e.g., Kagan 1970, Kessen 1967, Papousek 1967, Piaget 1952, Sameroff 1968, etc.) while research in psychobiology has concentrated mostly on the search for identifiable neural pathways corresponding to observed behavior (e.g., Cohen 1980, Penfield 1959, Posner 1975, Thompson 1980, Woody 1974, etc). The research presented here offers a first step towards a characterization of the constituent functional operators that comprise the learning process, in the hope that these primitive operators may each have specific instantiations that can be identified in the neural substrate. Toward that goal, a specific suggestion is presented at the end of this paper, tentatively identifying specific mental operators of the CEL model with the function of a particular brain structure, the hippocampus, based on results in psychobiology on both the normal functioning of the hippocampus and the deficits associated with lesions to the hippocampus.

The rest of this paper is organized into the following sections:

1. an analysis of three specific stages of learning that Jacqueline proceeds through with repeated experiences, corresponding to her behavioral ability to predict and discriminate among recurring episodes;

2. A description of the twelve memory operators of the CEL model, and their operation;

3. a detailed description of the operation of the CEL model in its progression from initial stages of innate hereditary abilities through the acquisition and operation of learned predictive and anticipatory behaviors;

4. a larger view of the extended chronology of development of the CEL model;

5. some conclusions, including specific suggestions about the possible localization in the brain of certain operators of the CEL model.

2.0 INTRODUCTION TO THE MODEL

2.1 Three stages of early episodic learning

Jacqueline can be said to pass through a series of three identifiable stages in going from her initial innate hereditary abilities to the eventual behavior described in Observations 2 and 3 above. (Note that although Piaget's observations of child behavior are used as examples in this paper, our theoretical model does not directly embrace his, and in fact some aspects of our analysis of behavior into stages conflicts with Piaget's.)

Following is a description of our analysis of the salient features of each of these three behavioral observations:

1. Sub-stage 1: Hereditary Behavior
   Initially the child opens its mouth in response to any touch on the mouth, and does not respond to other contextual cues of impending feeding, such as visual or aural cues.

2. Sub-stage 2: Acquired Predictive Behavior
   The child learns to open its mouth on the basis of other sensory input, e.g., sight, sound, smell, etc., before the mouth is touched, in circumstances which in the past have led to the child's getting fed.

3. Sub-stage 3: Acquired Discriminatory Behavior
   The child differentially opens or closes its mouth in response to particular contextual cues, depending on whether those cues have, in previous instances, preceded the child's receiving desirable

versus undesirable tastes.

(As stated above, these three stages are actually only sub-stages in a larger view of the overall chronology of learned episodic memories. An overview of this extended chronology is offered in a later section of this paper, following the description of CEL's operation within these three sub-stages of learning.)

2.2 The five categories of operators in the CEL model

The CEL model is an attempt to provide a well-specified and plausible process that can account for both the child's behavior at each stage and the child's transitions between stages. The model thus presents a unified theoretical framework within which to view the child's continuous progress towards complex learned behavior.

The first step in this framework is the subdivision of the overall functions of learning and memory into five basic categories, as follows:

1. Reception:
   The establishment of a temporary memory trace from incoming sensory data; i.e., creating a short-term memory trace.

2. Recording:

Consolidation of a temporary memory trace into a permanent memory trace, in such a way as to allow for the subsequent effective retrieval of that memory in appropriate situations.

3. Retrieval:

Activation of existing memories when and if they are appropriate to the processing of incoming experiential data.

4. Reconstruction:

The use of existing memories to process incoming data, e.g., to predict and react to new experiences on the basis of previously recorded and retrieved memories.

5. Refinement:

The alteration of memory traces on the basis of successes, failures and differences between recorded memories and new incoming episodes; e.g., strengthen and weaken associations, reinforce, extinguish, differentiate, etc.

Consider for instance Jacqueline's transition from stage 1 to stage 2, that is, the process of her learning to open her mouth in response to the sight of the bottle. In order for Jacqueline to acquire this predictive behavior, she must initially receive sensory input of events in the external world, and record in her memory some representation of the sequence of events in this feeding episode; we term the result of this recording an episodic schema. This initial recording becomes the 'kernel' schema for her subsequent learned predictive behavior in subsequent instances of the episode. Once recorded, she must be able later to retrieve this episodic schema, when similar subsequent sequences of events occur, and to make use of the retrieved schema to reconstruct both the afferent events that comprise the episode and the efferent actions that she must enact as part of the episode, all the while refining the schema to correspond ever more closely to the regularities and variations in recurring instances of the event sequence comprising the episode.

3.0 THE TWELVE OPERATORS OF THE CEL MODEL

Within the framework of this functional subdivision of memory processing, the CEL model identifies a set of twelve 'primitive' memory operators which, taken together, perform these five classes of memory manipulation. The CEL model, then, consists of the operation of these twelve operators on episodic schemata. The model describes the child's behavior at each stage and transitions between stages, all in terms of the performance of these operators to receive, record, retrieve, reconstruct and refine episodic schemata. The following sections provide introductory descriptions of the processing of each of the twelve CEL operators.

3.1 Reception and Recording

3.1.1 The Reception operators

The CEL model contains two Reception operators, termed DETECT and SELECT, which modulate the reception of experiential input: the DETECT operator reads streams of sensory inputs, while the SELECT operator moves inputs to 'short-term' memory, thereby establishing a temporary memory trace.

The DETECT operator can be thought of as a sensory input mechanism, monitoring inputs from the senses, modulated by the relative state of arousal of the organism. A great deal of work in psychobiology has been done on attention mechanisms (see e.g., Posner 1975, Weinberger 1980); the CEL model doesn't focus on problems of attention or arousal, and hence makes the simplifying assumption that the organism is attending to all sensory input, and therefore will reliably DETECT all incoming sensory stimuli. The SELECT mechanism chooses which of the incoming DETECTed inputs should be written into temporary or short-term memory, to establish an ordered list of representations of experiential events. These two operators are discussed further in a later section of this paper.

3.1.2 The Recording operators

Once representations of external experiential events have been established in a temporary memory trace, the Recording operators may act to move parts of that trace into permanent memory.

CEL's first Recording operator, NOTICE, monitors the characteristics of events written into the temporary trace by the SELECT operator, checking those characteristics against an internal set of known desirable and undesirable features; a match will cause NOTICE to trigger the rest of the Recording mechanisms, initiating the movement of the temporary trace into long-term or permanent memory. Children are born with certain inherent likes and dislikes, e.g., certain tastes, sounds, touches that they react to immediately (see e.g., Bower 1974, Kessen 1967, Piaget 1952, Sameroff 1971). It is this set of built-in or 'hereditary' likes and dislikes that initially invoke the NOTICE mechanism in the CEL model.

The actual movement of a temporary trace into long-term memory is performed by the second Recording operator, COLLECT, which simply 'copies' the contents of temporary memory into permanent memory, whenever it is triggered by the NOTICE operator. The result is the first step in the creation of an episodic schema. This schema initially consists of simply the ordered list of events up to and including the event that invoked the NOTICE mechanism.

Once a memory trace is in permanent memory, it must be able to be retrieved later on, at just the appropriate times for it to be used to predictively process subsequent similar event sequences. The

COLLECTion of a memory trace into permanent memory is not by itself sufficient to enable that memory to be subsequently recalled at appropriate times, any more than flinging a set of documents into a large file drawer means that the documents have been saved. In either case, the records are not retrievable except by either exhaustive search or by 'stumbling upon' them by accident. To be retrievable, then, i.e., to be available to Jacqueline's memory at subsequent appropriate times, the episode must be indexed, according to the situational circumstances that that memory might prove useful for predictive processing later on. CEL's third and final Recording operator, INDEX, adds to the COLLECTED memory trace a pointer that will later be matched with experiential input indicating that this memory might be relevant to the processing of the new input.

3.1.3 Summary: Reception and Recording Operators

The CEL model hypothesizes five operators to perform the functions of Reception and Recording: the two Reception operators, DETECT and SELECT, modulate the establishment of a temporary memory trace from experiential input, and the three Recording operators, NOTICE, COLLECT and INDEX function to create a usable permanent memory trace (an episodic schema) from the temporary trace.

Figure 1 illustrates the operation and interaction of these five operators.

<FIGURE 1 GOES ABOUT HERE>

3.2 Retrieval and Reconstruction

When Jacqueline subsequently experiences some event that initiated the previously-recorded episode, she retrieves that memory and uses it reconstructively to behave predictively in the new episode.

3.2.1 The Retrieval operators

When an episodic schema has been indexed according to some particular early event in the sequence (e.g., seeing a bottle before being fed), then the next time that event occurs, the entire schema is recalled. This 'reminding' phenomenon (see Schank 1981) is a result of the schema's index being matched against the new occurrence of the event. This matching process is constantly going on: i.e., every new experience written into temporary memory is checked to see whether it could be an index into an existing episodic schema in long-term memory. The CEL operator that performs this continual matching function is called REMIND.

(Note that if the Reception operators either fail to DETECT a particular sensory input, due to low arousal state, etc., or fail to SELECT that sensory input to be written into temporary memory, due to 'selective attention' (see e.g., Posner 1975, Weinberger 1980), then the experience will not cause REMINDing, and the relevant episodic schema may not be retrieved. As was mentioned earlier, the CEL model currently does not account for such issues of arousal or selective attention.)

Once an input has REMINDed the CEL model of a particular episodic schema, then another operator, ACTIVATE, attaches that schema to the upcoming Reconstruction processes, so that the schema can be used to process the current incoming experiences.

3.2.2 The Reconstruction operators

Once an episodic schema has been found and retrieved via the REMIND and ACTIVATE operators, the organism (e.g., Jacqueline) will 'reconstruct' the memory as though the current episode were a new instance of the remembered one. This reconstruction process has two components: (1) monitoring the similarities and variations between the afferent events occurring in the current episode and those in the retrieved schema; this function is performed by the SYNTHESIZE operator; and (2) actually producing efferent 'motor' actions corresponding to those which were recorded as having occurred in the original episode; that is, the organism re-creates the mental and physical states associated with each of the events in the schema, via the ENACT operator. In the case of efferent events (those performed by the child, e.g., opening mouth, moving arms, moving eyes), ENACTing the event results in the performance of the motor action itself. In the case of afferent events in the schema, however, (things that happen to the child, e.g., sensing a visual input, sensing a taste input, etc.), the child can only re-create the mental and physical state associated with having sensed the particular afferent event, and cannot of course by itself cause the afferent event to recur.

Figure 2 illustrates the coordinated operation of the four Retrieval and Reconstruction operators.

<FIGURE 2 GOES ABOUT HERE>

3.3 Refinement

The process of reconstruction results in a SYNTHESIZEd record of the similarities and differences between the previously-recorded episode and the one just experienced. This record is used to refine the memorial schema corresponding to these episodes, so that it will accurately reflect the overall regularities and variations in such episodes. The CEL model contains three Refinement operators: REINFORCE, BRANCH and DETOUR.

The REINFORCE operator acts to increment the strength of connections between individual events in an episodic schema; each recurrence of a particular event in an episode results in an increment to the strength of this link.

Reciprocally, the BRANCH operator causes a new branch to be created in the episodic schema being reconstructed, based on any match failure by the SYNTHESIS operator.

Both REINFORCE and BRANCH are triggered only by the SYNTHESIZE operator, depending on whether that operator finds a match or a mismatch, respectively, between the incoming experienced event and the (predicted) event in the schema being Reconstructed. The final Refinement operator, DETOUR, is triggered by the INDEX operator, in cases where the schema to be indexed was triggered (NOTICEd) by an undesirable state (e.g., a bad taste). The DETOUR operator functions to prevent the recurrence of any episode that leads to an undesirable result state; e.g., when Jacqueline is fed something with a bad taste, she NOTICEs and COLLECTs the sequence of events leading to this undesirable outcome, but she presumably does not wish to repeat it in the future, but rather to avoid it. Hence, in an episode with an undesirable outcome, the INDEX operator triggers the DETOUR operator to create a route around the events leading to this outcome, thereby acting to prevent its recurrence.

Further discussion of the three Refinement operators is provided in later sections of this paper; Figure 3 illustrates each of these operators' functions.

<FIGURE 3 GOES ABOUT HERE>

3.4 Partial summary: the twelve CEL operators

Twelve operators have been introduced to perform the five learning and memory functions described above:

<u>Reception</u> operators
- DETECT
- SELECT

<u>Recording</u> operators
- NOTICE
- COLLECT
- INDEX

<u>Retrieval</u> operators
- REMIND
- ACTIVATE

<u>Reconstruction</u> operators
- SYNTHESIZE
- ENACT

<u>Refinement</u> operators
- REINFORCE
- BRANCH
- DETOUR

These operators act in parallel and semi-independently in the CEL model; e.g., during reconstruction of a retrieved episodic schema, an incoming experience may cause the REMINDing of yet another schema. Figure 4 roughly illustrates the overall flow of control of the twelve operators. Some of the more complex interactions that arise among operators are discussed in a later section of this paper.

<FIGURE 4 GOES ABOUT HERE>

The following sections contain brief discussions of some work in psychology, and in the neurobiology of learning and memory, illustrating some of the observations that have played a part in the development of the CEL model.

3.5 Brief discussion of some related work

3.5.1 Piaget

Piaget (1952) offers a number of incisive observations of infant and child behavior, in support of his view of learning as the operation of the reciprocal functions of 'assimilation' and 'accommodation' on memory structures he terms 'schemata'. While providing a tantalizing glimpse of a unified learning and memory process underlying a wide range of observations, Piaget fails to specify any sort of effective procedure that might perform aspects of the assimilation or accommodation functions. Piaget does offer a useful categorization of types of schema acquisition, including a chronology of the stages of learning a child passes through. The CEL model is compatible with Piaget's observations, and is even compatible with much of his theoretical views regarding the growth of memory schemata. However, since his theories are primarily descriptive in nature and do not analyze the process components of assimilation or accommodation, nor explain how they are carried out, the CEL model has had to 'fill in' a great deal that may have been implied by Piaget but is not explicit in his work. Even so, the CEL model accounts for only a small fraction of the huge chronology of learned behavior that Piaget presents.

3.5.2 Pavlovian conditioning

One of the traditional learning paradigms of psychobiology is that of classical conditioning, i.e., the presentation of sequences of events to an organism, such that the organism eventually learns to react to the initial event by behaving in a manner that was previously only associated with the final event in the sequence. In terms of the CEL model, classical conditioning is viewed as just an instance of the episodic learning evidenced by predictive reactions. Experiments in conditioning have led to the creation of (at least) two schools of investigation of learning: the 'behaviorist' and 'cognitive' approaches. The behaviorist view is an extreme one, asserting that learning is no more or less than the 'pairing' of stimuli to behavioral responses; that is, what is learned is the observable behavioral response itself, not any internal memory representation (e.g., Hull 1943, 1951, 1952).

More 'cognitive' views of learning admit of memory structures and brain mechanisms that manipulate them (see e.g., Tolman 1949), and are more compatible with the approach presented here. The CEL model views conditioning as the acquisition of an episodic schema that begins with the conditioned stimulus (CS) and passes through the unconditioned stimulus (UCS) to the (conditioned) response (CR). Furthermore, the existence in an organism of any initial pairing of unconditioned stimulus and response, i.e., reactive behavior exhibited upon presentation of a stimulus without prior conditioning, is evidence of the presumed existence of an episodic schema (either innate or previously learned) that begins with the UCS and leads to the response. An example is that of the (hereditary) schema in a child that begins with the sensory input of a touch to the mouth and leads to the efferent action of opening the mouth and sucking (see e.g., Sameroff 1971).

Among the traditional aspects of conditioning not accounted for by the CEL model, are the phenomena associated with the time and number of trials it takes to learn particular tasks. Though the CEL model does contain mechanisms for the reinforcement, habituation and extinguishing of learned behavior (via the Refinement operators) the model does not accurately predict the variations in learning time that have been observed experimentally and modeled mathematically (see e.g., Norman and Rumelhart 1970, Wickelgren and Norman 1966).

3.5.3 Some AI models of memory and brain function

Arbib and Caplan (1979), in a discussion of AI models of the neurology of linguistics, argue for a 'coordinated control program' to account for the neurological underpinnings of language processing. A major problem here is that the low-level functioning of the brain is so far removed from the higher cognitive processes of language use that it is crucial, in attempting to form any bridge between them, to acknowledge the intervening stages of processing between language and brain function. In a response to Arbib and Caplan's (1979) paper, Locke (1979) asks: "how 'nonlinguistic' neurological functions - the cellular, the distributed, the systematized, and the behavioral - are translated in hierarchical form to culminate in language" (p.471). The CEL model does not attempt an explanation of the acquisition or use of language; rather, it is an attempt to analyze the functions underlying much more simple and low-level behavior first, before attempting to build a bridge up from these low-level functions to higher cognitive processes.

Another problem with Arbib and Caplan's (1979) theory is their adoption of the HEARSAY system as a proposed model for neurological functioning. HEARSAY was not designed with neurological modeling in mind, but rather was an engineering task (of mammoth proportions) which was intended to provide a control structure within which other AI systems could be constructed. Hence, it is important for Arbib and Caplan to explain how it is that HEARSAY could have accidentally become a good model of neurological function. They attempt such an explanation, but, as Marshall (1979) responds: "it is totally unclear what specific hypotheses are supposed to be embedded within the blooming, buzzing confusion of the implementation. ... It follows from the failure to distinguish theory and implementation that HEARSAY is unlikely to suggest a new account of, for example, jargon aphasia or transcortical motor aphasia" (p.472).

Small, Cottrell and Shastri (1982) have also worked on the question of language understanding in the context of what they call 'connectionist models' (based on Feldman and Ballard 1982) which consist of interactive nets of 'computing units' which have states, inputs and outputs, and which are on the whole suggestively designed to resemble aspects of neural nets. In particular, Small et.al. intend to "emphasize a processing structure [for natural language understanding] which is closer to the neuronal hardware" (p.247). Much the same objection must be made here as to Arbib and Caplan, above; namely, that the neuron level is entirely the wrong level for an analysis of language use; rather, much more low-level cognitive abilities such as simple prediction and discrimination must be accounted for first, since the (human) brain acquires these cognitive abilities first, and may use them as 'building block' abilities along the way to laying a foundation for eventual learned language abilities. A model that attempts to explain language use directly in terms of neuronal assemblies is, in our view, skipping a huge number of intermediate stages in the probable processing chain from language down to brain structures.

Becker (1973) presented a theoretical system for the encoding of experiential information, which has served as part of the initial inspiration the CEL model. Becker denies that his model has any relation with "the physiological representation of experience in the brain" (p.396), but implies that the system is intended to be a cognitive model, both by the name of the model (JCM) and the terminology of 'schemata' throughout. Nonetheless, Becker's system focuses on details of the operation of his model system in an artificial environment, without directly relating the design decisions that went into the model to any psychological observations or neurobiological data.

Schank (1981) has presented a model of memory organization based on MOPs (Memory Organization Packets), which attempt to account for the phenomena of 'reminding' that occur as a person understands a situation:

> At the root of our ability to understand is our ability to find the most relevant memory at just the right time. This can mean being able to tell a good story that illustrates a point, as well as being able to recall a prior experience that will shed light on how we should act during the experience we are currently processing. To bring to mind exactly the right experience at exactly the right time requires a memory organization that is capable of indexing episodes in such a way as to have them available for use when they are needed. This implies an indexing scheme that has at its base processing considerations. That is, if a particular memory is relevant to processing at a certain point, it should ideally be indexed in terms of its processing relevance. Processing relevance means the ability to come to mind at just the point where that memory would be most useful for processing (Schank 1981, p.41).

We view our model as compatible with and complementary to Schank's theory of memory organization; in terms of the CEL model, MOPs theory concentrates on the formation and retrieval of complex indices that an adult human would (eventually) develop in order to organize his knowledge of real world situations. In comparison, CEL so far deals with relatively simple indexes, because it is a model of an extremely early stage of development -- i.e., our domain is that of a child with very little experience of real world events as yet. The episodic schemata of the CEL model, then, are intended to be compatible developmental precursors of MOPs, but the focus of our research is on the memory operators that manipulate memory structures, rather than on the structures themselves; i.e., the operators that enable the reception, recording, retrieval, reconstruction and refinement of such memory structures, in such a way as to account for both the acquisition and operation of very early predictive reactions in children.

3.5.4 Some psychobiological results

Many researchers in psychobiology have pursued the goal of identifying the neural pathways underlying specific low-level behaviors, in the context of a constrained 'model' system. For instance, Cohen (1966, 1969, 1974, 1978) has pursued a decades-long program of research aimed at identifying the neural pathways underlying a specific small set of behaviors: that of the conditioned heart-rate change of the pigeon in response to a simple visual cue.

If this line of research proves successful, there will still remain the task of identifying which particular parts of the overall neural pathway are performing which of the component functions of the overall learned (conditioned) behavior. In order to do this, there must first exist some theoretical characterization of the underlying constituent operations that comprise the processes of learning and memory, such that these theoretical constituents might then be correlated with particular brain structures. Or, in Tolman's (1936) words: "A psychology cannot be explained by a physiology until one has a psychology to explain" (p.90).

While some researchers (e.g., John 1972, 1980) have suggested the extreme hypothesis that the entire brain may be involved in nearly every mental event, most research in psychobiology assumes some component of localization of function. As a representative instance, Diamond et. al. (see e.g., Diamond 1976, Bennett, Diamond, Krech and Rosenzweig 1964), have attempted to map regional anatomical changes in rat brains (e.g., increases and decreases in number and length of synapses on dendritic spines in the cerebral cortex), in response to differences in the environments of caged rats. Having established a number of such regional synaptic changes in the brain, Diamond then asks, in conclusion, "What do all of these anatomical changes mean with regard to brain function?" (Diamond 1976, p.237). Again, this question is calling for a theoretical characterization of the constituent functions that comprise the brain's overall operation, so that these theoretical constituents might be correlated with particular brain structures. It is hoped that the CEL model may provide a first step towards such a characterization.

4.0 OPERATION OF THE CEL MODEL: AN EXTENDED EXAMPLE

This section examines in some depth the theoretical operation of the CEL model in the process of learning first simple predictive behavior and then simple discriminatory behavior. The example presented here is that of Jacqueline, progressing from stage 1 to 3; at each stage, and each transition between stages, the model's operation is described and illustrated with a diagram.

4.1 Behavior of the model at stage 1

The initial operation of the model (i.e., at stage 1) is driven by innate schemata, and by experiential input. The innate schema associated with the example of Jacqueline's feeding behavior consists of three events, the first of which is afferent and the next two efferent:

1. child's mouth is touched
2. child opens mouth
3. child sucks, swallows

Hence, when the model receives sensory input of its mouth being touched via the DETECT and SELECT operators, the experience will REMIND the model of this innate schema, and the schema will be ACTIVATEd. The model will then reconstructively ENACT the efferent actions in the schema, i.e., perform the motor actions of opening its mouth, and sucking and swallowing. The 'operator transition diagram' in Figure 5 illustrates the coordination of these operators to produce the observed behavior at stage 1.

<FIGURE 5 GOES ABOUT HERE>

4.2 Progression of the model from stage 1 to stage 2

When the model experiences a taste that it innately finds desirable (e.g., milk) then the model will NOTICE this desirable event, will COLLECT the contents of short-term memory into a new episodic schema, and will INDEX that schema by (at least) the context of events initiating the schema (e.g., visual cues such as the room surroundings, the sight of mother, the sight of the food and containers, etc). In the specific case being analyzed here, the events COLLECTed into the schema will be as follows:

1. Child sees surroundings (e.g., bottle, mother, room, chair, etc.)
2. Child's mouth is touched (thereby triggering hereditary sucking schema via REMINDing and ACTIVATION)
3. Child opens mouth (i.e., ENACTing the ACTIVATEd schema)
4. Child sucks, swallows (still ENACTing)
5. Child tastes (desirable) milk.

It is this final tasting experience that causes the NOTICE mechanism to trigger the COLLECT and INDEX mechanisms. (The strength of this schema is incremented, i.e., reinforced, in subsequent REMINDed experiences, via the Refinement operators). Figure 6 diagrams part of the process of these operators establishing a kernel episodic schema corresponding to the new feeding episode.

<FIGURE 6 GOES ABOUT HERE>

4.3 Behavior of the model at stage 2

The model has now established an episodic schema beginning with the sight of the bottle and progressing to getting fed milk. When the model is presented with new instances of the sight of the bottle, the schema is REMINDed and ACTIVATEd, and the the Reconstruction operator ENACT begins to re-create the mental and physical states associated with each of the events in the ACTIVATEd schema.

Since the first two events are afferent, the ENACT operator can only re-create the mental state of sensing the afferent event, and cannot cause the event to recur, as discussed above, in the section introducing the Reconstruction operators. The first event (seeing the bottle) has already occurred, causing the REMINDing in the first place, but the second event, sensing a touch on the mouth, has not yet occurred. Nonetheless, the child ENACTs the mental correlate of sensing that touch, and goes on to the next event, without having to wait for that touch to actually occur in the external world. The next events are efferent (opening mouth and sucking), and hence those events are carried out as motor actions. It is this aspect of the ENACTing process that causes the apparent phenomenon of 'predictive' behavior; i.e., the child now opens its mouth before being touched, apparently in direct response to the sight of the bottle. Hence, the apparent predictive behavior is actually a side-effect or artifact of the process of Reconstructive ENACTing of a pre-recorded episodic schema.

Figure 7 illustrates the operation of the model to exhibit this predictive behavior.

<FIGURE 7 GOES ABOUT HERE>

4.4 Progression of the model from stage 2 to stage 3

When the child is presented with a feeding episode that begins similarly to previous feeding episodes, (e.g., contains the same or similar visual, aural and other cues) then the child will likely be REMINDed of the predictive schema developed above. If some particular episode, however, results in an undesirable taste (e.g., of a new food such as soup), then a number of mental events will be triggered. First the undesirable taste will be NOTICEd, just as the desirable taste was in the first step of the transition from stage 1 to stage 2, described above. The NOTICEing will initiate COLLECTion and INDEXing, and a new episodic schema will be established, beginning with, say, some initiating visual cues and leading to an undesirable state.

Simultaneously, the undesirable taste will trigger (via REMINDing and ACTIVATION) another innate episodic schema, corresponding to the 'gag reflex', i.e., is initiated by the afferent event of an undesirable taste and leads to efferent actions of the child spitting and closing its mouth. Hence, the child will ENACT those efferent events in response to the bad taste.

Because this episode leads to an undesirable result state, the INDEX operator triggers the Refinement operator DETOUR to block the path to this event sequence, preventing it from being re-enacted; and to provide an alternative path, if possible, around the undesirable sequence. Alternative paths are provided any time some additional episodic schema is triggered via REMINDing, during the Reconstruction of the undesirable episode. Such an alternative path is provided in this particular instance, by the REMINDed innate schema for gagging in response to an undesired taste. Hence, that schema is pointed to by the DETOUR operator as the alternate schematic path to pursue in subsequent instances of this episode. That is, the memory of the entire sequence of events will be recorded just as it occurred, but it will be indexed (via the DETOUR operator) in such a way as to cause the child to ENACT the alternate episodic path (gag reflex), instead of the one leading to the undesirable taste, whenever this schema is next Retrieved.

This is the most complex process the CEL model has performed so far, containing as it does both an unexpected branch of an episode and an undesirable result to that branch. Figure 8 illustrates the performance of the operators that carry out this process.

<FIGURE 8 GOES ABOUT HERE>

4.5 Behavior of the model at stage 3

Once the model has created the appropriate branches and detours in the relevant episodic schemata (i.e., by stage 3), its behavior is much simpler to explain than was the transition between stages 2 and 3. Whenever the visual input contains a match with the description of the appropriate object (e.g., soup bowl, juice glass, bottle, etc.), the model will pursue the schema (or schema branch) that is pointed to by that initiator. In cases of desirable outcomes, the appropriate schema is pursued; in cases of undesirable outcomes, the alternate 'detour' branch of the schema is pursued. Figure 9 illustrates the sample behavior of the model in response to the sight of the soup bowl in the proper surroundings.

<FIGURE 9 GOES ABOUT HERE>

4.6 General discussion

There are a number of interesting aspects of the model's operation that are worth noting. This section contains a brief discussion of some of these aspects; Granger (1982) contains some more extensive discussions.

1. Prediction is an artifact of reconstruction:

   As pointed out at stage 2 above, apparent predictive behavior of the child is actually explained in the CEL model in terms of the Reconstructive ENACTing of a pre-recorded schema. It is only because the child need not wait for the external world to match his ENACTing of <u>afferent</u> events that he appears to be performing the (observable) efferent events in anticipation of the outcome of the schema.

2. Pursuit vs. avoidance:

The CEL model does not provide a completely adequate account of how a child learns to prevent undesired states, as opposed to pursuing desired states. In the example above, the model uses the innate gag reflex to avoid a bad taste, but a more general reaction such as pushing the food away with her hand might not be so readily explained.

3. Individual differences:

The model is based on the assumption that the child depends on experiential inputs in order to create new schemata. This assumption will mean that different children will construct schemata with different initial kernels, depending on what event sequences they happen to be presented with (and which ones they attend to). However, through the mechanisms of Reconstruction and Refinement, the differences among initial schema kernels between different children will be largely erased over enough repeated experiences with a recurring episodic sequence. Hence, given children that are presented with similar episodes, the eventual constructed schemata will not be excessively sensitive to initial individual differences, though such differences may of course persist to some extent.

4. Attention:

Before the model can learn to react to, e.g., visually experienced events, it must learn to reliably attend to a visual event long enough to represent and record it. For instance, the child must learn to hold his gaze on a particular object in the visual field (e.g., the bottle) before he can learn to use that visual input to predict what will happen next.

In particular, the CEL model can acquire sensorimotor 'recognitory schemata' which consist of interleaved events of motor eye movements alternating with sensory SELECTion of visual input, accounting for the child's ability to perform a pattern of 'scanning' an object with his eyes, checking for the existence of 'salient' features of the object. What was represented above as a single visual event (e.g., seeing a bottle) is actually a shorthand for a sequence of visual scanning events that selectively identify features of the object in the visual field, thereby 'recognizing' the features as matching similar features that were 'learned' in the form of a recognitory (scanning) episodic schema. Hence, the first visual event (seeing the bottle) initiating the predictive 'feeding' schema is itself actually a whole sequence of visual inputs and eye movements. (On the other hand, direct sensory stimulation (e.g., touching the child's mouth) does NOT require any coordinated recognitory schemata on the child's part, and hence can be used as initiators to innate schemata without any prior learning being necessary.

5. Reinforcement and extinction:

Reinforcement occurs in the model simply by the operation of the REINFORCE operator, which adds a link between events in a schema. Extinction of a learned response occurs by a branch being formed in the schema, indicating a failure of the events to occur the same way as before; and sufficient numbers of subsequent REINFORCEments of that new branch will eventually overpower the original path through the schema. That is, a number of different branches may radiate from a given particular event in a schema, and each such path may have been repeated, and therefore reinforced, a number of times. Whenever the ENACT operator reaches such a juncture, it takes one or another of the available paths (not including paths that have been DETOURed around). Hence, after enough reinforcement of an alternate path, that path will be more likely to be pursued than other paths that have not been reinforced as much.

6. Three types of generalization:

The operation of the model results in three different types of modification of schemata, all of which can loosely be termed 'generalization'; we term them 'recognition-generalization', 'result-generalization' and 'sequence-generalization'.

Briefly, the first occurs when a visual initiator of a schema contains a number of salient features, e.g., the surroundings when Jacqueline is fed. In such cases, variations in the visual surroundings will be tolerated, i.e., will still cause REMINDing of the appropriate episodic schema, because the child will not have SELECTed all of the possible features in the scanned visual field to be initiators of the schema. Hence, as long as the SELECTed features are present, then other omissions or additions will be irrelevant. If, on the other hand, some different outcome occurs during some instance of the episode, then the SYNTHESIZE operator will trigger the BRANCH mechanism to create a differential branch on the basis of the differing features.

'Result-generalization' denotes the fact that the child will allow minor feature variations in the result state at the end of a schema, again depending on what features of that result were SELECTively attended to.

'Sequence-generalization' refers to the model's ability to record versions of an episode that begin similarly but go through differing sequences of events before arriving at the same result. Again, this is accomplished not by a specific internal 'generalization' mechanism, but as a side-effect of the BRANCH operator's establishment of separate branches of a single schema, in response to variations in the event sequence noted by the SYNTHESIZE operator's comparison function.

4.7 Extended chronology of CEL's learning

The three sub-stages of learned behavior that have served as the focus for this paper actually comprise only a small example of the set of learned behaviors that can be accounted for by the twelve operators of the CEL model and its expandable store of episodic schemata. Following is a brief outline of a larger view of the chronology of learned reactions, from innate hereditary behavior to advanced conceptual behavior.

1. Hereditary Schemata
   - orienting and defense reactions
   - sucking reaction
   - sucking-search reaction
   - others: eye-tracking, limb movement.
2. Early Acquired Sensorimotor Schemata
   - hand-eye coordination
   - predictive and discriminatory reactions
   - goal-directed episode initiation
3. Advanced Acquired Conceptual Schemata
   - object permanence
   - object categorization indices
   - action categorization indices (e.g., primitive ACTs)
   - situational categorization indices
     (e.g., causality, intention)
   - communication indices

In this 'timeline' of learning, the CEL model accounts only for behaviors up through the 'Early Acquired Sensorimotor Schemata'. The acquisition of the 'Advanced Conceptual Schemata' that follow in human learning requires an Extended CEL model, discussed in the Conclusion section of this paper. The following sections very briefly discuss some aspects of these additional examples of learned behaviors. A more extensive discussion of the chronology of CEL's learning is contained in Granger (1982).

4.7.1 Hereditary schemata

The 'orienting' and 'defense' reactions (Sokolov 1963) are innately present in all organisms, and consist roughly of increased heart rate, respiration, blood flow, etc., etc., in reaction to the presentation of virtually any new stimulus. These reactions presumably underlie the Reception mechanisms DETECT and SELECT, and the Recording mechanism NOTICE, since these are the operators that must respond to new stimuli, before there exist any schemata to deal with these stimuli.

The 'sucking-search' reaction has been described by many researchers (see e.g., Bower 1974, Bruner 1973, Piaget 1952). This is the innate reaction that causes head-turns in the infant as soon as parts of his face are touched. The innate versions of these head-turns are uncoordinated, i.e., they are as likely to turn the child away from the touch as towards it; but the schema is very quickly extended to cause the head to turn in the direction of the touch.

Eye-tracking reactions by infants have also been extensively observed (e.g., Kessen 1967); again, these reactions begin as uncoordinated motor movements of the eye, but soon are refined into schemata that cause the eyes to move reliably to keep a particular object in the visual field, thereby 'tracking' the object. Similarly, the innate 'grasping' reaction requires learning trials before the child can reliably move its limbs in the direction of a seen object.

4.7.2 Early Acquired Sensorimotor Schemata

All of the above innate hereditary schemata become refined as a natural effect of their use, and eventually give rise to more coordinated schemata that appear in the form of apparently more 'purposive' behavior on the part of the child. The examples of predictive and discriminatory behavior during feeding have already been discussed, and it has been shown how those behaviors can be developed via reconstruction and refinement from simple built-in hereditary schemata. Other examples of acquired sensorimotor schemata include the ability to maintain a field of view, arising out of the hereditary eye-tracking and head-turning schemata; scanning objects in the field of view (e.g., faces), also arising out of the above two hereditary schemata (we have referred to the schemata underlying such visual scanning behavior as 'recognitory schemata'); simple hand-eye coordination arises out of the tracking schemas together with the grasping schema. The acquisition and operation of all of these schemata can all be explained within the theoretical framework of the CEL model.

4.7.3 Advanced Acquired Conceptual Schemata

Human children are able to go beyond the above learned behaviors to exhibit such advanced abilities as 'object permanence', categories, causality, intention, and language. The CEL model does not account for the acquisition of any of these abilities. It is interesting to note that these abilities are much the same ones that most other animals (besides man) also seem incapable of learning. One of the questions we hope to address in future research deals with the question of just what extra underlying mental abilities or operations in humans enable the acquisition of these advanced abilities? This question is discussed further in the Conclusions section of this paper.

4.8 Summary of extended chronology of stages of learning

We have offered an extended chronology of the stages of learning that an organism will pass through in terms of the CEL model. This chronology is intended as more of a suggestive exercise than an exhaustive or detailed analysis. It is simply meant to place the three detailed stages of learning presented in this paper into a larger context of learned abilities in terms of the CEL model.

5.0 CONCLUSIONS

5.1 Characterization of the limitations of the CEL model

The above section characterized by example some of the limitations of the CEL model; i.e., it can account for the learning of sensorimotor schemata, but no more. It is interesting to note that these are much the same limitations as those of many mammals, e.g., dogs and cats. We are pursuing the accurate characterization of the limitations of the CEL model in part so that we may pose the following question: In what way would one have to augment the learning and memory operators of a CEL-like limited organism, in order to enable it to go beyond these limitations to acquire some of the abilities unique to humans?

For each such 'extended' ability, we hope to specify precisely the extra abilities that would have to be added to the CEL model, in the form of additional operators, extended functioning of operators, extensions of episodic schemata or their indices, etc., in order to enable the learning of these extra behavioral abilities. In other words, we intend to specify the extra components that an "Extended" CEL model, or ExCEL, would have to possess, in such a way as to account for the extended behavioral abilities that that model would exhibit. We view this as an important line of investigation to pursue; i.e., comparative characterization of the limits of the CEL model and the limits of the learning abilities of organisms may shed some light on the additional capacities that are needed to allow certain organisms to advance beyond the abilities of other organisms.

5.2 Psychobiological considerations

5.2.1 Components of learning and localization of function

One of the stated goals of the construction of the CEL model was the hope that the components that emerged from our analysis of the learning process might correspond to specific neurobiological structures. It has long been the case that psychobiology has sought to find specific brain structures (or combinations thereof) that corresponded to specific observed behaviors or abilities. This has been a goal at all levels of brain research, from the search for the lowest-level synaptic changes underlying learning (e.g., Thompson et.al. 1980, Cohen 1969, Brons and Woody 1980, Weinberger 1980, etc.), to the search for localization of certain observable functions, from the occipital pathways of vision (e.g., Hubel and Weisel 1968, 1978, Wurtz 1969, Mountcastle 1976, etc.), to the Broca-Wernicke pathways associated with certain aspects of language comprehension and production (see e.g., Penfield 1959, etc).

Indeed, Geschwind (1980) has cautioned AI researchers that

> "there is no evidence for the existence of any all-purpose computer [in the brain]. Instead, there seems to be a multiplicity of systems for highly special tasks" (Geschwind 1980, p.191).

The research described here has indeed led us away from viewing learning and memory as arising from a "general purpose computer"; we have ended up instead deriving a set of special-purpose mechanisms: the twelve operators of the CEL model.

One major difference between the CEL model and previous models is that most previous researchers in psychobiology have sought to isolate and localize observable special-purpose functions, that is, those with more or less observable behavioral correlates such as visual perception, sentence production, etc. In contrast, our componential analysis of the learning process cuts across such gross behavioral categories as vision, language, etc., and attempts instead to identify those mental operations that comprise the functional constituents underlying a wide range of learning tasks. It may be the case that our analysis could yield a set of special-purpose functions or operators that are more closely identified with particular systems of brain structures.

The following section explores a specific example of this possibility: the hippocampus may be associated with some subset of the three Recording processes proposed in the CEL model. In particular, it is shown that hypothetical lesions to any of the three Recording operators of the model will predict certain deficits in the behavioral abilities of the model without damaging other abilities; these predicted deficits of the model appear to correspond remarkably well to the deficits associated with bilateral hippocampal lesions in humans.

5.2.2 The Recording operators and the Hippocampus

There are a number of results in the literature of psychobiology that have dealt with the behavioral correlates of damage to the hippocampus, and, by inference, therefore relate to the possible function of the undamaged hippocampus in a healthy brain. Some widely-known results on memory and the hippocampus are reported by Milner and Penfield (1955), Penfield and Milner (1958), Milner (1958), and Milner (1959). The gist of the reported hippocampal effect on memory is that a (human) patient with a damaged hippocampus has trouble with new learning, while the patient's previously-learned skills and knowledge seem to suffer no noticeable deficit. That is, the patient can retrieve already-existing memories, but cannot permanently record new memories. This remarkable deficit is best illustrated by one of Milner's (1959) case histories of an epileptic patient (known by his initials "H.M."), after having had most of his hippocampus surgically removed:

> As far as we can tell this man has retained little if anything of events subsequent to operation [radical bilateral medial temporal-lobe resection], although his I.Q. rating is actually slightly higher than before. Ten months before I examined him his family had moved from their old house to one a few blocks away on the same street. He still has not learned the new address, though remembering the old one perfectly, nor can he be trusted to find his way home alone. He does not know where objects constantly in use are kept; for example, his mother still has to tell him where to find the lawn-mower, even though he may have been using it only the day before. She also states that he will do the same jigsaw puzzles day after day without showing any practice effect and that he will read the same magazines over and over again without finding their contents familiar (Milner 1959, p.49).

The details of such cases are absolutely striking; this man can read, can converse, can do all the tasks he used to be able to do before his operation, and his IQ test scores have not lowered. Yet he cannot record new episodes in such a way as to be able to retrieve them. (There are more complex aspects of this case; see for instance Sidman, Stoddard and Mohr, 1968). In terms of the CEL model, these findings imply that EITHER: (a) H.M. cannot NOTICE new episodes, i.e., his brain fails to decide that these episodes are 'worth recording', or (b) he cannot COLLECT new episodes into schemas, i.e., even if noticed, he fails to be able to package the events comprising an episode into a schema, or (c) he cannot INDEX new episodic schemas in such a way that they can be subsequently retrieved in the proper context, i.e., even if the episode is collected into a schema, he fails to attach any appropriate index pointing to the schema, and hence when later on he is in a circumstance in which he should be reminded of that schema, he is not reminded of it. Hence, although the schema might actually have been created and exists somewhere in his mind, it was not pointed to by any appropriate index, and hence was 'lost' to his retrieval memory, having failed ever to be appropriately anchored by a useful index.

In contrast, it could not be the case that the man's Retrieval operators have been affected, since he is still readily able to retrieve and reconstruct already-existing episodic schemata. Also, it cannot be the case that specific records of episodes are what has been lost, since there is no corresponding loss of previous abilities, nor of previous memories; just the apparent inability to establish new permanent memorial traces.

The CEL model, then, offers a specific prediction corresponding to the deficits arising from hippocampal lesions in humans. In particular, according to the theoretical framework of the CEL model, a lesion to one or more of the three Recording operators should result in a deficit in the ability to learn new memories, without impeding any of the other operators of memory function. This theoretical deficit corresponds remarkably well with the observed deficit associated with hippocampal lesions in humans. Hence, we may hypothesize that one or more of the three Recording operators (NOTICE, COLLECT, INDEX) is performed by the hippocampus in humans; and, therefore, damage or removal of the hippocampus will result in inability to carry out this operator or operators, resulting in the documented inability to record new schemata, while having no effect on the retrieval of already-existing schemata, and hence causing no deficit in the performance of tasks that rely on those existing schemata.

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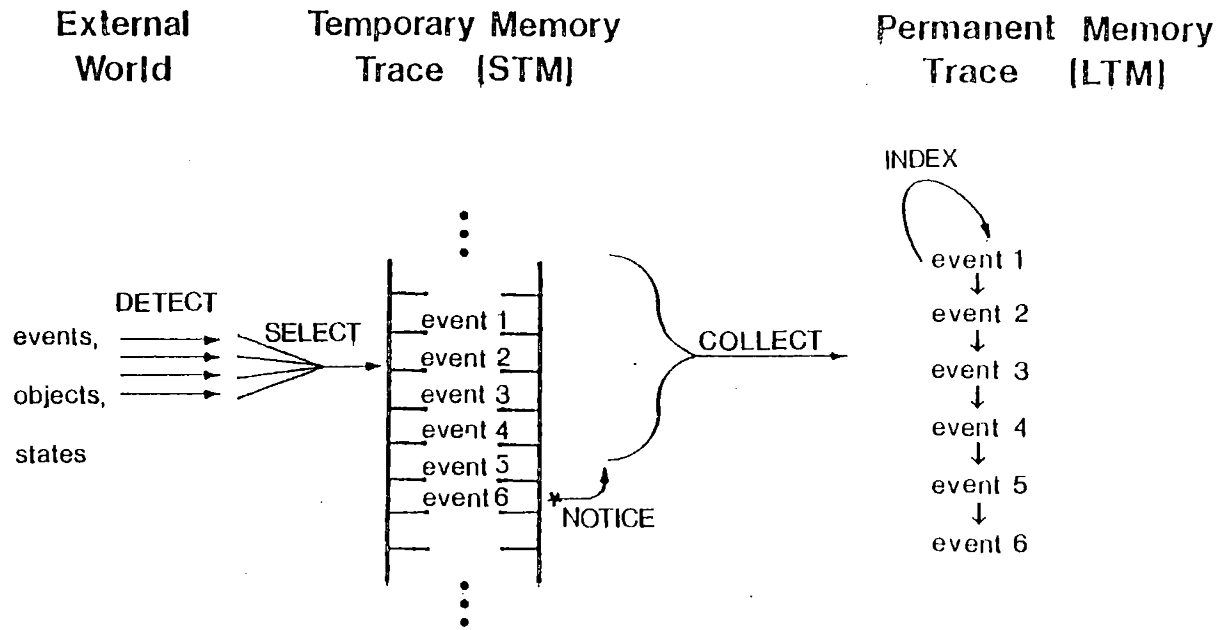

FIGURE 1

THE RECEPTION AND RECORDING OPERATORS

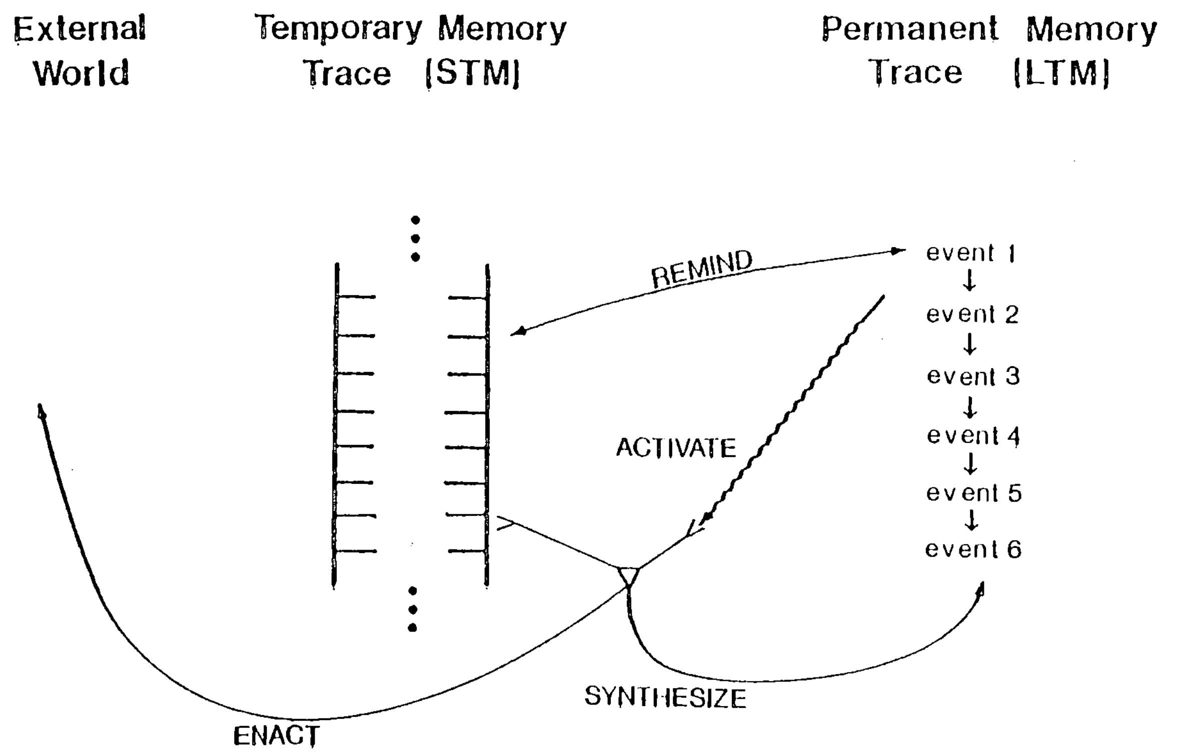

FIGURE 2

THE RETRIEVAL AND RECONSTRUCTION OPERATORS

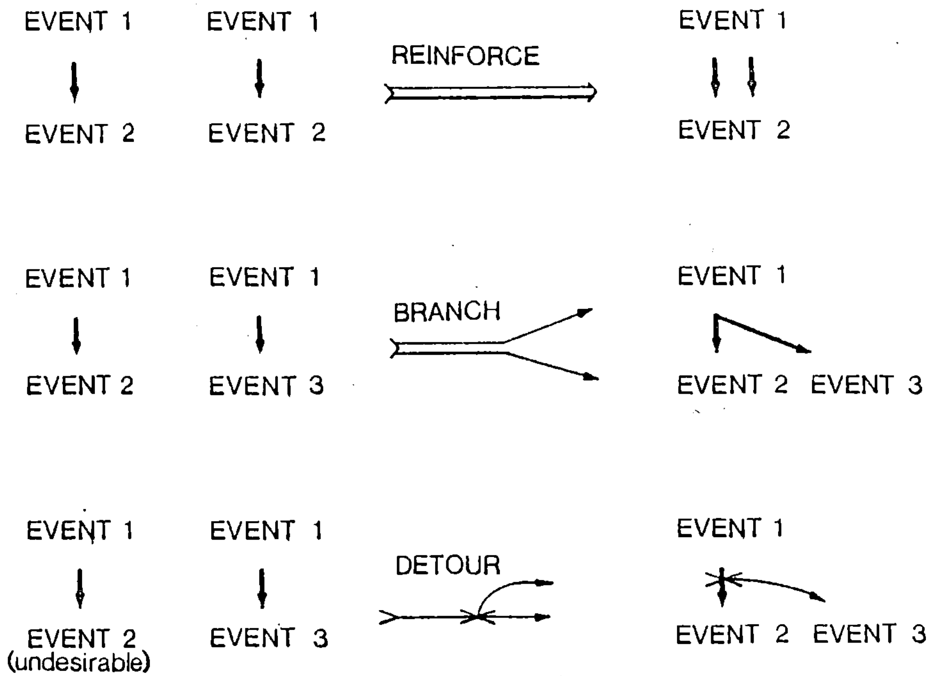

FIGURE 3

THE REFINEMENT OPERATORS

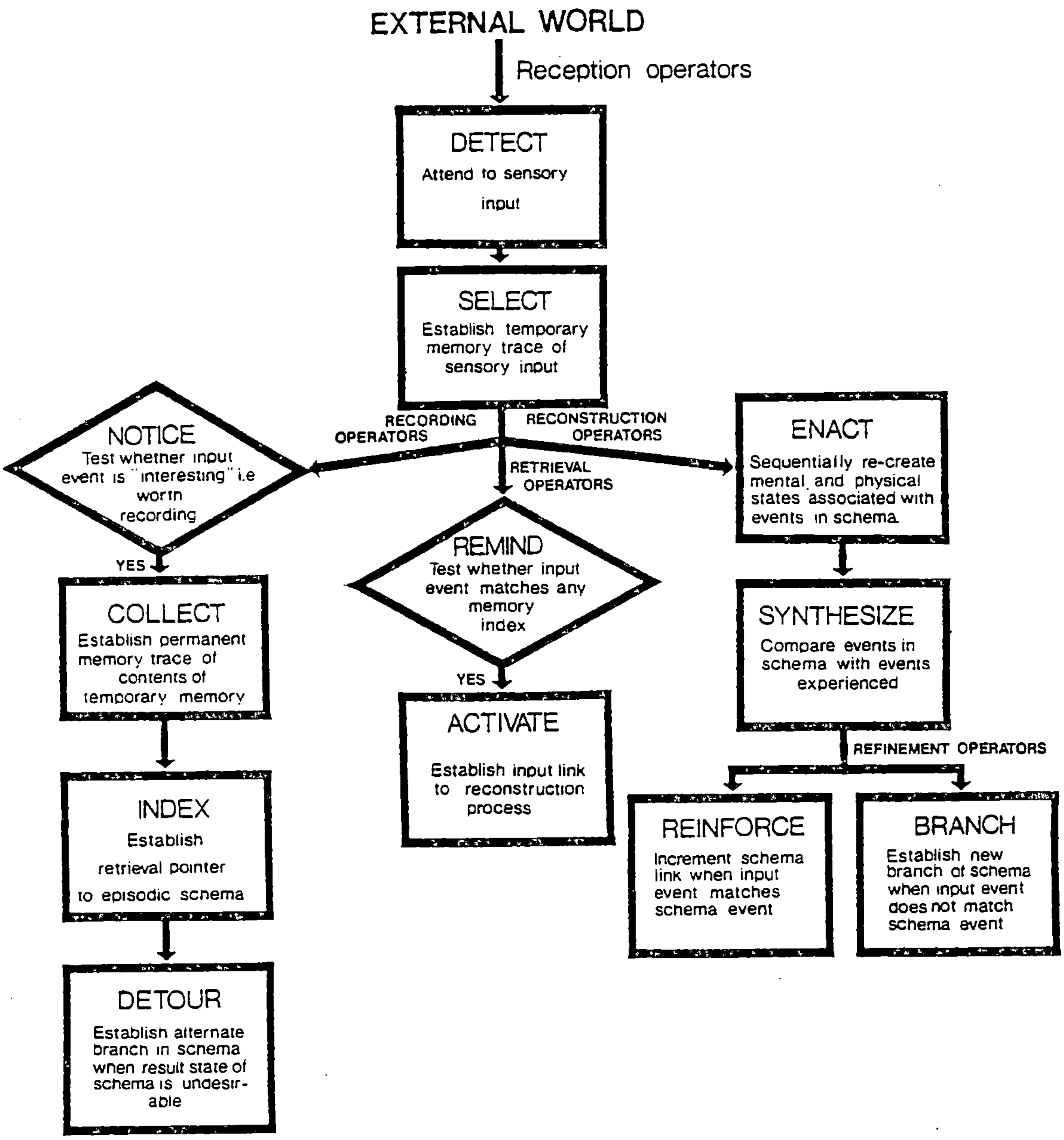

FIGURE 4

THE TWELVE OPERATORS OF THE CEL MODEL

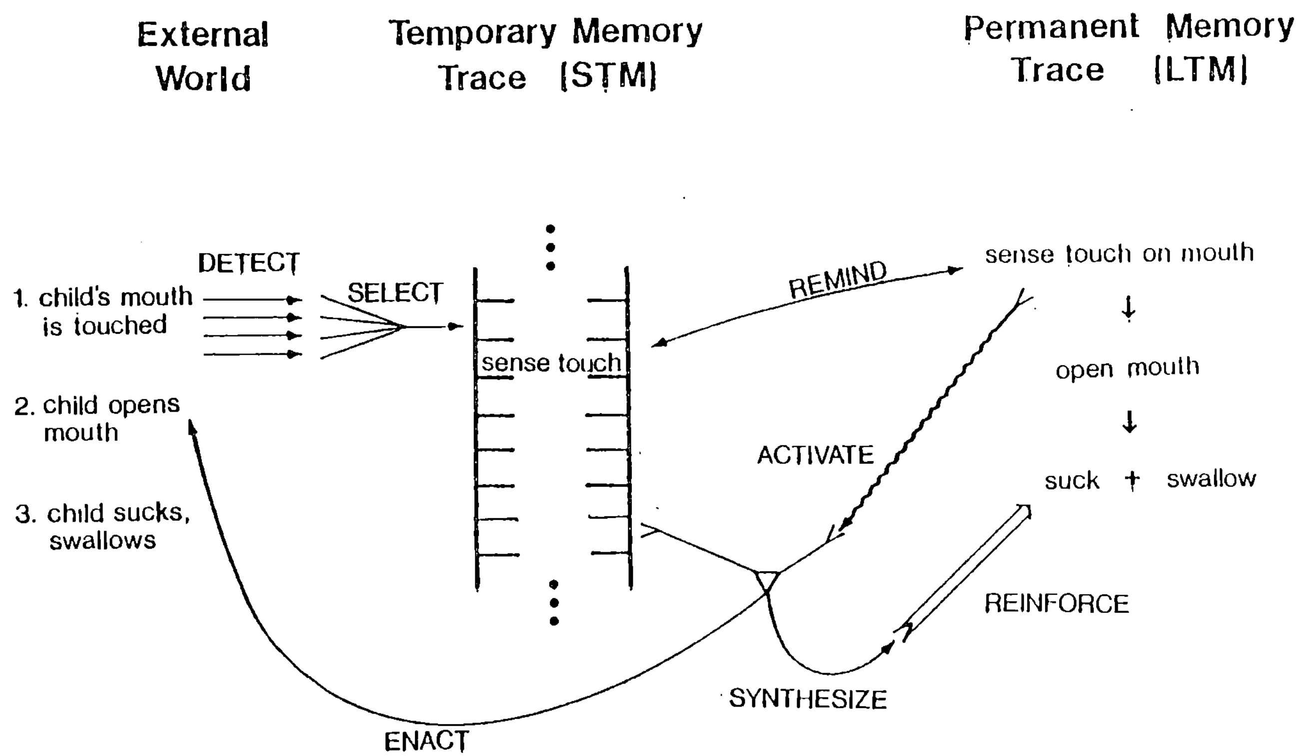

FIGURE 5

BEHAVIOR AT STAGE 1

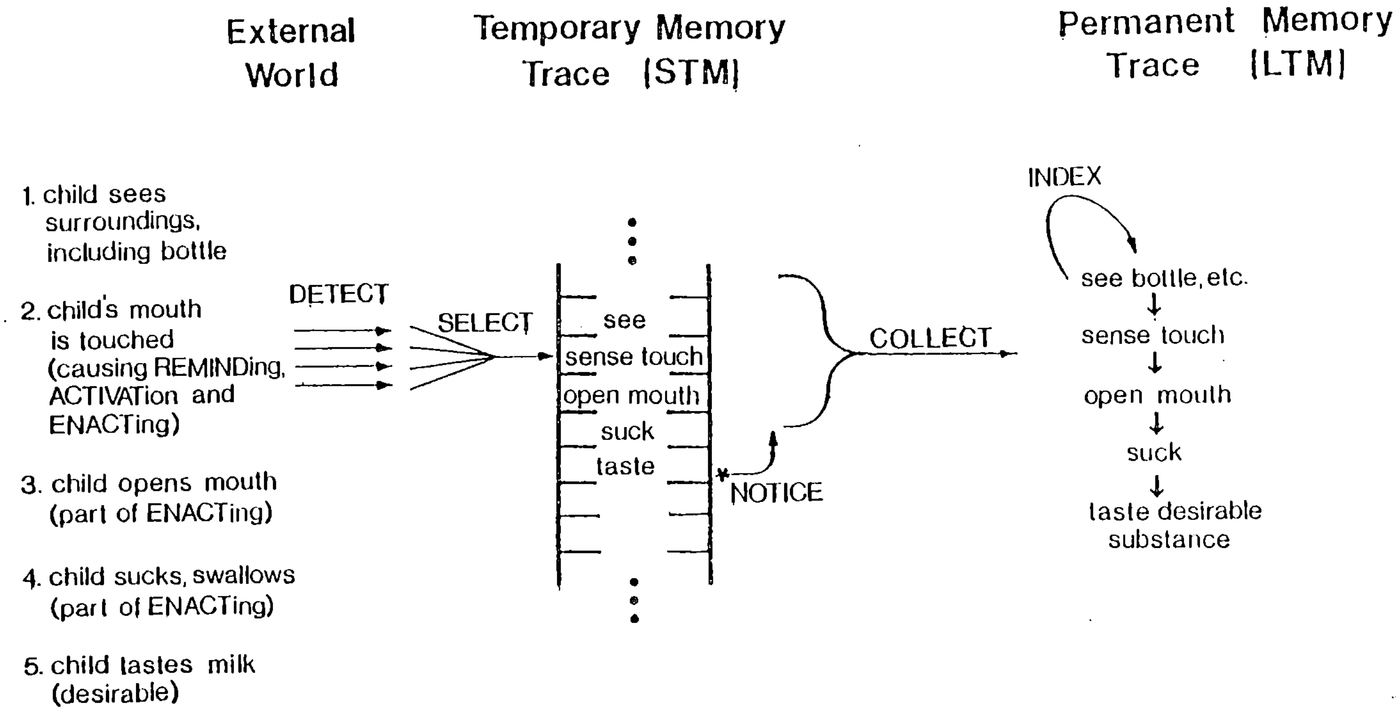

FIGURE 6

PART OF TRANSITION FROM STAGE 1 TO STAGE 2

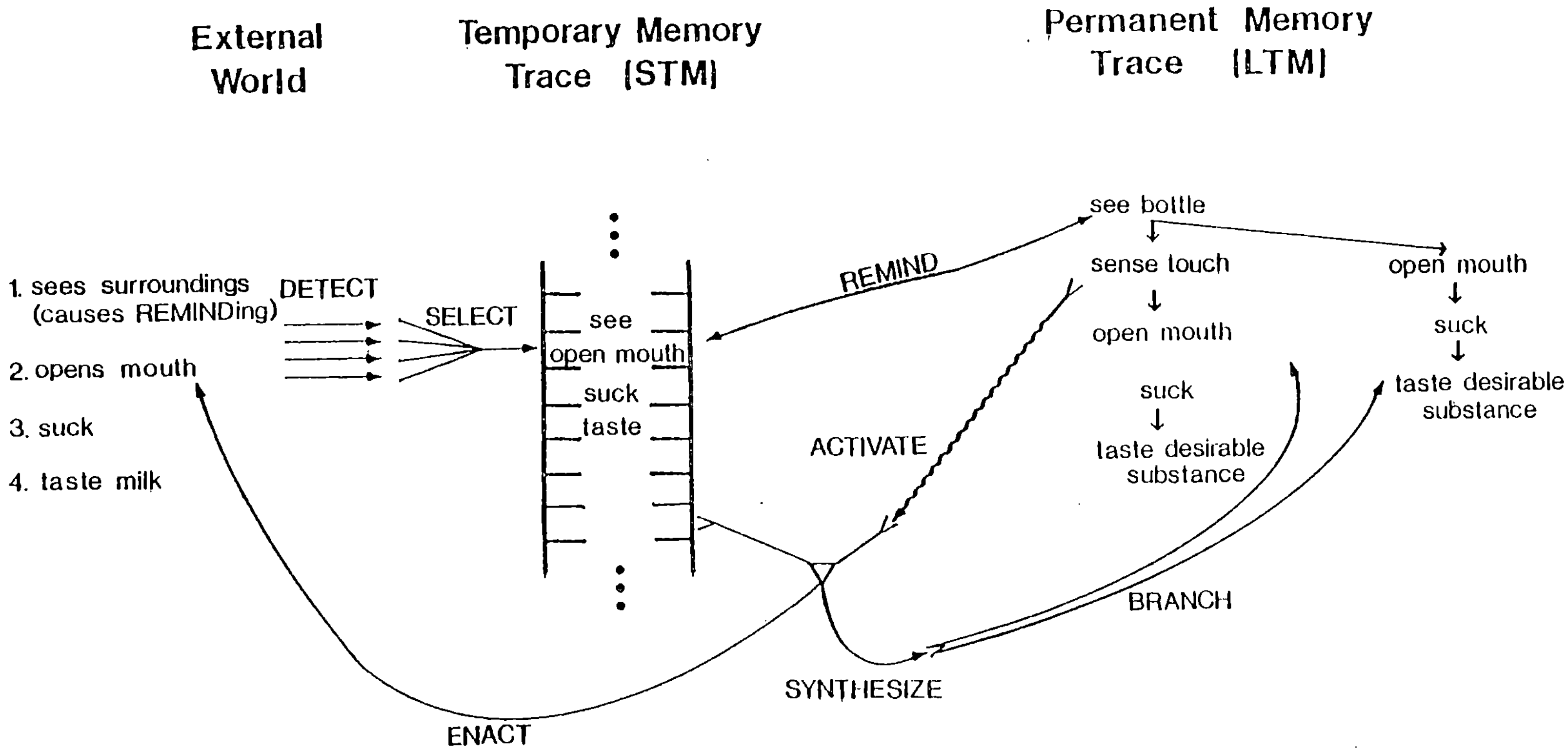

FIGURE 7

PART OF BEHAVIOR AT STAGE 2

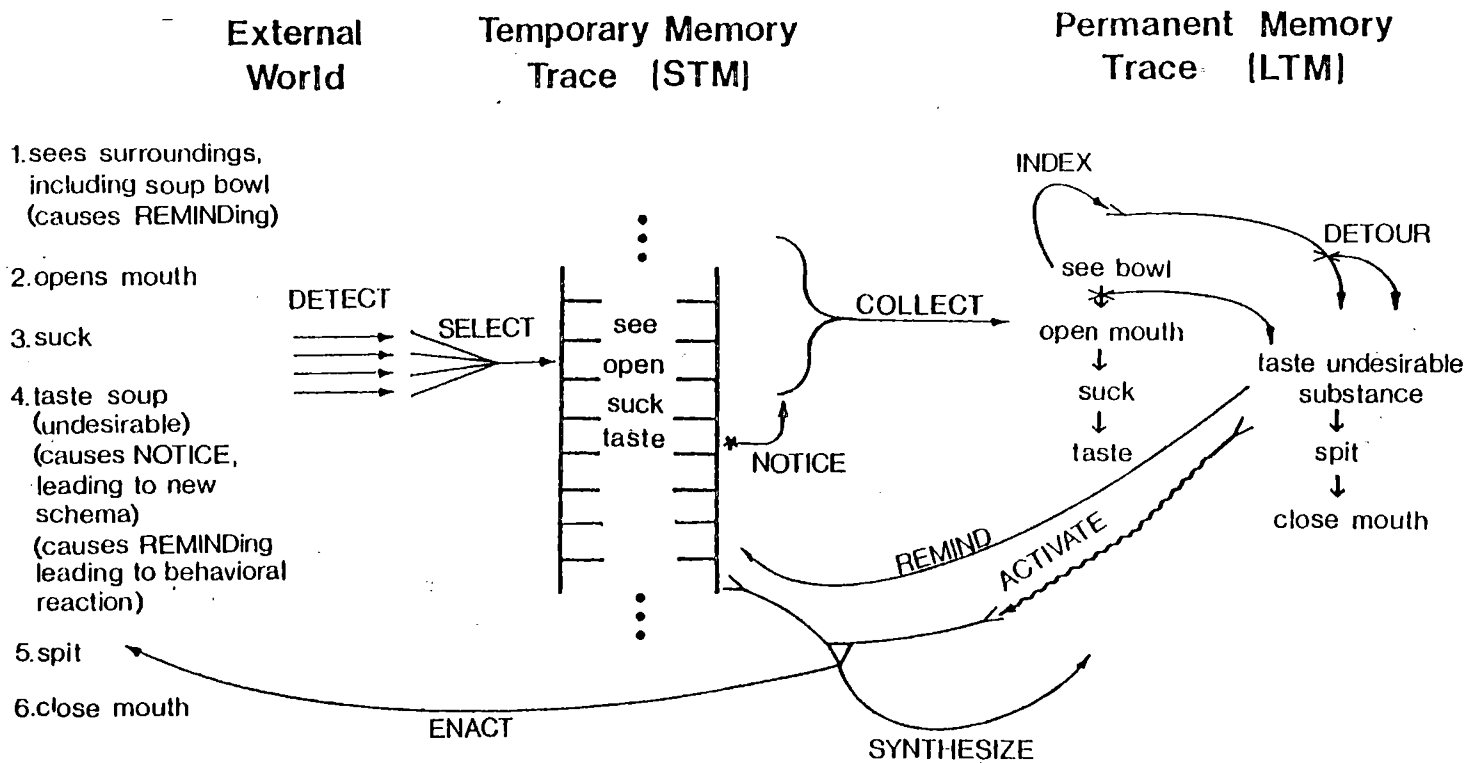

FIGURE 8

PART OF TRANSITION FROM STAGE 2 TO STAGE 3

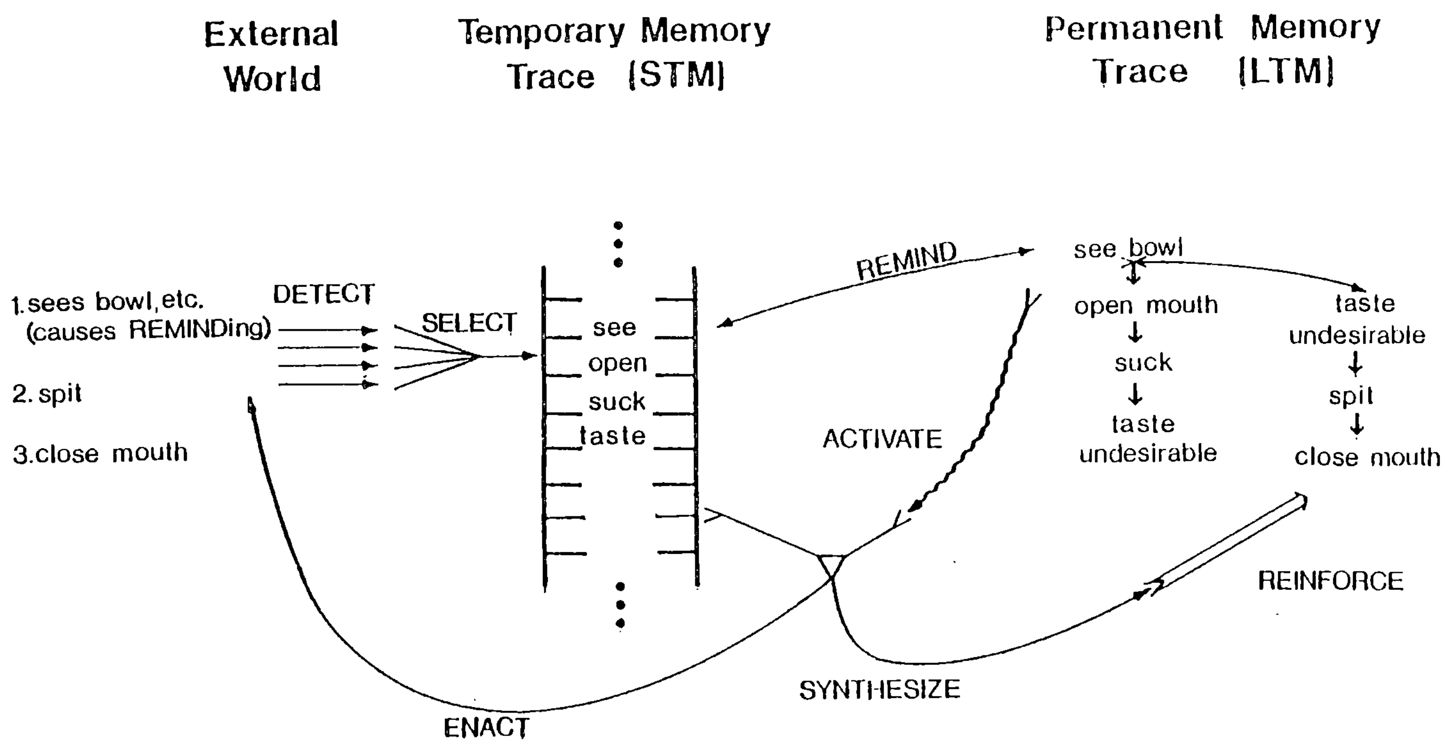

FIGURE 9

PART OF BEHAVIOR AT STAGE 3