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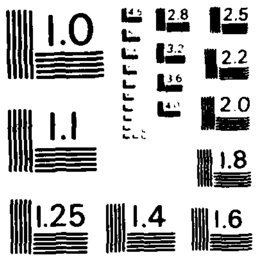
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# A UNIFIED MODEL OF ATTENTION AND PROBLEM SOLVING

Earl Hunt and Marcy Lansman

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The concept of production-executing machines has been used to construct a number of simulations of human problem solving. With a few exceptions the simulations have been of problem solving in situations in which there is no real-time pressure to respond. Such situations are typical of the paradigms used to study attention and performance. A model of production selection and execution has been developed that subsumes the previous problem solving models and that can be applied to real-time situations. The model has been

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) used to simulate human performance in choice reaction time, stimulus repetition, dual task, and cue-conflict (Stroop) situations. This extends the use of production system models to encompass both problem solving and attention limited behavior.

A Unified Model of Attention and Problem Solving *

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Running head: ATTENTION AND PROBLEM SOLVING





The development of theories of attention and the study of problem solving represent distinct traditions in the study of cognition. In this paper we present a model of human performance that is intended to integrate theoretical concepts derived from the two fields. Two concepts are central to the model. One idea, taken from the study of problem solving, is the idea that thinking can be described as the activation of productions - pattern-action rules that constitute the elementary steps in problem solving. The second idea, taken from the study of memory and attention, is that memory records can be thought of as a set of interconnected nodes, called a semantic network. In a semantic network model, memories are aroused by the automatic spread of activity through the network. In our model a production is associated with each node in the semantic network, and that production is aroused when the corresponding node reaches a critical level of activity. The details of pattern recognition and production arousal processes are spelled out below. Because the model deals with the interaction between spreading activation and production execution, it will be referred to as the Production Activation Model.

The model has been implemented as a computer program.

This has made possible the simulation of a variety of phenomena from the literature on attention. Attentional phenomena were chosen for simulation because they depend upon the interaction between semantic activation and production execution. This contrasts with phenomena tht depend upon the characteristics of either the production system, alone, or the semantic network, alone. To illustrate, Newell and Simon's (1972) simulations of human problem solving were determined entirely by the characteristics of production systems they used. Their program did not contain an analog of a semantic network. On the other hand, Anderson (1983, a, b) reports a simulation of the "fan effect," the fact that the time taken to recall a fact about an object increases with the number of facts that are known. The simulation of the fan effect depended only upon the process of activation in a semantic network.

The decision to focus on the interaction between semantic activation and production execution does not mean that the resulting model is unable to handle phenomena that depend on either process alone. Since the model is capable of executing productions, it inherits the capability for simulating problem solving that has already been demonstrated for production system models in numerous



studies. (See, in particular Newell and Simon, 1972). Since it contains a semantic network, the model could be used to simulate phenomena produced by semantic activation. In computer terminology, the model can be looked upon as an interpreter of production systems. Therefore it can execute any simulation of problem solving that is stated as a production system program.

The attempt to deal with attentional and problem solving phenomena within the same model is challenging, because studies that focus on only one of these fields can afford to ignore problems that must be dealt with by the other. Consider problem solving. Previously reported production system models have been used to simulate the accuracy of problem solving in situations in which the subject was asked to perform a single task, without any constraints on attention. These studies dealt with neither the time pressures involved in problem solving, nor the effects of distracting concurrent stimulation. The production activation model deals with both. On the other hand, theorier of the activation of memories rarely give a satisfactory description of the process by which increased activation is translated into action. A model in which the units of memory are productions rather than (ill-defined) engrams makes the connection between activation and action explicit.

This paper is organized into three sections. The first contains a description of the model and the *simulation program*. The second presents the results of simulations of some of the phenomena seen in popular paradigms of the attention and performance literature. *The paper does not go into great detail* in discussing any one simulation, since the intent is to show the breadth of the model rather than to explore its potential for depth of explanation. (*Subsequent, more specialized papers are* planned to discuss each of the simulations in more detail.) The third section discusses the psychological significance of the model, and compares it to other *models of mental action*.

Description of the model

We assume that when a stimulus is presented two concurrent information processing sequences are initiated. One involves a pattern recognition process that culminates when a label identifying the stimulus is placed in working memory. The label provides an interpretation of the stimulus that can serve as a trigger for further actions. This *sequence* of pattern recognitions, actions, and



further pattern recognitions will be called the "controlled" information processing sequence. In addition, stimulus *presentation* is assumed to initate an "automatic" processing sequence that behaves in quite a different way. Instead of relying on pattern recognition guided by information in working *memory*, the automatic processing sequence relies upon the spread of activation levels from one engram in memory to associates of that engram, without involving the working memory *system*. In the *following* section, these two systems are described in detail.

<u>The Controlled Processing System</u>

As mentioned above, controlled processing can be envisaged as the operation of a *production system* interpreter (Newell, 1973). Such interpreters contain two parts: a set of productions (pattern-action pairs) stored in long term memory, and a blackboard area that contains *information* about the current situation. At each cycle the pattern parts of all productions are compared to information on the blackboard. If any patterns are *recognized*, one or more of the associated actions are taken. Figure 1 shows the relationships between the blackboard and long-term memory utilized in the Production

Activation Model. The blackboard itself is divided into three areas: two sets of external channels (one visual and one auditory) that contain information presented to the system, and a working memory area that contains information that the system itself generates as it interprets problem solving situations.

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Figure 1 here

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The information flow implict in Figure 1 will now be explained. Information is placed in the external channels by the "environment," i.e., by a process outside the scope of the model itself. The information presented may be in either an "auditory" or a "visual" code. These names have been chosen for their obvious analogy to sensory modalities, but computationally the only distinction between them is that the stimuli are described in different codes. Information in the external channels is examined by the productions available in long-term memory. When an auditory or visual pattern is recognized, an internal label for the stimulus is placed in the working memory area. The internal label may either be in the (auditory or visual) sensory code in which the stimulus was presented, or it may be in an internal "semantic"



code. If the label is in a sensory code, it is placed in either the "auditory" or "visual" channel of the working memory area. These channels provide a way for the system to respond to internally generated stimuli, represented as sensory codes. The internal channels are thus analagous to Baddeley's (1976) concept of auditory and visual buffers in working memory.

If the internal label is in the semantic code, it may be placed in any of the the several semantic channels in the working memory area. Baddeley and others have stressed the need for a modality free representation of information in working memory. The semantic code provides such a representation.

The productions in long-term memory continually are matched against both the external and working memory channels. Thus configurations of working memory may themselves serve as stimuli for further actions. For example, suppose that two stimuli were placed on separate external visual channels. The model could be "programmed" (i.e., provided with an appropriate production system) that would select one of them, place it in the visual channel of working memory, and then use the internal visual code as a stimulus to place a semantic intepretations of the original stimulus in the semantic *working memory area*.

The following example, which is based on an actual simulation study, illustrates the process in more detail. Consider a two-choice reaction time study in which either of two visual stimuli - Stimulus 1 or Stimulus 2 - can be presented. The subject's task is to identify the stimulus, by making Response 1 if Stimulus 1 has been presented and Response 2 if Stimulus 2 has been presented. A production system can be constructed *using two pairs of* rules:

1. If stimulus x (x =1,2) appears on a visual channel, *place the signal "recognised stimulus x" in* working memory. Two productions are required, one for each value of x.

2. If the signal "recognised stimulus x" is in working memory make response x.

The condition part of a rule (the "if" clause) will be referred to as the pattern of a production. The consequent part (the "then" clause) will be referred to as the action. In controlled processing, a sequence of



productions is executed in an order that is determined by their level of activation. The first step in controlled processing is determination of the extent to which there is a *match between the stimulus* and each of the patterns in long-term memory. A complete model of how stimuli and patterns are matched would constitute a *theory of* perception, which is quite beyond the scope of our work. Instead of including such a theory, the model includes a pattern recognition process that is proposed as sufficiently descriptive of human perception for our purposes.

The stimulus is represented as an ordered list of features, drawn from a feature alphabet, or code, appropriate to that particular type of stimulus. Distinct similarity matrices are associated with auditory, visual, *and semantic codes*. The (ij)th entry of this matrix is a number, between zero and one, indicating the extent to which the ith value of a feature in that code resembles the jth value. For example, if the stimuli were figures of varying shape, the entry for (triangle, circle) would be near zero, and the entry for (circle, ellipse) would be near one. The diagonal (ii) entries of the feature matrix are always one, indicating that a stimulus feature most resembles itself.

The similarity matrix *notation* provides a flexible way of describing features, since it allows for the possibility of a confusion without requiring that all conceivable confusions be permitted. For instance, a stimulus similarity matrix could be constructed to permit confusion between colors (e.g., red and orange) or forms (triangle and square) but never between colors and forms. *Psychologically* it would be more realistic to think of sub-dictionaries (and confusion matrices) within a large dictionary of visual or *acoustic features*. In practice, it is easier to maintain a single dictionary for each type of sensory code.

Patterns are defined by ordered lists of pairs, (f,w), where f is a feature in the appropriate code and w is an indicator of the importance of the feature to the pattern. The value of w may vary from -1 to +1, depending on whether the feature is contraindicated, irrelevant (w=0) or mandatory. The resemblance of a stimulus to a pattern is computed using Luce's (1956) choice rule,



$$\text{(1)}\quad \text{Resemblance of stimulus to pattern} = \frac{\sum_{j=1}^{k} w(j)\ sim(s(j),p(j))}{\sum_{j=1}^{k} w(j)}$$

*In* this equation, k is the number of features in the stimulus and the pattern, s(j) is the jth feature of the stimulus, p(j) is the jth feature in the pattern, sim(s(j),p(j)) is the similarity of feature s(j) to feature p(j), as specified by the similarity matrix, and w(j) is the weight of the jth feature in the pattern. The possibility that a stimulus may not contain all the features of a pattern ( or vice versa) can be handled by including a null code within each *code dictionary*. The null code must not resemble any other code, i.e., the off-diagonal entries for the null row of the similarity matrix must be zero.

In some experiments patterns must differentiate between the appearance of a stimulus on an expected or an unexpected channel. This distinction is particularly important in studies of divided attention, where a person may be told to react to the presence of a *signal in the* right but not the left ear, or to a signal in the right but not the left of the visual field. To allow *for this* possibility, a pattern is further defined to have an additional "feature," corresponding to the channel on which the stimulus is expected. The importance of stimulus location is specified by stating a channel weight, c, varying from 0 to 1, where c=0 indicates that the channel is irrelevant, and c=1 indicates that the pattern is defined exclusively for one channel. The strength of a match between a stimulus and a pattern is then computed by the rule

$$\text{(2)}\quad \text{Match between stimulus and pattern} = \begin{cases} \text{resemblance if the stimulus is on the expected channel} \\ (1-c)(\text{resemblance}) \text{ if the stimulus is on an unanticipated channel.} \end{cases}$$

The distinction between channels and features deserves comment. Computationally, a channel is an array



variable that takes as its value a vector of features. The pattern part of each production is similarly a vector of features, and "perception" is the process of comparing the value of a channel to the pattern part of a production. This establishes a hierarchy of dimensions of variation for stimuli. Stimuli may differ in their features, and differ in the channel on which they appear. The distinction is computationally important in the model, because patterns are first matched to stimuli by computing a weighted sum of matches based on corresponding features, and the resulting value then multiplied by a weight determined by the channel. An alternative scheme would be to treat a channel as an additional feature of the stimulus. Consider visual figures that varied in shape, *size, and color. Shape and size are determined by contour* and color is not. Should color be considered as a feature *to be added* [illegible] *with shape and size, or should a simulation* be able to treat color in a completely different manner; i.e. as a channel? We have chosen the alternative of distinguishing between channels and features. The implications of the other alternative have not been studied.

No claim is made that the similarity computation rule is a theory of perception. (It would be of interest to replace the rule with a psychologically more justifiable one.) Using the similarity computation rule allows us to proceed with the task of studying the post recognition phenomena simulated by the Production Activation Model itself. This point is developed in more detail in the general discussion section.

The stimulus complex may contain information that matches several patterns to varying degrees. Therefore a "conflict resolution rule" is required to determine which production is to have its associated action executed. Conflict resolution is a general characteristic of production systems (McDermott and Forgy, 1978). In the Production Activation Model, the pattern part of each production has associated with it a non-negative real number, a, called its activation level. One, but only one, of the factors involved in determining an activation level is the extent to which the pattern matches some part of the stimulus complex. The other factors are explained below. The important point here is that the conflict resolution rule is a procedure for comparing activation levels.

As a computational device, the program's state is computed for finite steps of time, called cycles. All



computations within a cycle tak[illegible]ce functionally in parallel. Within a cycle, at m[illegible] semantic, visual, or acoustic pattern may be sele[illegible]for execuation. Therefore, patterns within a si[illegible]odality (or code) are compared with one another to de[illegible]ich one, if any will be selected. The conditions [illegible] selection are

1. The pattern's activation level must be above a preset threshold that is a characteristic of the pattern, and

2. The activation level of the selected production must exceed the activation level of any other pattern stated in the same code by an amount, DELTA, that is a parameter of the system.

The fact that the controlled system can respond to at most one semantic, one visual, and one acoustic pattern within a single cycle will be referred to as the "bottleneck condition." The points at which productions compete for action selection will be referred to as bottleneck points. The Production Activation Model contains three bottleneck points, one associated with each of the codes.

A strong restriction of the model is that patterns are stated in terms of the features on a single channel. Thus it is not possible to define a pattern in terms of concurrent features on two channels, i.e., in terms of a multimodal stimulus complex. It is possible for the system to react to multi-channel, multi-coded stimulus complexes by recoding the components of these complexes to internal stimuli in the semantic code, and then reacting to the constructed *semantic stimulus*. The point is that intervention by the controlled system is always required to construct such an internal system. There is no way that the *system can react* to multi-channel stimuli within a single time cycle.

*Any production* system could be realized within the controlled processing framework of this model. Since unrestricted computing systems are equivalent to Turing machines, it is generally held that they provide too much power to be realistic psychological simulations. The usual way to avoid the problem is to introduce the restriction that patterns must not exceed a fixed length, $k^*$, that could be looked upon as a limit on the capacity of working memory. There are then only a finite number of possible productions, corresponding to the finite number of possibly discriminable stimuli, given that each



stimulus must consist of not more than $k^*$ elements from a finite code.

There is another restriction, not stateable in the terminology of Turing machines but stateable by reference to the Production Activation Model, that may be far more important in limiting human capacity. It is the concept of interruptability. Furthermore, this restriction interacts with limitations in the size of working memory. Imagine that the Production Activation Model, or some similar device, contains a production system that is *logically* sufficient to do an arbitrarily chosen calculation after a minimum of n steps (n > 0). Suppose further that there is some probability, q, that any arbitrarily chosen step may fail to execute because of an interruption. That is, the device is thought of as being embedded in an environment in which high priority stimuli for productions *outside of* the set in question appeared randomly on an external channel. If such a signal appears, its processing takes priority over the computaton *currently being done*. Let P(n) be the probability of completing an n step computation. Then

(3) $$P(n) = (1-q)^n$$

*which becomes arbitrarily close* to zero as n increases.

Finally, suppose that the size of a production pattern is limited. The effect of this limitation would be to force a large computation to be broken down into several steps, thus increasing n. Clearly the computing power of the model is limited by the size of the patterns that it can recognize, and that limitation is exacerbated by the fact that the system is interruptible by "irrelevant" stimuli.

## The Automatic Processing System

The automatic processing system operates in a quite different manner than the controlled system. It is best understood by conceptualizing each production as a node in a network that is similar to the semantic networks described by Collins and Loftus (1975) and Anderson (1976,1983, a,b). The connection between any two productions, i and j, is stated as an association value, a(i,j), that takes some value between 1 and -1. If production i has activation level x(i,t) at time t, the activation level of production j will be increased by the amount a(i,j) * x(i,t) at time t+1. Thus information is passed from production to production by spreading activation, avoiding bottleneck points. All productions transmit information about their activation level simultaneously. A single production may send and receive



activation from several productions, including itself. If the association link between two productions is negative (a(i,j) < 0) the sending production is said to inhibit the receiving production.

The two choice reaction time example can be extended to illustrate the automatic information processing system. Here it is useful to think of Stimuli 1 and 2 as associated with Responses 1 and 2 as a result of instructions, training and/or stimulus-response compatibility. For instance, suppose that Stimulus 1 is a right arrow ("->") and Stimulus 2 a left arrow ("<-"), and that Responses 1 and 2 consist of the movement of a lever to the right or left, respectively. Figure 2 shows the network of associations that would be used to simulate this situation. Three principles were used in constructing the network (1). They are

1. All productions activate themselves, positively. That is, 0 < a(i,i) < 1 for all i.

2. Any production whose action might produce the precondition for a subsequent production is positively associated with the subsequent production. Thus the production recognizing Stimulus 1 primes the production

that would *recognize* the *associated* semantic signal. (To illustrate, a(v1,s1) > 0 in Figure 2.)

3. If the pattern parts of two productions represent logically exclusive interpretations of the stimulus, then the two productions inhibit each other. For this reason, a(v1,v2) < 0 and a(v2,v1) < 0 in the figure.

These rules were chosen because they have been found useful in a number of studies of self organizing systems. Note that Rule 3 is a logical analog to lateral inhibition, a phenomenon widely observed in the nervous system. The rules have been applied to the construction of semantic networks in all our simulation studies. In addition, only one value each is permitted for all self associations (a(i,i)), all *positive* associations, and all negative associations. The same values were used in all the studies reported here. The fact that reasonable results could be obtained without recalculation of *parameters* indicates that the model is robust.

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Figure 2 here

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Decay, Noise, and Refractoriness

If the automatic system operated exactly as described, activation would spread through the system *without limit*. To *avoid this*, a *decay* mechanism has been introduced. At the end of each time cycle, all activation levels are reduced by a fixed fraction d ( 0 < d < 1). (In all of our work, d has been set to .5) In addition, *biological information processing systems are assumed* to be subject to minor perturbations. These perturbations are modeled by adding a randomly distributed noise element to each production's activation level during each cycle. The noise element is distributed normally with expectation of zero and a standard deviation, e. The e parameter is thought of as a fixed characteristic of an individual at a given point in time. Except where noted, a constant value of e was used in all simulations. Similar decay and noise processes are required in virtually every associative network model of learning and cognition.

In production executing systems, the activation level of a production must be reduced once its action is taken. Otherwise the system will keep repeating its selection of the *same* production until new input is received (McDermott and Forgy, 1978). In order to avoid this undesireable outcome, a refractory process has been introduced.

*When a production* is selected for activation its threshold is reset to a value halfway between its original threshold and its current activation level. *Subsequently*, the threshold decays toward its original level at a rate determined by the decay parameter, d. This induces a *refractory* period, during which time new productions can be activated.

### *Selected Results*

This section presents a brief description of selected results that have been obtained with the simulation program. Results have been chosen to illustrate principles rather than to present a complete explanation of the phenomena in question. Four experimental *paradigms* will be considered. The first is the choice reaction time paradigm. In choice reaction time studies the participant knows that exactly one of a limited number of stimuli will be presented on each trial. The task is to identify the stimulus as rapidly as possible. This situation was chosen for study because it represents a protypically simple stimulus identification situation. Repetition paradigms complicate the choice reaction paradigm by introducing carryover effects from one trial to another.



(In "pure" choice reaction studies such effects are statistically controlled by randomizing the sequence of stimulus presentations.) Choice reaction time *and* repetition paradigms deal with the identification of a single stimulus, that can be treated as a unitary percept. In both paradigms the participant knows where and when the stimulus will appear; the only problem is to identify it. *By* contrast, in *dual task* studies; two or more stimuli may appear on a single trial. Typically the stimuli will appear at different places in the participant's perceptual field. The participant must split attention across the different sources of input. Finally, in "Stroop" paradigms two different *stimuli are presented* simultaneously. The two stimuli may be associated with incompatible responses. The participant's task is to attend selectively to a preselected stimulus category, while ignoring other stimuli.

Our simulation studies have focussed on simple versions of each of these four paradigms, in order to illustrate the basic principles of the model. The numerous complications that are possible within each paradigm will not be dealt with here. Future papers that explore the simulation of specific paradigms in greater detail.

<u>Choice Reaction Time Studies</u>

Choice reaction time studies have produced a number of highly replicable phenomena, some of which have assumed the status of "laws" in psychology.

1. <u>Hick's Law</u> . The illustrative example dealt with a two choice reaction time study, i.e., on any trial, one of two stimuli appear. Choice reaction time studies may be extended to n-choice studies, by allowing the presentation of any one of n pre-defined stimuli on a given trial. As before, each stimulus is associated with a single *response*. *If* each of the n stimuli are equiprobable, average reaction time increases as a function of the logarithm of the *number of possible stimuli*. This finding is known as "Hick's Law."

An n-choice reaction time study was simulated by expanding the production systems and networks shown in Table 1 and Figure 1 to allow for 2, 4, or 8 stimuli and responses. The results are shown in Figure 3, where the number of time which plots the relation between number of choices (on a logarithmic scale) and the number of time cycles before a response. "Response" refers to the execution of a production whose action included an



external reponse. In this graph and all others each point was determined by averaging over roughly 1000 equivalent trials. Figure 3 also shows results of a study by Taylor (1982), using human subjects. Clearly the results with the simulation mimic the human results up to a ratio *transformation (milliseconds per cycle)*.

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Figure 3 here

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2. <u>Speed-accuracy tradeoffs</u> . The relation between speed and accuracy of responding in choice situations has been the subject of considerable study. If a person speeds up his/her response in a particular choice situation the probability of an error increases. The relation between probability of correct response and time taken to respond is almost always a monotonically increasing, negatively accelerated function (Pachella, 1974). On the other hand, changes in either the *conditions of* the task *or* the state of the individual that produce slower reaction times almost always also increase the *frequency* of errors. These two *effects will* be refered to as the negative and positive speed-accuracy relations.

Both the negative and the positive relations can be produced by the simulation, by manipulating different parameters. Figure 4 shows the effect of manipulating the DELTA parameter. Recall that this parameter determines the extent of dominance that a production must have over its competitors, before its associated action is taken. Loosely, at high values of DELTA conflict resolution takes longer, but is less likely to result from random fluctuations in production activation levels. Thus manipulating *DELTA* will produce a negative speed-accuracy relation.

Figure 5 shows two different ways of producing positive speed-accuracy relations. Figure 5A was produced by holding the DELTA parameter constant and varying the size of the noise parameter. Increasing the values of the noise parameter both slowed responding and decreased accuracy. This can be thought of as being an analog of studies that compares responding across people of differing information processing characteristics, e.g. people of markedly different ages. Figure 5B shows a positive speed-accuracy relation produced by holding the DELTA and noise parameters constant, and varying the parameter establishing the simlarity between the two visual stimuli. This is analogous to plotting data from an experiment in which the stimuli to be identified vary



in distinctiveness.

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Figures 4, 5 here

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<u>Stimulus repetition effects</u> : In two choice CRT experiments response time is a function both of the choices available on the current trial and the relation between the current and the previous trials. There are two aspects to this relationship; the effect of the sequence of stimuli presented and the effect of the response-stimulus interval, i.e. the time beween the occurence of a response and the presentation of a new stimulus. The two variables interact to produce fairly wide variations in the response time. A subsequent paper will present the simulation of inter-trial effects in considerable detail. Here only the basic phenomena will be presented.

A <u>repetition</u> is defined to be the presentation of the same sequence on two or more successive trials. An <u>alternation</u> is defined to be the presentation of different stimuli on successive trials. While an alternation could be defined for experiments involving any number of stimuli, only the 2-choice experiment will be considered here. Thus if the stimuli are arbitrarily labeled 1 and 2 a repetitive sequence would be a sequences of repeated presentations, as in 1..1..1..1, while alternation would be represented by the sequence 1..2..1..2. An experiment by Kirby (1976) provides a good illustration of the basic phenomena. *Responses to* repetitive sequences were rapid at a response-stimulus interval (RSI) of 50 msecs, while responses to alternating sequences were rapid at an RSI of 2000 msec.

The production activation model accounts for the short RSI repetition effects solely by the activation of the automatic system. Assume that a correct response to stimulus 1 has just been produced. By definition, the activation levels of the productions associated with identification of, and responding to, stimulus 1 will have been higher than the activation levels of any competing production. In fact, the only thing that keeps the response from being repeated is the temporarily elevated response threshold of the production producing the response. *If the same stimulus information is* re-presented, on the next trial, the automatic system will already be biased toward production of the appropriate response. However, the bias can be eliminated if the RSI



is sufficiently long so that the decay process reduces the activation level of all productions to some *low*, near-zero value.

Alternation effects are generally accounted for by assuming that the *decision maker has a more or less* conscious bias against expecting stimulus repetitions, i.e. a crude version of the famous gambler's fallacy (Kirby, 1976). This assumption can be modeled by assuming that there exist productions in the controlled system that bias the program toward alternation. To simulate such an effect two additional productions were added to the production system for the choice reaction simulation. The first production had as its pattern the stimulus that response 1 had occurred, the other pattern recognized that response 2 had occurred. Upon recognition of response 1, as a stimulus, the appropriate production placed an internally generated stimulus that resembled stimulus 2 in the visual working memory channel. In computing terms, "resembled" simply means that the stimulus similarity between the actual stimulus 2 and *its internally generated* expectation was greater than zero, though less than 1, and was also greater than the resemblance between the internal stimulus and stimulus 1. Following the terminology used by *Posner* (1978), this can be thought of as an internally generated signal that primes the productions associated with identifying stimulus 2. The production for recognizing response 2 primed the productions associated with recognizing stimulus 1 in a similar manner. Clearly these productions, acting alone, would produce an alternation effect, because the presence of the priming signal in working memory would effectively lower the thresholds of all productions associated with the expected stimulus. However, the alternation mechanism can only be effective if the RSI is long enough for the relevant productions to be selected. This contrasts with the repetition mechanism, which can only be effective at short RSIs.

Figure 6 demonstrates response and alternation effects at short response-stimulus intervals. Panel A shows the effects in data produced by the production-activation model. Sequence AAAA represents the repetitive presentation of the same stimulus on four successive trials, sequence ABAB represents presentation of alternating stimuli. In the runs that produced this data stimuli were presented immediately after the model had made a response. There is a strong repetition effect and no alternation effect. Panel B of Figure 6 is a replotting of Kirby's (1976) data for his 50 msec RSI



condition. As in the model, there is a repetition effect but not an alternation effect.

Figure 7 presents similar data for long RSI's. Panel A shows the result of model runs that contained and introducing a blank period (i.e. no stimulus present) of six internal cycles between the response and the next stimulus presentation. During this period the model continued to redistribute activation, and to react to any internally generated stimuli in the manner described above. Panel B is a replotting of Kirby's data for the 2000 msec. RSI condition. In both the simulated and the human data, repetition effects do no appear, but alternation effects do.

In the human data, responses at the 2000 RSI condition were more rapid, overall, than responses in the 50 msec RSI condition. This is not true in the model. No attempt has been made to reproduce this effect, which may be due to properties of the motor system rather than to the interaction between expectation and stimulus identification.

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Figures 6 and 7 here

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Splitting attention. In choice reaction time studies the participant must identify a stimulus that appears in a known location. The next series of studies involve the detection of stimuli that appear randomly at different locations. An experiment by Kinchla (1980) provided the motivation for the simulation. Kinchla's observers had to attend to two small lights, at different locations in the visual field. In terms of the model, the two locations were treated as separate external visual channels. On each trial one or the other of the lights might flicker briefly. The observer's task was to indicate whether or not a flicker had occurred on either channel. Thus the dependent variable was the probability of a correct detection, rather than the latency of a response. The chief independent variable in the experiment was the priority that the observer was to assign to each channel. Priority was determined by instructions, and by points rewarded for a correct detection.

The simulation for this task was closely related to the CRT simulation. Information was presented over the two



visual external channels. Initially both channels had null signals (S1) placed on them. These signals corresponded to the lights. Then, on experimental trials, a target (S2) signal was placed on one of the channels briefly. Catch trials were also included, in which no target signal was presented. (Naturally, Kinchla also used catch trials.) The target signal was then replaced with the S1 signal.

To permit false alarms, which do occur in this type of study, the resemblance between S1 and S2 stimuli was set at .50.

The production system used is presented in Table 1. It contains two productions associated with each visual channel. The two productions can be thought of as miniature "choice reaction" productions within each channel. One recognized stimulus S1, and the other recognized stimulus S2. A trial on which a signal was presented was judged correct if either of the productions for recognizing S2 was selected for execution. On catch trials, the firing of one of these production was recorded as a false alarm.

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Table 1 Here
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Figure 8 shows the semantic activation network associated with the production system. All productions were assigned to the visual code. Since all productions were at the same level (detection of an elementary visual display) each production positively primed itself, and inhibited all other productons.

The notion of priming was used to simulate the effect of instructions, in a manner similar to that developed for the study of alternation effects. It was assumed that, given appropriate instructions, a person could generate an internal "priming" signal that would have the effect of lowering the response thresholds of all productions associated with a particuar channel. Thus the threshold value for each channel served as the primary dependent variable. Thresholds varied between 1 and 0, complementarily. That is, if threshold x was assigned to the productions of channel 1, threshold 1-x was assigned to the productions of channel 2.



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Figure 8 Here
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Data from this sort of study is usually represented as a "performance operating characteristic" (POC), in which the accuracy of detection of targets on one channel is plotted against the accuracy of detection of targets on the other channel. In Kinchla's (1980) study the POC was linear, providing that performance was plotted in terms of "hit rate", the percent of targets correctly detected. For the POC to be meaningful, though, false alarms should occur on only a small percentage of the trials. (It is important to have some false alarms, to ensure that the subject has not set an excessively high criterion for target detections (Pachella, 1974).)

Figure 9 presents the POC obtained by the simulation. It is clearly linear. The error rate for catch trials was about 5% overall, with somewhat more false alarms occurring when high priority was given to one or the other of the channels. Whether or not the last effect is characteristic of human responding is unknown. Kinchla's data is also shown for comparison. Note that in Kinchla's study subjects never completely ignored the less relevant stimulus, so the POC does not cover the extreme points that could be simulated.

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Figure 9 Here

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<u>Stroop studies</u> . The last simulation to be reported deals with the Stroop task, a situation considerably more complicated than the other paradigms described here. In Stroop situations signals are presented simultaneously on two separate channels. The participant is instructed to *make an identifying response to the stimulus on one* channel, while ignoring the other. The two stimuli will be *referred to as the relevant and irrelevant stimuli,* respectively. There are three basic experimental *conditions. In the neutral condition the relevant and* irrelevant stimuli are not associated with either common or *mutually exclusive responses. In the conflict* condition the relevant and irrelevant stimuli have strong, and *mutually contradictory, associations with the possible* responses. In the facilitating condition the relevant and irrelevant stimuli are both highly overlearned cues for the same response.



There are a variety of Stroop situations, each of them producing a somewhat different pattern of responses. This report deals only with a simulation of a standard Stroop task, based on Stroop's (1935) original experiment. (A much more detailed study of Stroop tasks will be reported subsequently.) In Stroop's experiment participants had to name the color of ink in which words were printed. The words were themselves color names; e.g. *the word GREEN printed in red ink. This, obviously, is a* conflict condition. In a facilitation condition GREEN would be printed in green ink, while in a neutral condition either a color patch or a non-color word (e.g. *DOOR) would be presented in colored ink. In general, if* people are asked to name the ink color there is a marked *slowing of identification responses in the conflict* condition, and a negligible increase of speed in the facilitation condition (Dyer, 1973). Reading the word takes half as much time as color naming, and is relatively uninfluenced by ink color.

The simulation of performance in the Stroop task was based on the model proposed by Morton (1969). Morton used a somewhat specialized vocabulary, so his ideas will be restated using the vocabulary of the Production Activation

Model. For those who are familiar with Morton's notation, his logogen corresponds roughly to a node in the semantic network. In Morton's model there is no element corresponding directly to our "production," but the idea of a production's being activated seems in the spirit of his notion of the activation of logogens.

Stimuli are assumed to appear on two visual channels, as in the case of the simulation of split attention. The actions subsequent to recognizing visual stimuli, though, are much more complex than in the case of the detection experiment. Table 2 shows the production system for a simple Stroop task in which the words RED and GREEN might be presented in red and green ink. It consists of three parts. The visual productions are somewhat analagous to those in the detection study; each channel has associated with it productions for recognizing either the words or colors for "red" or "green." The action parts of these productions each generate an appropriate semantic stimulus, indicating to the system that a "red" or "green" stimulus has occurred. The semantic stimulus, in turn, is recognized by semantic productions that generate an internal auditory code indicating to the system that an external verbal response is required. When the auditory internal signal is recognized the appropriate verbal



response is made. (Naturally, the computer does not actually make this response. It is simply recorded as being executed.)

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Table 2 Here

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The two part translation from visual to semantic codes, and from semantic to verbal responding, may seem clumsy. It was included to extend the simulation to situations in which external instances of internal concepts must be recognized, and the concepts themselves must be used to guide the selection of "response codes", usually for auditory responses. See Morton (1969) for further justification of the basic theory.

The visual productions contain two features in their pattern part; one referring to the external stimulus and one referring to the instructions. Instructions are presumed to act as internally generated goal stimuli that prime particular productions, in the manner described earlier for the split attention and stimulus alternation studies. Thus it is possible for a stimulus to fully match a visual production only if the stimulus is relevant to the instructions given. However irrelevant stimuli may partially match their associated productions.

Figure 10 displays the semantic network associated with the productions. Several assumptions from Morton's model are incorporated in the figure. One is that, as a result of overlearning, the forms of words (and hence their associated productions) will have become associated directly with the acoustic codes for words. By contrast, color stimuli, and their associated productions, are assumed to be associated with the semantic codes for colors, rather than the name codes. However name codes and semantic codes for colors are both assumed to be associates of each other. The effect of these assumptions is that in a Stroop conflict situation the controlled production system and the automatic semantic network system partially work against each other. Irrelevant word *stimuli should be more effective interferers than* irrelevant color stimuli because the word stimuli have a rapid path to the (incorrect) response, via the automatic processing system.



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Figure 10 here

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Figure 11 depicts the results of a simulation of the six possible Stroop conditions. Most of the Stroop findings are replicated. The color naming-conflict condition produces by far the slowest responding. Facilitation effects are relatively small for color naming, and non-existent for word naming. There are two exceptions to the normal Stroop finding. One is that the "word reading" conditions are not as much faster than "color naming" as they should be. The second contradiction to human data is that conflict is found in the word reading condition. That is, it takes longer for the simulation to "read" the word RED printed in green ink than it takes to read RED printed in a neutral color. A *detailed analysis of the simulation* indicates that these effects could be markedly reduced by increasing the power of the forward association between word recognition and auditory pattern recognition. This would involve manipulating a parameter that has been a constant in all other studies reported here. While the manipulation seems a reasonable one, the data in Figure 10 are reported for consistency, and because our aim is to show that the same simulation can handle the gross phenomena from a variety of paradigms, rather than to demonstrate how the model can be tuned to mimic the data from a single situation in great detail.

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Figure 11 here

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## Related Theoretical Studies

*This section will compare* the Production Activation Model to three other theoretical proposals; the ACT* model developed by Anderson (1983a,b), the cascade processing model developed by McClelland (1979; Rumelhart and McClelland, 1982), and Eich's CHARM model of memory storage and retrieval. These models should not be considered as contending explanations of the same phenomena analysed using the Production Activation Model, nor do they contend with each other. The different models represent complementary and compatible approaches to distinct, but related, cognitive behaviors.



### The ACT* model

Anderson's ACT* model of memory and problem solving resembles the Production Activation Model in several ways. Both are systems for interpreting productions in order to determine actions. Both represent information in long term memory using semantic networks. ACT* contains three types of internal stimulus codes; codes for spatial information, temporal order, and for abstract propositional information. The three codes are loosely analagous to the visual auditory, and semantic codes of the Production Activation Model.

The most striking discrepancy between the two models is in the complexity of the patterns that serve as cues to production activation. In ACT* production patterns may be complex conditional statements. For example, Anderson (1983b, pg. 144) presents an eighteen term conjunction as the pattern part of a production for recognizing the word EACH. Several of the terms in this conjunction are themselves conjunctions. Such patterns are clearly much more complex than the patterns dealt with in the present studies of the Production Activation Model. However, complexity alone does not represent a basic distinction. It would be possible to represent Anderson's eighteen term conjunction within the Production Activation framework, and there is every reason to believe that people do have the ability to recognize complex situations. A more basic difference between the models is in the techniques that are used to match stimuli to patterns.

In ACT* patterns are matched to stimuli using a computational method known as data-flow pattern matching (Forgy, 1979). Explaining the details of such a mapping would be beyond the scope of this paper. The important point is that a commitment to the data flow matching does not restrict the logical complexity of the description of the class of stimuli that activate a given production (1). By contrast, the Production Activation Model uses a linear discrimination procedure to determine the relative strengths of matches between the current stimulus and the patterns stored in long term memory. There are interesting, relatively simple classification rules that cannot be realized by a linear discrimination procedure (Minsky and Papert, 1968). For instance, the biconditional rule (An item is a member of class X if it has both features a and b or if it has neither feature) cannot be realized by such a procedure, although it could be realized by data flow pattern matching. Therefore more powerful productions can be stated within the ACT*



framework than within the Production Activation framework. Whether this should be regarded as a strength or weakness is a matter of debate. Linear systems can be justified by reference to simple neural models. However linear systems are probably not powerful enough to model all human pattern recognition. Does such modeling require a system of the complexity of data flow networks? The answer to this question is not known.

A similar remark can be made about the use of codes to define the pattern parts of productions. The Production Activation Model contains the strong assumption that patterns are defined only within a code type. It is for this reason that productions compete for activation only within classes of productions; auditory productons with themselves but not with visual productions, and so forth. Although ACT* has three code types, there is apparently no requirement that the pattern of a production be restricted using only one code type. ACT* could recognize a cross-modal stimulus, such as a barking dog, by activating a single production. Thus ACT* assumes a primitive ability for cross-modal integration, while the production activation model requires a sub-model of the integration process.

In the Pattern Activation Model a stimulus is defined as an ordered set of features on a particular channel. ACT* does not have a similar concept of channels within a code type. Thus ACT* has the capability of reacting directly (i.e. by the matching of a single production) to a stimulus defined by the totality of features present in the external world, while the Production Activation Model must build up an internal representation of that stimulus, by recognizing the presence of patterns on different stimulus channels, and using these recognitions to piece together an internally generated coding of the total stimulus complex.

The distinction between production activations based on restricted or unrestricted pattern recognition is a serious theoretical issue. In the ACT* framework a cross modal stimulus, or a cross-channel stimulus within a particular mode of presentation, could activate a production directly. Therefore it could initiate automatic data processing within the semantic network. While something resembling cross model (or cross channel) automatic data processing could occur in the Production Activation model, through partial arousal of patterns, the amount of automatic information processing would be limited. This raises an important empirical question. Is



it possible to automate responding to stimuli defined in terms of more than one internal code? Or defined in terms of the combination of information on more than one channel?

ACT* and the Production Activation model also differ markedly in their treatment of reaction times. In the Production Activation system response times are derived from the dynamics of the development of activation levels associated with the various productions. In ACT* reaction times for memory retrieval are computed as a function of properties of the distribution of activation in a stable semantic network, after the dynamic phase of a response to a stimulus has been completed. The difference in emphasis is appropriate, considering the difference in the type of process being studied. The Production Activation Model studies have been focussed on situations requiring rapid responses to easily recognized stimuli. The response times being modeled are seldom more than a second. The retrieval processes studied in ACT* simulations (Anderson, 1983a) may take several seconds. It seems reasonable to regard them as the result of a search process that examines stable activity of a semantic network, instead of the being an offshoot of the initial dynamic response of the system to stimulus presentation. Anderson does not offer a model of the search process itself.

These differences between the models can be resolved by regarding ACT* and the Production Activation Model as complementary models that deal with different phenomena, in a compatible manner. ACT* models have been proposed for the retrieval of information from memory, and for complex cognitive acts, such as solving problems in plane geometry. An analysis of such actions by models that began with phenomena at the level of physical stimulus recognition would quickly become hopelessly complicated. The Production Activation Model has been designed to deal with these precisely more molecular situations (2).

We conjecture that ACT* could be recreated as a set of productions to be executed by the Production Activation Model. Data flow networks, which are treated as primitives by ACT*, would be treated as decision processes to be modeled. The complex patterns recognized directly by ACT* would then be "named", as a response, by the *Production System model. Similarly, cross model* integration could be simulated using the Production Activation model, and the output of the simulation used as an "elementary" stimulus feature in the ACT* framework. The resulting simulation program would almost certainly be



a clumsy computational device, so one would hardly propose developing a working model for use in extensive simulations. The development of one or two simulations to test the extent of complementarity would be interesting exercise in theory development.

There are some minor discrepancies between the models that require brief comment. ACT* and the Production Activation model differ in the details of the algorithms that are used to execute various actions; e.g. to compute the spread of activation levels through the semantic network. Given the current state of knowledge concerning the simulation of cognitive action, the use of slightly different algorithms is a minor discrepancy. At some point, though, a theoretical justification should be offered for all algorithms used in a simulation. This point will be discussed again, in connection with McClelland's cascade model of information processing.

Finally, ACT* is programmed in LISP, while the Production Activation Model has been programmed in PASCAL. This discrepancy is purely a technical one, and has no psychological significance whatsoever.

## Cascade models of pattern recognition

In the Production Activation model processes associated with the selection of a production at one stage of information processing can begin before the completion of processing at prior stages. For example, if a visual stimulus is presented the activation of relevant visual patterns can feed activation forward to semantic patterns, before any production breaks through the visual bottleneck point to be executed. This contrasts with *serial models* of information processing, which require the completion of analyses at one stage before a subsequent stage can begin. McClelland (1979) coined the term "Cascade Processing" to refer to models which have this characteristic. He presented a detailed description of a particular class of cascade models. Subsequently, Rumelhart and McClelland (1982) used the cascade model as the basis for a simulation of visual word recognition.

In McClelland's cascade model, concepts in memory are represented by nodes that vary in their level of activation. The nodes in a network are divided into subsets ("levels"). Connections between nodes on the same level are predominately inhibitory, while connections between nodes in different levels are generally



facilatory. This is exactly the scheme used to connect the nodes representing "semantic", "visual", and "auditory" patterns in the Production Activation Model (3). Therefore the networks used in the Production Activation Model could be thought of as specific examples of the cascade networks that McClelland describes.

McClelland's models have been applied to the simulation of word recognition of words (Rumelhart and McClelland, 1982; McClelland and Rumelhart, 1981). In these studies the process of recognition begins with the identification of very simple visual features, such as horizontal or vertical line segments, and word and letter recognition is derived. In the Production Activation studies stimulus recognition at the word level is asserted as a primitive process. It would be possible to regard McClelland's work as an analysis of how activation is spread from level to level, and the Production Activation studies as analyses of the consequence of that spread. The same view could be taken of the relation between McClelland's work and Anderson's.

McClelland's models deal only with pattern recognition and memory arousal. In the terminology of the Production Activation model, cascade processing is a mechanism that could be used to produce automatic responding. The cascade model does not deal with mechanisms for controlled responding.

There is one conflict between McClelland's models and the models explored within the Production Activation framework. In McClelland's model the spread of activation from node to node is controlled by an algorithm that has the desireable property of limiting the maximum activation level of any node to a pre-established asymptotic value. The algorithm used in the Production Activation model could, in theory, produce an arbitrarily high level of activation at any one node. While this situation has not been encountered in practice, its possibility is bothersome because the potential for a limitless activation level seems unrealistic. A few attempts have been made to reproduce the simulations reported here, using McClelland's algorithm for spreading activation through the network. In none of the cases studied did the model's behavior resemble human data. Interestingly, Anderson (1983b) reports similar results when McClelland's algorithm was incorporated into ACT*. Given the success of the algorithm in simulating the data from stimulus recognition situations, its failure in these simulations is puzzling. Solving this puzzle would be a useful study



in the mathematical analysis of psychological theories.

The CHARM Model

Eich (1982) has developed a "Composite Holographic Association and Retrieval Model", hence the acronym. In the CHARM model a stimulus is a vector of feature strengths. Associations between two stimuli are established by storing the convolution of the two stimulus vectors. Storing the convolution of stimulus vectors produces an information storage system similar to the "memory" displayed by a holograph, which stores the convolution of the light spectra falling on it from different sources. Eich has shown that the information contained in the convolution may be combined with information in a probe stimulus (i.e. a recall cue) to reconstruct the original stimulus.

Eich's model does not contain a production system stage, which is not surprising since the model has been presented solely as a model of memory. CHARM is discussed here because it could be incorporated into the Production Activation Model as an explanation of the pattern recognition process that is a primitive in the Production Activation model. In the model specified here stimuli are recognized by a computing the similarity between the stimulus complex and the pattern recognition part of a production. Similarity is defined to be a weighted sum of the resemblance between features of the stimulus and features of the pattern. How the pattern came to be in long term memory is a problem outside of the scope of the model. Eich's proposal provides motivation for an alternative model, in which each pattern is a record of the convolutions of the stimulus-stimulus sequences that the system has experienced. If Eich's model were to be incorporated as the pattern recognition process for production activation, this would at once provide an elementary learning mechanism and offer a mechanism for pattern recognition that could be justified by appeal to supporting psychological studies, rather than to the assertion that it produces reasonable results.

While the idea of incorporating both the cascade processing and CHARM models within the Production Activation framework is a conceptually appealing one, the technical problems of incorporation should not be underestimated. Both the CHARM and cascade processing models require extensive numerical computation. The computational burdens of the Production Activation model itself are not trivial (4). The computational problem may



not be solvable without access to the very large, high speed array processing computers that are just now becoming available. The explorations of this class of psychological models may be well be limited by the computing power available to the researchers.

## Summary

The Production Activation Model incorporates two ideas; the use of a semantic network to activate concepts held in long term memory and the use of *production systems* to manipulate information in working memory. The semantic network is seen as controlling automatic, highly overlearned responding. The working memory system determines slower, controlled responding based on decisions made about the current stimulus complex. The model has been used to construct simulations of human behavior in a variety of paradigms in which people must choose quickly between possible interpretations of the stimulus, monitor two stimulus channels for relevant information, or respond to one channel while ignoring another. The success of the simulations indicates that the model has considerable breadth of applicaton.

The logical relation between the Production

Activation Model and other models of memory and attention was considered. The Production Activation Model deals with processes more molecular than those described in Anderson's ACT*. As a conjecture, we believe that the principle features of ACT* could be reprogrammed as a special case of the Production Activation model. In turn, McClelland's models of cascade processing and Eich's CHARM model of memory can be thought of as models for processes that are treated as primitive actions in the Production Activation Model.

Mathematical models of psychological phenomena have been criticized for being elaborate models of highly specialized laboratory paradigms. The work reported here partially refutes such a claim. What has been shown is that there is considerable compatability between the ideas used in the analysis of such disparate situations as two choice reaction time experiments and the analysis of protocols taken from master chess players. A great deal of further theoretical work remains to be done to explore various areas of compatability and incompatability. Some aspects of the further work will require extensive computing facilities in order to conduct the necessary simuations. Nevertheless, we are encouraged at the prospects for development of psychological theories that



are at once broad and precise.

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Author's Notes

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1. Anderson's data flow networks contain nodes that can compute logical functions of their inputs. See, for instance, the example provided in Anderson, 1983b, pg. 139-145. Given this much computing power, it is not clear that there are any limits to data flow networks other than those that apply to Turing machines. In more psychological terms, ACT* provides no principles to limit the complexity of patterns that can be recognized directly.

2. Anderson (1983b) has sketched ways in which ACT* might be applied to pattern recognition and attention and performance paradigms similar to those studied

here. His detailed studies, however, have been of much more complex situations involving learning, problem solving, and long term memory retrieval (Anderson, 1983a,b).

3. The organization of nodes in the Production System Model was based on earlier work by Hunt (1967). McClelland's (1979) detailed analysis of cascade models represents the parallel evolution of a similar idea. The general concept of lateral inhibition coupled with positive feed forward circuits also appears in a number of other proposals for mathematical models of biological information processing.

4. The simulations reported in this article required several hours of central processor time on a VAX 780 computing system. This does not include time for program development or for exploratory computations.



Figure Captions

Figure 1. A schematic of the architecture of the production-activation model.

Figure 2. The semantic network used to connect productions in simulating a two-choice reaction time study. V[x] is the rule "if visual stimulus x is recognized, create semantic stimulus S[x]." S[x] is the rule "if semantic stimulus x is present make response x."

Figure 3. A simulation of Hick's law. Reaction time increases logarithmically with the number of alternatives in the model. Human data from Taylor's (1982) study shows a similar relation.

Figure 4. Reaction time and accuracy are both increased by increasing the DELTA paramenter. This mimics the negative speed-accuracy relation.

Figure 5. Reaction time increases and accuracy decreases if noise is added to the system internally (Figure 5a) or if the similarity between stimuli is increased (Figure 5b).

*Figure 6.* Responding to repetitive stimuli (AAAA) of alternating sequences (ABAB) as a function of the position of the sitimulus in a sequence. Panel A shows data from the model. Panel B shows data from Kirby's (1976) study. Data is shown for short RSI conditions.

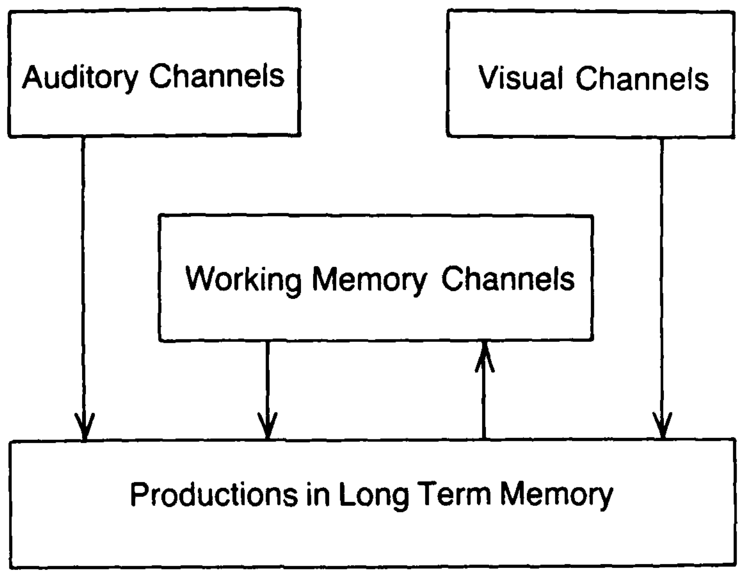
*Figure 7.* Responding to repetitive stimuli (AAAA) or alternating sequences (ABAB) as a function of the position of the stimulus in a sequence. Panel A shows data from the model. Panel B shows data from Kirby's (1976) study. Data is shown for long RSI conditions.

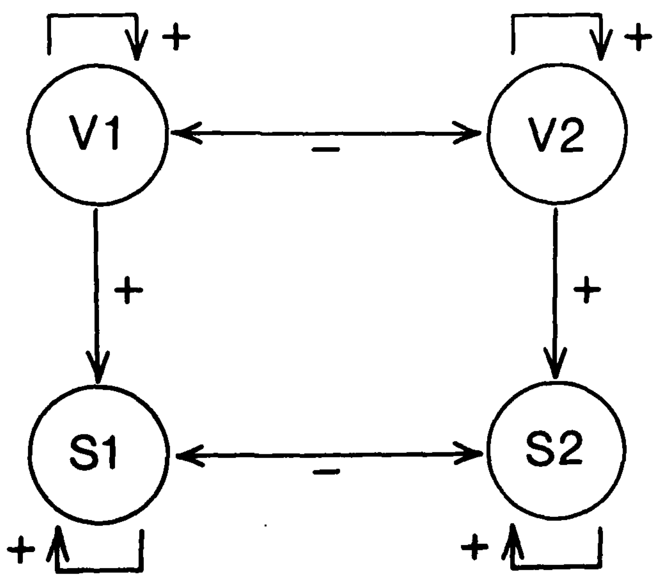
*Figure 8.* The semantic activation network used to simulate the simultaneous monitoring visual channels.

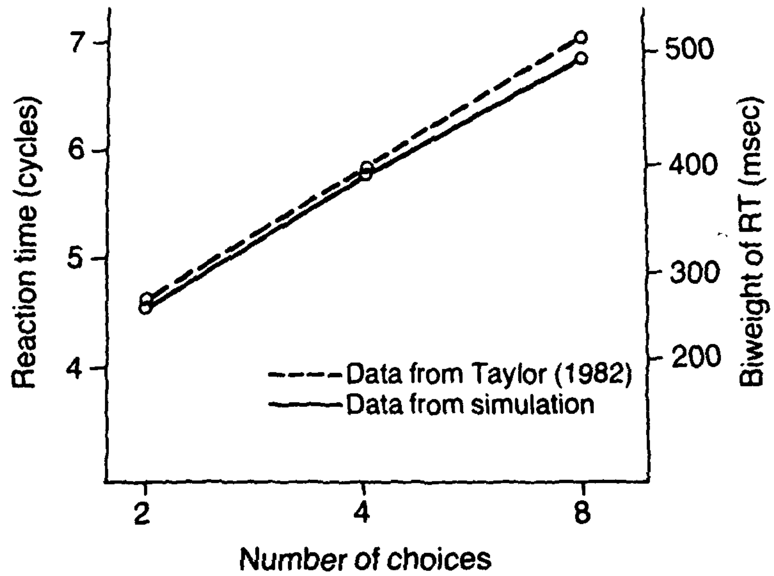
*Figure 9.* The performance operating characteristic for monitoring two channels. Squares are data produced by the model. Triangles are data replotted from Kinchla's (1980) study.

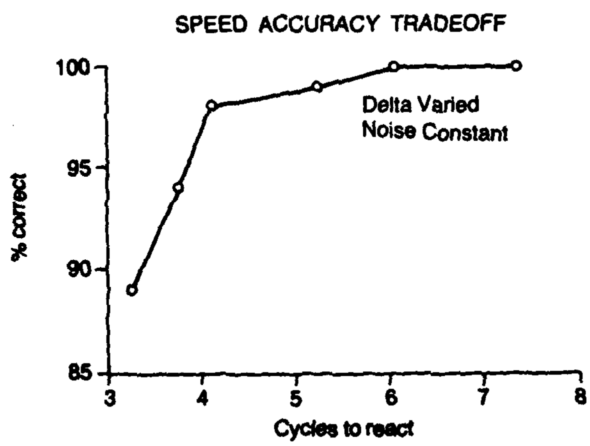
*Figure 10.* The semantic network used to simulate stroop phenomena.

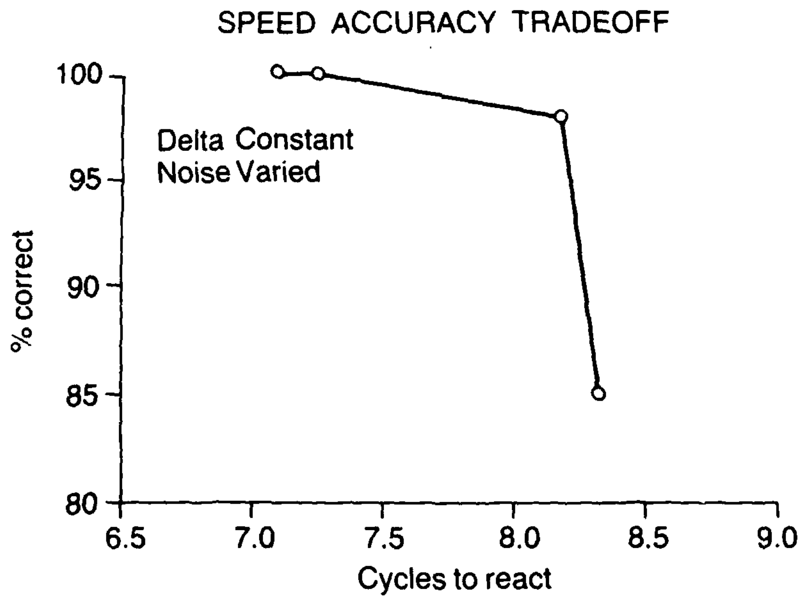
*Figure 11.* Time to react as a function of conditions in standard stroop paradigm.

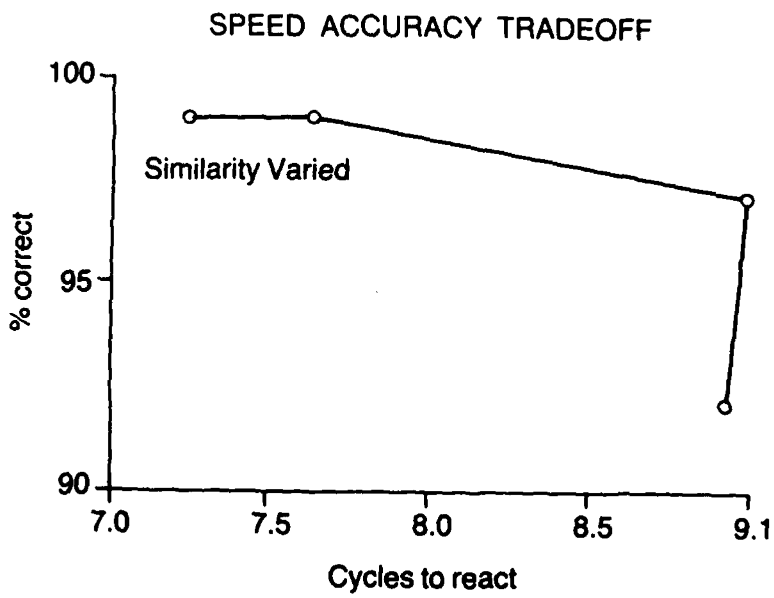

Auditory Channels
Visual Channels
Working Memory Channels
Productions in Long Term Memory

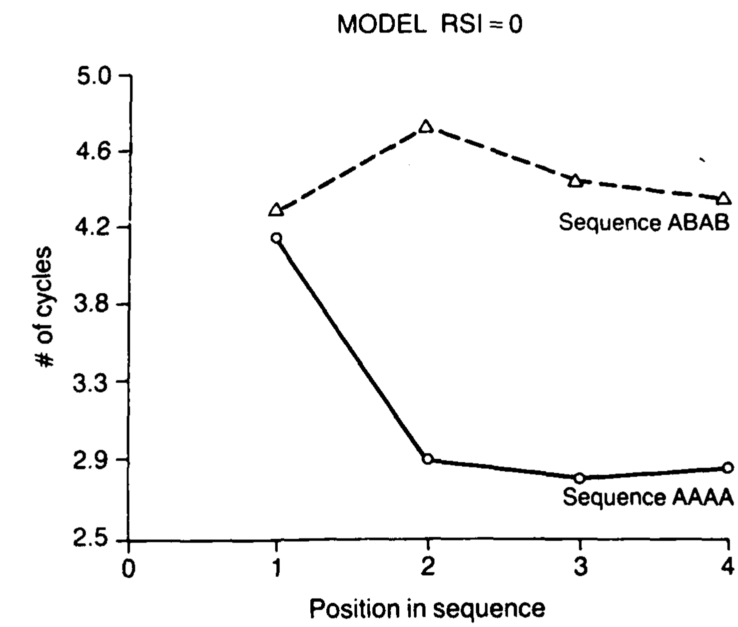

V1
V2
S1
S2
+
–

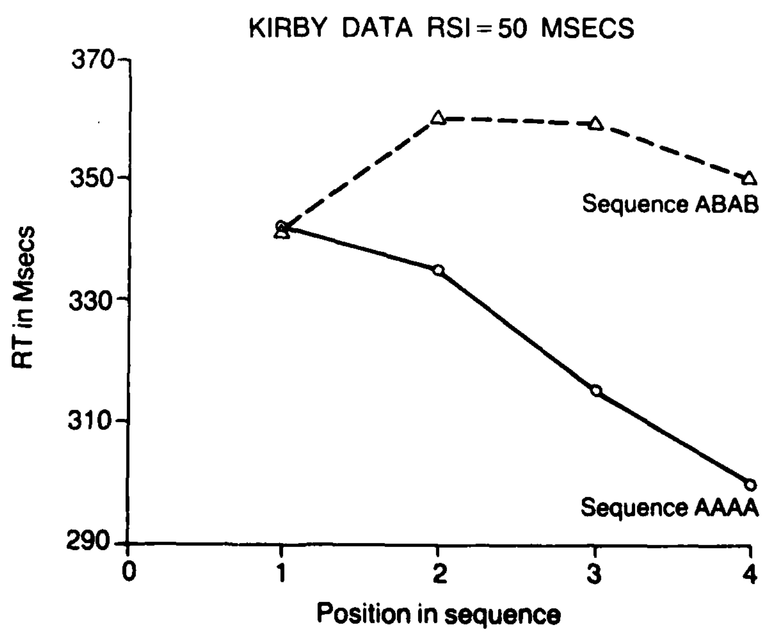

Reaction time (cycles)
Biweight of RT (msec)
Data from Taylor (1982)
Data from simulation
Number of choices

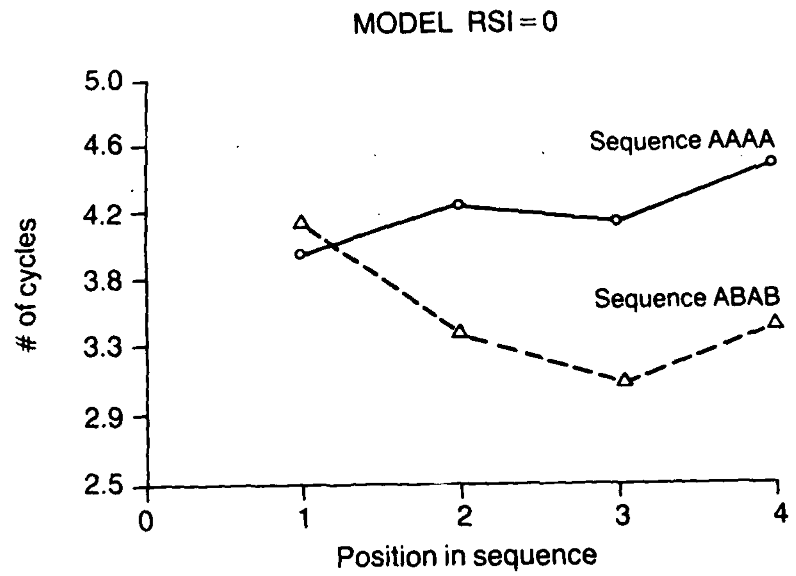

SPEED ACCURACY TRADEOFF
Delta Varied
Noise Constant
% correct
Cycles to react

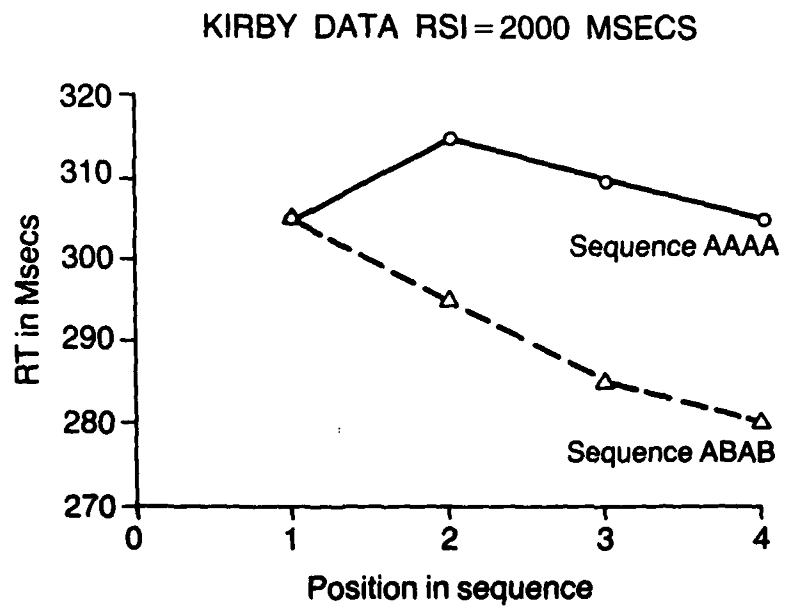

SPEED ACCURACY TRADEOFF
100
95
90
85
80
% correct
Delta Constant
Noise Varied
6.5
7.0
7.5
8.0
8.5
9.0
Cycles to react

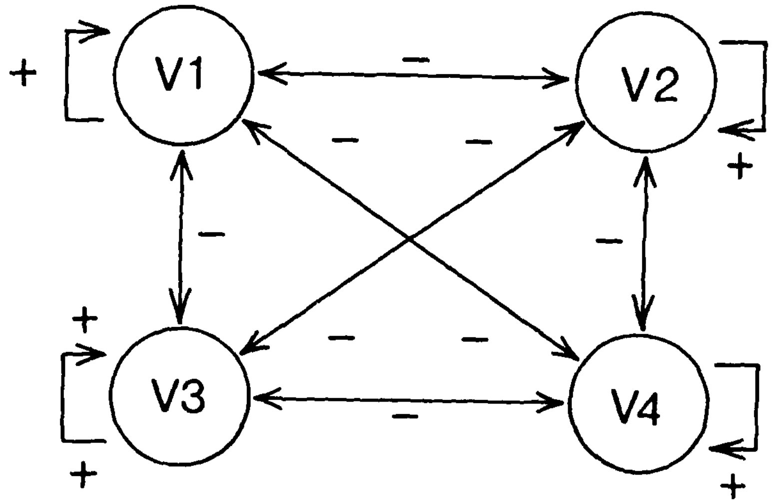

SPEED ACCURACY TRADEOFF
100
95
90
% correct
Similarity Varied
7.0
7.5
8.0
8.5
9.1
Cycles to react


MODEL RSI = 0
5.0
4.6
4.2
3.8
3.3
2.9
2.5
# of cycles
Sequence ABAB
Sequence AAAA
0
1
2
3
4
Position in sequence

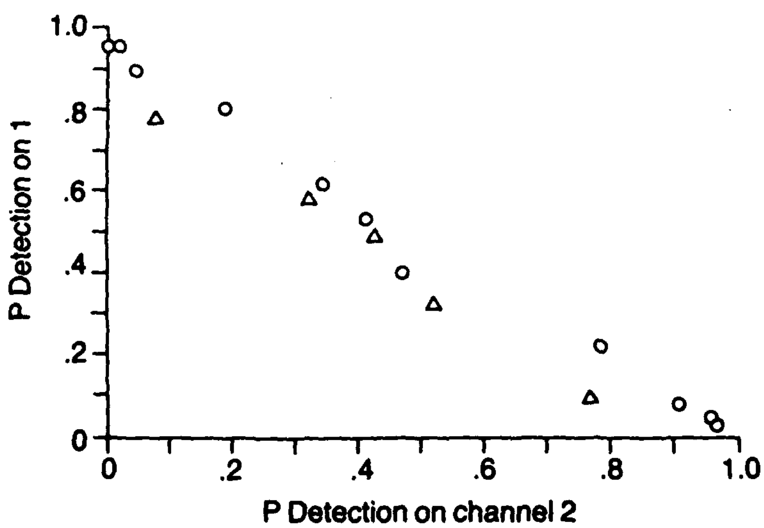

KIRBY DATA RSI = 50 MSECS
370
350
330
310
290
RT in Msecs
Sequence ABAB
Sequence AAAA
0
1
2
3
4
Position in sequence

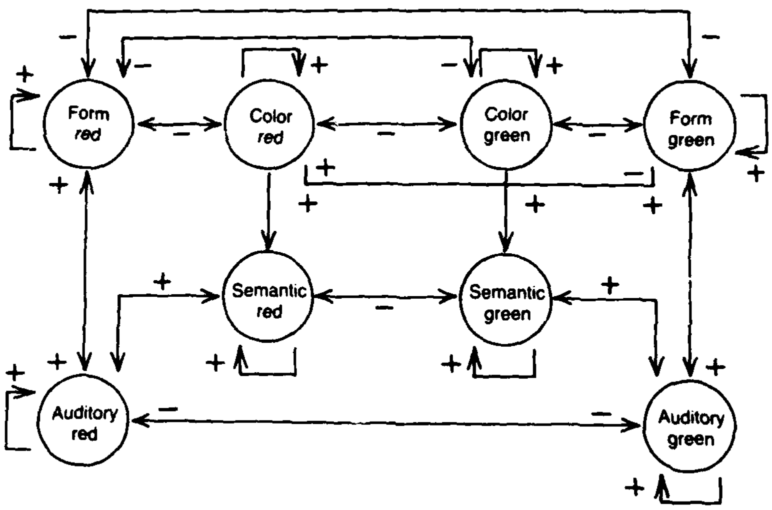

MODEL RSI=0
5.0
4.6
4.2
3.8
3.3
2.9
2.5
# of cycles
Sequence AAAA
Sequence ABAB
0
1
2
3
4
Position in sequence


KIRBY DATA RSI=2000 MSECS
320
310
300
290
280
270
RT in Msecs
Sequence AAAA
Sequence ABAB
0
1
2
3
4
Position in sequence




POC FOR DUAL VISUAL DETECTION




Form red
Color red
Color green
Form green
Semantic red
Semantic green
Auditory red
Auditory green

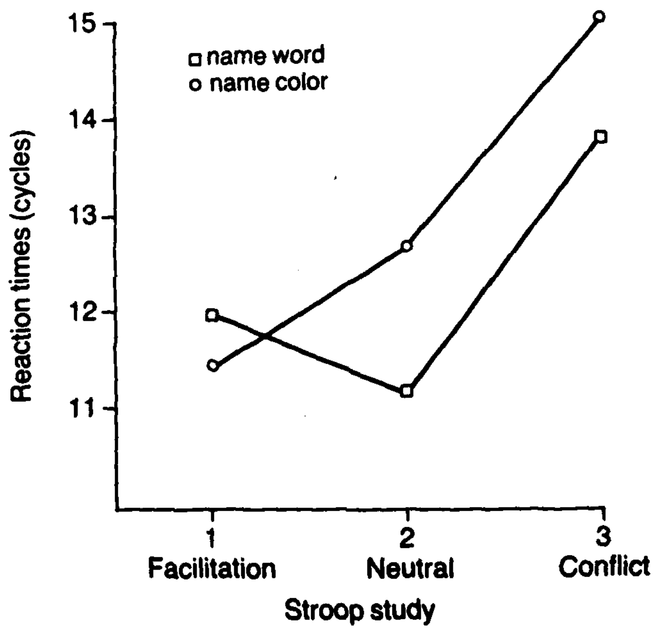

name word
name color
Reaction times (cycles)
15
14
13
12
11
1
Facilitation
2
Neutral
3
Conflict
Stroop study

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Table 1

1. If S1 is on channel 1 -> do nothing
2. If S2 is on channel 1 -> Mark "target"
3. If S1 is on channel 2 -> do nothing
4. If S2 is on channel 2 -> Mark "target"

Production System for Visual Monitoring Study

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Table 2

Visual Productions

If the instructions are to respond to the word and the word is RED then -->

Generate semantic code <u>red</u> .

If the instructions are to respond to the word and the word is GREEN then -->

Generate semantic code <u>green</u> .

If the instructions are to respond to the color and the color is red then -->

Generate semantic code <u>red</u> .

If the instructions are to respond to the color and the color is green then -->

Generate semantic code <u>green</u> .

Table 2 (continued)

Semantic Productions

If the semantic code is <u>red</u> then -->
Generate auditory code /red/.

If the semantic code is <u>green</u> then -->
Generate auditory code /green/.

Auditory Productions

If the auditory code is /red/ then -->
Make external response "red."

If the auditory code is /green/ then -->
Make external response "green."

Productions used to simulate Stroop Task.

END

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