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ABSTRACT
        A model of how automated and controlled processing
can be mixed in computer simulations of problem solving is proposed.
It is based on previous work by Hunt and Lansman (1983), who
developed a model of problem solving that could reproduce the data
obtained with several attention and performance paradigms, extending
production-system notation to time-constrained problem solving. Four
college students were required to do mental arithmetic rapidly,
keeping track of the running total of a visually presented series of
numbers using base three (to keep the task from being fully
automated). From time to time, they had to deal with an interruption
and then return to the arithmetic task. The students generally, but
not always, managed to remember the things they needed to remember,
and often became aware of an error after making it, indicating there
was a good deal of self-monitoring of behavior. The problem solver's
internal control of information seems to be an essential part of
real-time problem solving. These processes were reflected in the
simulation model, which is described in detail. (MNS)

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The computer science concept of production execution has been the basis of a large number of simulations of human problem solving. Typically these simulations have operated in a timeless environment, in the sense that they did not consider any constraints to solve problems quickly. In a previous technical report in this series Hunt and Lansman proposed an architecture for production-executing machines that could be applied to real-time problem solving. Hunt and Lansman supported their ideas by simulating data from laboratory studies
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drawn from the attention and performance field. In this paper Hunt and Lansman's approach is extended to the simulation of people doing a simple arithmetic task under considerable time pressure and when subject to interruptions. Data from the simulation is compared to data from college students doing the same task.

PROBLEM SOLVING UNDER TIME-CONSTRAINTS

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INTRODUCTION

Problem solving sometimes takes place under severe real-time constraints. Consider the problem of an automobile driver approaching an intersection. If the light is either red or green a highly overlearned response is appropriate. Little in the way of problem solving is required. If the light is yellow a decision must be made. The decision is based on several variables; the distance to the intersection, the speed of the auto, the speed and distance of any following auto, and perhaps its identity (e.g. is the following auto a police car?) A good bit of reasoning has to be completed, quickly, or the driver is likely to have a brief and unhappy career.

How is it that people perform such tasks quickly and, for the experienced, with very few errors? Saying that skilled performance is 'automatized' is unsatisfactory. To be sure, in many cases real-time performance is fast and accurate, a critical _descriptive_ attribute of automated behavior (Schneider and Shiffrin, 1977.) However a crucial precondition, consistent mapping between stimulus and response, is often not met. Consider again the driving example. When people drive in heavy traffic without accidents, they continually face new and complex situations. Furthermore, it is clear both from intuition and experimental results (Brown and Polton, 1961) that driving diverts attention from other ongoing activities. By definition, this means that the behavior is not automated.

The driving example is an illustration of a more general issue. Time-constrained problem solving depends upon a mixing of controlled and automatic processes. The mixing must take place rapidly enough to keep up with real-world demands on the problem solver. However, most computer simulations of problem solving do not consider the influence of real-time constraints on thought.

"Reaction time" studies are more traditionally assigned to the attention and performance field. Which aspects of the processing are automated? What are the control mechanisms and under what conditions is control exercised?

Here we present a model of how automated and controlled processing can be mixed. The model is based on previous work by Hunt and Lansman (1983), who proposed a model of problem solving that could reproduce the data obtained with several attention and performance paradigms. Their model is an extension of the widely used production-system notation to time-constrained problem solving. A production-system model of a task can be divided into two distinct components. One is the set of productions that are used to specify actions in the task itself. These will be specific to a given situation. The other component is the set of mechanisms that control production execution. A good analogy is to regard the productions used in a simulation as a program to model task specific behavior and to regard the mechanisms of production execution as a model of the content-free information processing mechanisms that must underlie all thought. Following Pylyshyn (1984), we shall use the term "functional architecture" to refer to the information processing mechanisms collectively.

What Hunt and Lansman did was to develop a functional architecture for production execution that was based upon models that have been proposed to explain "attention and performance" phenomena, such as dichotic listening, Hick's law, and response choice in the face of conflicting cues. Hunt and Lansman then used this architecture to execute a number of simple production systems, corresponding to a participant's understanding of the instructions that might be given in a variety of attention and performance tasks. The time required to execute the production system program was produced by an interaction between the logic of the production system and the mechanisms of the functional architecture, which was constant across tasks. Hunt and Lansman showed that the interaction could mimic human data in fairly simple laboratory tasks, including choice reaction time paradigms, a divided attention task, and a simple version of the Stroop paradigm. They suggested that the same approach could be applied to understand real time problem solving in more complex situations, but they did not carry their work to the point of simulating the more complex situtations.

This paper reports an extension of Hunt and Lansman's model to a situation in which people must do mental

arithmetic rapidly. In addition, the participants in our
work had to deal with a simple interrupting task. More
specifically, college students kept track of the running
total of a series of numbers. To keep the task from being
a fully automated one, we required that the total be kept
in base three (trinary) arithmetic. From time to time the
arithmetic task was interrupted. The participants had to
deal with the interruption and then return to the
arithmetic task. This situation was chosen as a
compromise between the extremely complex situations, such
as driving, that we would like to model and those tasks
that can be managed in a laboratory situation.

THE TASKS AND THE PARTICIPANT'S BEHAVIOR

Procedure

Participants were first trained to do Base 3
(Trinary) arithmetic. They were then given the task of
keeping a running total of a series of visually presented
trinary numbers. From time to time during the
presentation of the numbers to be added an auditory signal
was presented. The participant was to press a button in
response to the tone as soon as it was detected.

Three dependent variables were studied. These were
the speed and accuracy of the arithmetic responses and the
reaction to the tone.

Addition Task.

Subjects Four University of Washington undergraduate
students were recruited through advertisement. They were
paid for their time.

Training and instructions. Training included
memorization of the basic addition facts (e.g. 1 + 2 = 10)

and sufficient practice with both written and verbal
problems so that all participants achieved a perfect score
on a 120 item written test. The problems involved one to
four digit integers. Some of the problems required carries
across one or more columns.

The participants were instructed to do the problems
in trinary notation directly, rather than solving a
problem in decimal notation and then converting the
results to trinary notation. They were also instructed to
do multiple digit problems from right to left, one column
at a time. Both of these instructions were intended to
prevent subjects from adopting idiosyncratic methods for
particular addition problems. For example, during
training some subjects reported recalling from previous
trials the sum of 122 and 1 (i.e. 200) without
intermediate carrying from column to column. All
participants reported they had no difficulty in complying
with the instructions.

Participants were also instructed to emphasize both
speed and accuracy, that is, '...to respond as quickly as
possible but try not to make mistakes.'

Experimental procedures.   On each trial, the stimulus

digit (approximately 2.1 mm x 4 mm) was presented on a
video monitor located directly in front of the
participant, at a distance of approximately 75cm. The
persons's task was to maintain a running total of all
digits presented. As each digit was presented the
participant was to speak the new total into a microphone
located below the line of sight between the participant
and the monitor. The beginning of the verbal response
triggered a voice-onset key attached to the computer.
Three seconds after the onset of a verbal response (i.e.
approximately two seconds after its completion) the
computer presented the next number in the sequence. The
task continued for a total of twenty digit presentations.
Digits were selected at random, subject to the constraint
that the correct total for each sequence never be more
than 222 (i.e. three digits in length).

The Auditory Probe Task

Probe tones were presented during five randomly
selected trials in each sequence. The probe was a   130
HZ tone with a duration of 60 msec., presented 100 msec.
after onset of the visual stimulus. The participant
responded to the tone by pressing a button. Participants

11

12

were instructed to press the button before making a verbal response.

The participants were instructed to say 'stop' when they became aware of making an error. After stopping, they were asked to explain what the error was (e.g. forgetting to press the button, making an addition fact error). They then made a corrected response. Following the corrected response the remaining digits in the sequence were presented.

General description of behavior

Response latencies for experimental trials were generally between 300 and 2500 msec. and overall error rates were below 2 percent.

Perfect performances on the pretest and low error rates in experimental sessions demonstrated the subjects knew how to do the tasks. However, a number of different types of errors were observed. The following types of errors were considered:

1. Arithmetic fact errors. Even though the participants thoroughly learned the rules of addition for trinary arithmetic, they occasionally made errors,

just as most adults do with decimal arithmetic.

2. Speaking the stimulus digit rather than adding it to the running total. An example would be responding '2' to the second digit in the sequence 1, 2. Participants reported seeing the stimulus and speaking it without considering addition or the running total.

3. Not pushing the button in response to the probe. Frequently this error was not detected by the participants.

4. Pushing the button after making a verbal response. Participants reported that it was not a 'conscious' effort to correct for not pushing the button before the verbal response.

5. Forgetting the stimulus digit or the running total. Only one participant made this type of error and only when he interrupted himself to correct a previous error.

6. Carry errors, i.e. a failure to carry the 1 to the next column to the left and to do the appropriate addition. For completeness, we note that these errors are not the only errors that could be made. Hitch (1978) has reported more complex carry errors that cannot be distinguished from trinary arithmetic fact errors.

7. Transposition errors. Transposition errors (e.g. saying 221 when the correct response is 212)

are logically possible but we did not observe any.

The participants would often detect thei own errors as they made them. This will be called "error trapping."

To summarize, the participants generally, but not always, managed to remember the things they needed to remember. The fact that they often became aware of an error after making it indicates that there was a good deal of self monitoring of behavior. The problems solver's internal control of information seems to be an essential part of real-time problem solving. These processes were reflected in the simulation, which will now be described.

The Simulation

Terminology

As noted, the model consists of a set of productions that are executed by the functional architecture described by Hunt and Lansman (1983). The modified architecture will be described first. We then describe the productions that it executed.

Functional Architecture   The term 'functional architecture' refers, collectively, to mechanisms required for production selection and execution. The term will be used to include a specification of the major structural components of the system (e.g. the existence of input buffers and a working memory) and constraints on the nature and size of those components; and the nature of the pattern matching mechanism.(1)

The architecture consists of five structural components; an auditory input buffer , a visual input buffer , a motor input buffer , a working memory (WM) and a long term memory (LTM). The input buffers correspond to external sensory channels. They and the WM constitute a 'blackboard' area that contains the patterns that form an internal representation of the current situation. The WM is divided into five areas (or codes), semantic, visual, motor, auditory and a 'metacognitive' area. The LTM contains the productions that respond to patterns in each of the blackboard areas. Figure 1. shows the relation between components, and indicates permissible flows of information between them.

15   16

Fig. 1 here

The selection of the productions to be executed is
driven by the data in the blackboard area. The pattern
segment of each production is continuously compared with
the information in the input buffers and in WH. The extent
of agreement between a production's pattern and the data
on the blackboard determine the level of activation of the
production. Productions are also activated by spreading
activation from related productions. Thus the productions
can be thought of as being linked together in a semantic
network of associated concepts. Negative associations are
used when productions are logical alternatives to each
other (See Hunt and Lansman for a discussion of the
algorithms for pattern matching and the rules for linking
productions into a network). When a production's
activation level exceeds a threshold and is sufficiently
greater than the activation level of other productions the
action part of the production is executed.

The architecture used in this study modifies Hunt and
Lansman's system in three ways.

(a) In Hunt and Lansman's model information stayed
in a blackboard area unless it was specifically replaced.
In our model the 'clarity' of information in WH decays
over time unless it is explicitly refreshed. To represent
the decay, a decay rate parameter, $d(0>d>1)$ was associated
with WH. Instead of assuming that an object would be
matched (to some degree) to a pattern regardless of its
time in WH the match was computed with probability
$Pr(e|t)$ for an object that had been in WH for t cycles
without being refreshed. $Pr(e|t)$ was defined by the
equation $Pr(e|t) = (1-d)^t$, t=1,2,3 ... where t is the
number of discrete time cycles since the object was placed
in WH at time t=0.

(b) An additional motor code was added, with its own
buffer area and channel in WH.

(c) A metacognitive area was added to WH. The
productions responding to patterns appearing in this area
dealt with qualitatively different processes than those
responding to patterns in the other areas of WH. The
patterns in other areas represented actions needed to
solve the addition or the probe response task. The
patterns in the metacognitive area dealt with the system's
view of its own problem solving processes. As can be

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seen, this simulation contains two separate models for problem solving. 'One is a task model that is specific to the problem at hand; here either arithmetic or probe responding. The second is a model for monitoring problem solving actions.

we believe that this is characteristic of real time problem solving. The problem solver must be able to monitor where he (it) is in the problem solving process at any time.

The task model contains the following submodels:

1. An addition task submodel containing productions required for trinary addition.

2. An auditory probe task submodel containing the productions that recognize the probe tone.

3. An input/output submodel containing those productions that translate patterns from the sensory buffers into areas of WM, and those productions that translate certain patterns appearing in WM into external responses. These patterns will have been produced by the addition or auditory probe submodels or the metacognitive

error trapping submodel.

The metacognitive model contains:

1. An articulatory submodel containing productions that detect a need to rehearse information currently in WM. Rehearsal is accomplished by moving patterns into auditory WM, recognizing them, and then placing the product of pattern recognition back into a semantic WM area. These productions are used to simulate subvocal articulation.

2. A goal insertion submodel containing productions that insert goal patterns into the semantic area of WM. The goals are used to guide the   task model.

3. An error trapping submodel containing productions that identify specific errors, such as not pressing the button. These productions then produce patterns indicating the type of errors that are then output by the verbal output system.

Productions.

Although it is technically correct to think of our

20

19

simulation program as being a production system, the usual if-then notation of production systems do not capture adequately the important interactions between productions. To do this we use an abbreviated form of the dataflow graph notation presented by Sowa (1984).

Dataflow graphs.

A dataflow graph is a finite, connected, directed, bipartite graph with the following characteristics:

a. The nodes are partitioned into concept and actor nodes.

b. Arcs may connect concepts and actors, but arcs between concepts and concepts or actors and actors are not permitted.

c. An arc directed from a concept c to an actor a is termed an input arc of a and the concept c an input concept of a.

d. An arc directed from an actor a to a concept c is termed an output arc of a and the concept c an output concept of a.

e. An actor must have one or more input concepts and must have exactly one output concept.

f. A concept c may be an input concept for more than one actor.

To map from patterns and actions to concepts and actors, let patterns be represented by input concepts and actions by actors and output concepts.

The data flow graph illustrates how the productions relate to each other. This is shown in Figure 2, which illustrates some key features of the graphs. Concepts are drawn as rectangles, actors as diamonds, and the arrows on arcs indicate direction. This graph has two actors, nodes $a1$ and $a2$. These correspond to the action parts of two productions, $p1$ and $p2$. The concept nodes $c1$ and $c2$ correspond to the pattern part of production $p1$, and the concept nodes $c2$ and $c3$ correspond to the pattern part of production $p2$. An interpretation of this graph in terms of productions is that the action of production $p1$ is executed in response to the pattern consisting of concepts $c1$ and $c2$. Concept $c3$, resulting from the

action of production $p1$, together with concept $c2$
constitute the pattern of production $p2$, and concept $c4$
results from the action of production $p2$ being executed.

Figure 2 here

Concepts : Concepts are concatenations of primitive
features (symbols) that are either objects or labels.

a.   Objects . Objects are internal symbols that
correspond to physical stimuli. The objects we deal with
include:

   1. The trinary digits.

   2. The probe tone.

   3. Columns   These are the units 3s, 9s, and 27s
digit positions of a trinary integer.

   4. The (perception of the) fingerpress.

   5. The null object, i.e. the absence of an object.

Objects may be concatenated to form compound objects. For
example, the objects 2 and 1 concatenate to form the
object 21 . The only objects that will be compounded are
digits and columns. The occurence of an object symbol
(hereafter referred to as an object) in a blackboard area
can be interpreted as the occurence of a specific number
of a set. For example, the digit 2 is a member of the
set of integers . (as well as a member of the set of
numbers greater than zero etc.)

Labels . Labels are primitive features that are attached
to objects by the actions of specific actors, thus
assigning additional meaning to the objects to which they
are attached. In general, labels specify the cognitive
roles that the objects play in the task at hand. For
example, when the object 2 is labeled as an integer it is
identified as belonging to the set of integers, thus
enabling further processing specific to integers.

The labels used in the model are:
   1. Stimulus - classifies an object appearing in an
input buffer a stimulus.
   2. Integer - classifies a physical digit as a
number.

3. _Addend_ - classifies an integer digit as an addend. In order for an integer to serve as input for an addition process it must be classified as an addend.

4. _Total_ - classifies the integer output from an addition process as a sum.

5. _Carry_ - classifies 1 as the carry digit in an addition.

6. _Units_ - classifies a column or a single digit integer as being in the rightmost position in a multi-digit integer.

7. 3s - (see Units).

8. 9s - (see Units).

9. 27s - (see Units).(2)

10. _Zero_ - classifies an integer as zero. This label activates productions that deal with the number zero.

11. _Blank_ - classifies a column as blank (i.e. there is no integer labeled as belonging to that column).

12. _Not_ - may be combined with other labels to classify an object as not belonging to a particular set (e.g. Not Zero or Not Blank).

13. _Input_ - combined with a label that designates an input buffer (e.g. Auditory) to classify an object as input to the system.

14. _Output_ - combined with a label that designates an output system (e.g. Verbal) to designate an object for output (i.e. to be translated into an external response).

15. _Auditory_ - combined with the label Input, classifies an object as having appeared in the auditory buffer (i.e. as Auditory Input).

16. _Visual_ - (see Auditory).

17. _Somatic_ - (see Auditory).

18. _Verbal_ - combined with the label Output, classifies an object as verbal output (i.e. enables actors that will translate the object into an external verbal response).

19. _Manual_ - (see Verbal).

20. _Same_ - classifies two objects as belonging to

the same object type (e.g. if two objects are both labeled as the Units Integer then they might be labeled as Same).

21. **Different** - (see Same).

22. **Old** - when a total for the addition task has been output as an external verbal response that total is labeled Old to distinguish it from the New total that will be computed from the old total and a stimulus integer (see New).

23. **New** - when a new total has been computed for the addition task it is labeled as New. (see Old).

24. **Null Label** - absence of a label.

Actions The actions permitted to productions are:

a. **Label** - Attach one or more labels to one or more objects. For example, a particular actor labels the object 2 as an Integer. Labeling produces a refined definition of an object that may cue subsequent actors.

b. **Insert** - Place an object in an area of WM. For example, one of the 'arithmetic fact' actors recognizes

the pair of integer addends 1 and 1, and places object 2, labeled as a sum, in the semantic area of WM.

c. **Translate** - Move an object from an input buffer to an area of WM or from one area of WM to another. A translation from an input buffer to an area of WM retains the original sensory code of the object. Certain actors also translate objects from WM to external verbal and manual output systems. (These output systems are not further defined in our model).

Individual actors may act upon more than one object and may execute more than one of the three basic actions on the object(s). For example, the arithmetic fact actor that Inserts object 2 into the semantic area of WM also Labels that object as New and as Total (4).

Patterns, concepts, and the contents of the input buffers and WM.

Each blackboard area contains discrete primitive features, consisting of objects and their attached labels. An object and its labels must always be in the same blackboard area.

A **concept** consists of a concatenation of labels and

objects. A concept may contain one or more labels, with
or without the object to which the labels are attached, or
may contain an object, with or without the labels attached
to it.

A pattern consists of one or more concepts. The concepts
that make up a particular pattern must be in a single
blackbnard area.

For example, consider a situation in which the current
total is 1 and the digit 2 is shown. Once the stimulus
digit was recognized WM would contain the following
features:
    a. stimulus & integer & 2 & not zero.
    b. old & total & units & integer & 1 & not blank

These are instances of the concepts: (stimulus & integer &
not zero) and (old & total & units and not blank). Each
concept is defined in terms of the labels attached to a
single object in this example (but not generally) and
neither concept includes the object. The two concepts are
the input concepts (on the pattern) for an actor that
labels each object as an addend. After this actor
executes, the contents of the semantic area of WM would
be:

    a. stimulus & integer & 2 & not zero & addend
    b. old & total & units & integer & 1 & not blank &
    addend.

The augmented description would trigger the arithmetic
fact rule for adding 2 and 1.

Behavior of the Simulation

This section presents a dynamic description of the
simulation. First, the addition and auditory probe task
submodels will be presented, using block diagrams. Then,
a detailed walkthrough of a specific example will be
given, with the aid of a dataflow graph. Finally, we
describe the actions of the various "metacognitive"
submodels; articulation, goal insertion and error
trapping.

The Addition Submodel

Figure 3 provides an overview of the addition task
submodel.
    Block 1 . " Evaluate Input ": Input is 'sensed' by
the appearance of a (digit) object in the visual buffer.
The symbol is transferred into the visual area of WM. The

29

30

digit is labeled as an integer, and as a stimulus. It is
then translated into the semantic area of WM, where it is
labeled as zero or not zero. Each transfer or labeling is
achieved by production selection and execution.

This is the point at which the first of several
possible errors may occur. The productions that can
cause it to 'speak' the name of a digit may be activated
instead of those that deal with the digit as an addend.
Looked at another way, enroute to creating the addend
pattern the system comes close to creating patterns that
trigger the speaking actions of block 3 of Figure 3.

Block 2. Labeling : The old total is labeled as blank
or not blank. Based on this information and whether the
stimulus is zero or not a decision is made either: to
label the stimulus as verbal output (Block 3), to label
the old total as verbal output (Block 3) or to add the
stimulus and the old total to form a new total (Block 5).
The last decision is the most interesting case, so it will
be considered first.

Block 5. Adding : The stimulus and the unit column
digits are labeled as addends. The sum of the two digits

is inserted in the semantic area of WM and labeled as the
new units integer. If a carry is necessary, and the next
column (3s column) is labeled as blank or not blank, the
integer 1 is labeled as the 3s integer and the 3s column
is then labeled as not blank. If the 3s column is already
labeled as not blank, then the 3s column integer and the
carry integer (i.e. 1) are labeled as addends. The sum of
these two digits is inserted in the semantic area of WM
and labeled as the new 3s integer. The labeling and
insertion process continues across columns, until the
addition process is completed and a new total is formed.
(Note that columns to the left of the units column are not
processed unless there is a carry.)

Block 6. Output The new total is labeled for output
as a verbal response.

The output label activates the productions. Control
is in Step 7, where a verbal response is created. Note
that Step 7 may be activated by any of several prior
steps.

Fig. 3 here

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The Auditory Probe Submodel

Figure 4 is a block diagram that represents the
auditory probe task submodel.

__Block 1 Recognition.__ When a tone appears in the
auditory buffer it is translated into the auditory area of
WM. There it is labeled as the stimulus tone and
translated into the semantic area of WM.

__Block 2.__ When the tone is recognized in semantic WM
the fingerpress object is inserted in semantic WM as a
goal and labeled as a manual response output.

__Block 3 Response Production.__ When a stimulus in
semantic WM is labeled as an output the external manual
response is made.

Fig. 4 here

An Illustrative Example .

Figure 5 displays parts of a dataflow graph
summarizing the action of the addition task submodel for a
single trial. Suppose that the old total is 12 (Decimal 5)
and the digit 1 appears. The following actions will take
place. The number or letter in parentheses before each
comment locates the action in the graph of Figure 5.

(1) The object 1, labeled as a stimulus integer is
translated from the visual to the semantic area of WM.

(2) Actor 2 labels the stimulus integer 1 as not
zero.

(3) The old total integer (for this example 12) is
not blank.

(4) Because the stimulus integer is not zero, and the
old total is not blank Actor 4 labels the stimulus integer
and the units integer of the old total as addends. The
trinary addition '1 + 2' is to be performed.

(5) Actor (5), an arithmetic fact, carries out the
addition. Note that actor 5 has objects labeled as
addends as its input concept. The object 0 is placed in WM
labeled as an integer total, and the object 1 is placed in
WM, labeled as a carry integer. .

(6) The old 3s column is not blank, as the old total
is 12.

(7) Because the stimulus integer and units integer
have been labeled as addends, and there is a carry integer
and the 3s column is not blank, actor (7) labels the carry
integer (i.e. 1) and the 3s integer (i.e.1) as addends.

(8) Actor (8), an arithmetic fact, carries out the
addition and inserts object 2 in semantic WM as an integer
and new column total (in this case the 3s column). Note
that there is no carry integer.

(9) Because the 9s column and 27s column are blank,
and there is no carry integer, actor (9) labels the column
totals 2 (i.e. 3s) and 0 (i.e. units) as the new total,
and labels them as verbal output.

                                    Fig. 5 here

The Metacognitive Behavior .

The metacognitive model is a set of procedures that
monitor the performance of the other models. Three types
of data are monitored. These are the quality of data in
working memory, the progress of each task model toward its
problem solving goals, and the existence of conditions in
WM indicating that an error has occurred. The model
itself is divided into three submodels, each of which

accomplishes one of these functions.

The articulatory submodel : This submodel contains
processes that protect the information in WM against
decay. The submodel contains actors that translate
objects from semantic area to the auditory area of WM and
back again. The action of translating has the effect of
refreshing the object, by inserting a fresh copy into WM.
The actors that translate from semantic to auditory are
triggered by an object's being in the semantic area for
some time without being acted upon (i.e. Labeled or
Translated).

The goal insertion submodel : Actors in this submodel
insert goals into the semantic area of WM. The goals are
concepts consisting of a null object and various labels
that, collectively, represent a desired future state. The
goal would be attained if the labels could be attached to
an object. The goal insertion actors execute after an
object(s) has been in the semantic area for some time and
usually has been refreshed (translated) by the
articulatory actors one or more times without otherwise
being acted upon. (This condition arises if processing on
a task is stalled). For example, suppose that the
stimulus integer and the units integer are both labeled as

addends and have been so labeled some time. After these
objects have been translated by the articulatory submodel
actors one or more times a goal insertion actor may insert
a null object labeled as a 'new column total' into the
semantic area.

The execution of the goal insertion actors raises the
activation level of the relevant task submodel actors as a
result of their linkages in the association network. This
guides processing toward satisfaction of the appropriate
goal.

Error trapping submodel . Various actors in this Submodel
identify errors (i.e. patterns consisting of incorrect
sets of labeled objects), label the objects as errors, and
make a verbal response that identifies the error. For
example, if a tone, labeled as the auditory probe, is in
the semantic area of WM, and an integer, labeled as a new
total and as auditory input, (i.e. the new total has been
spoken and is heard) is in WM, but there is no
fingerpress, labeled as motor input, (i.e. the key pressed
and the motor response felt) in the semantic area, then
the simulation "knows", in effect, that a verbal response
was made before responding to the auditory probe, which is
an error. This condition is the input pattern for an

actor that identifies the error.

Comparison to Human Data

To evaluate the success of the model in accounting
for the particpants' performance we compared both
qualitative and quantitative aspects of human behavior to
the simulation program's behavior. The simulation can
clearly perform the addition and probe response tasks.

Depending on the value of the internal parameters the
simulation can produce all seven of the error types
described earlier. We have not explored settings that
produce carry and transposition errors, as these do not
appear in our data. Table 1 lists the error types, the
observed frequencies for our participants, whether or not
the error type was trapped by participants, and the
mechanisms in the model that produce each error type. The
model is also able to trap all the error types trapped by
the participants.

                                       Table 1 here

Comparing reaction time data provides a more

37

quantitative contrast between the model and the human
date. Two typos of responses can be made, additions and
key press responses to the probe and signal. Table 2 lists
each particpant's median reaction times to addition
problems under four conditions: when a probe was present
and not present, and when a carry operation was and was
not required. The table also lists the median reaction
times for responses to the probe tone when the concurrent
addition trial did or did not require a carry.

The table also shows the number of discrete time
cycels the simulation required to make the same responses.
The simulation's responses also have to be averaged
because there is some variation due to internal noise in
the system.

Table 2 here

In order to facilitate a comparison between the
simulated and actual data all data were converted to times
(or cycles) rolative to the time required to respond to a
probe while doing an addition without a carry. This was
the quickest response for both the simulation and the
human subjects. The resoaled numbers are shown in Table

3. The simulation generally did a good job of predicting
the relative reaction times for each of the six
conditions.

Table 3 here

40

39

A. No error producing productions were used. This
is a contrast to the work of Brown and Burton (e.g. Brown
and Burton, 1977), who explicitly used 'buggy' productions
to model children's arithmetic errors. We assumed that
our adult subjects knew how to do the experimental tasks.
Thus we are forced to conclude that errors arise from the
misapplication of correctly formed productions. The
errors that our model permits arise from the mechanisms
listed in Table 1. As we have noted, these are sufficient
to produce all errors that were observed.

B. The complexity of the productions that we used
was severely constrained.

1. Decisions that direct the behavior of the
system were made by the interaction of productions rather
than by the action of individual productions. For
example, the decision to make an arithmetic response by
naming the stimulus integer, the old total or with a new
total was made by the actions of the several productions
that determine if the stimulus was zero, if the old total

was blank, and so forth.

2. The patterns that initiate productions were
relatively simple, compared to those used in other
simulations (e.g. Anderson, 1983). The most complex
patterns that occur in our model are those used by the
productions that trap errors. These do not require more
than four concepts in a single pattern.

3. Patterns were constructed from a small set of
primitive features. This is widely accepted as a
requirement for production system models (Newell, 1980).
The sharing of features across concepts and patterns and
the possibility of confusion arising from
misidentification of them is a basic mechanism in our
model for producing errors.

4. The actions taken by productions were simple and
limited in number.

5. There was no branching within individual
productions. At least two versions of this constraint are
possible. The weak version constrains a production to
take a similar action on any set of target objects (e.g.
doubling single digit integers). The resulting output
then varies with the input. Such a production,
instantiating a nontrivial function, must not only match a
pattern but also distinguish between inputs. The strong
version of the no branching constraint requires individual

productions to produce invariant output.

We adopted the stronger constraint. This leads to a significant difference between our model and John Anderson's ACT* model (1983), which utilizes local variables and thus follows the weak constraint. In this respect our model is like that of McClelland and Rumelhart (1981).

C. Patterns and actions were all object-oriented. This constraint limits the denotational power of productions by requiring a physical object reference for abstract concepts (e.g. the concept that an integer is not zero).

D. Goals were structured and processed in a fashion similar to other concepts. In our model goals are concepts constructed from the same primitive features as other concepts and processed in the same way. As a result, the model is entirely data-driven at the level of individual productions.

Significance.   In the course of our work we found several ways in which the architecture of the original Hunt and Lansman model was insufficient for the job of modeling the complex real-time problem solving studied here. We have modified the architecture in the ways described earlier.

As in any simulation, some aspects of the present model are obviously tied to the particular arithmetic and probe tasks we have studied. These specializations are in the production systems, and are of little general importance. The effects of the restrictions on production system design are more interesting. We have shown that a relatively complex real-time task can be modeled by a production system mechanism that conforms to a substantial number of constraints. The major importance of this work is that it provides a further link between the 'time-less' problem solving studied in most simulations of cognition and the highly simplified, but tightly time bound, situations used to develop models of human information processing.

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43

44

Footnotes

1.   Our use of the term functional architecture is similar
to Anderson's usage (1983) and somewhat more limited than
Pylyshyn's (1984).   Pylyshyn's usage includes general
characteristics of productions such as constraints on the
kinds of actions that productions can execute and what
counts as a semantic primitive (i.e. pattern feature).
Although we would concur with Pylyshyn that such things
are properly 'architectural' our exposition of the model
is simplified if we present them in our discussion of
Productions (section III B) and in our general discussion
(section VI A) rather than as part of the functional
architecture.

2.   The longest correct total for the experimental task
was three digits. Occasionally subjects made errors that
led to four digit responses (i.e. an integer in the 27s
column).

3.   This seems to permit very powerful actors in the
model, but is necessary for keeping the simulation within
practical computing limits.   Each actor that executes more

than one basic action or acts on more than one object
could be replaced by separate actors each executing only
one basic action and acting on a single object, without
affecting the logic of the simulation.

4.   We would like to compare the relative frequency of
each error type for the simulation with the frequencies
produced by participants, however, the partipants' overall
error rate was less than two percent and such a comparison
would require several thousand trials for the simulation.
This would be prohibitively expensive in computing costs.
For example, to run a total of 3200 trials as our four
subjects did would require over 80 hours of system
operating time on the VAX/780 that we used for the
simulation.

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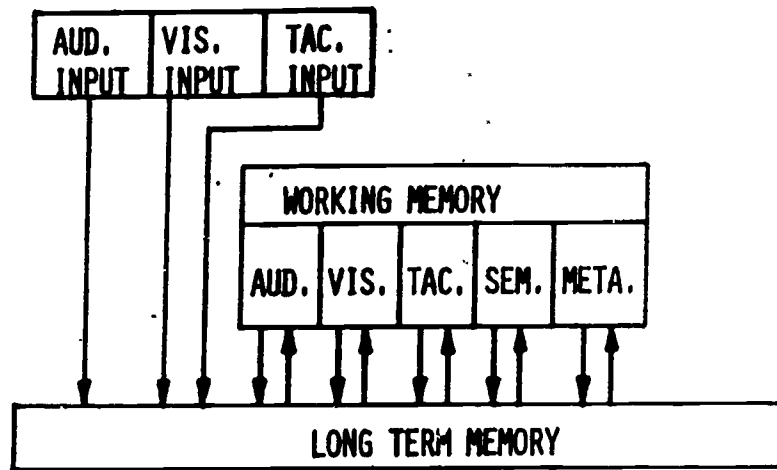Sowa, J.S. (1984) Conceptual structures: Information processing in mind and machine. Reading, MA: Addison-Wesley Company.
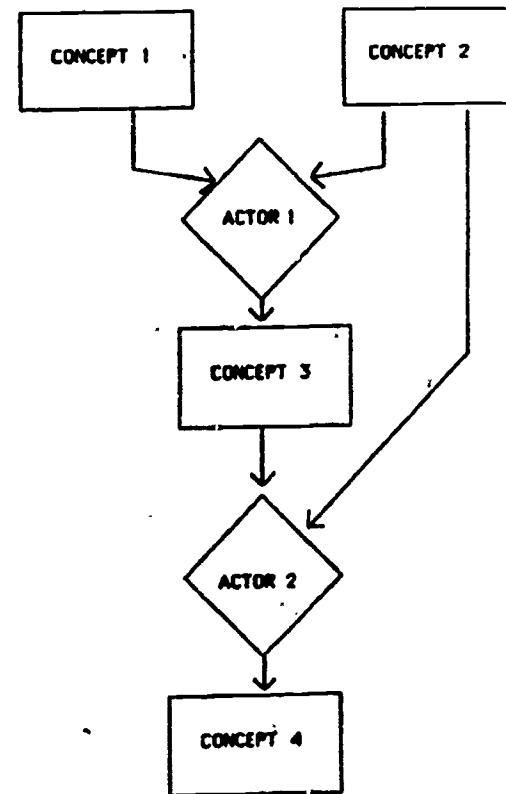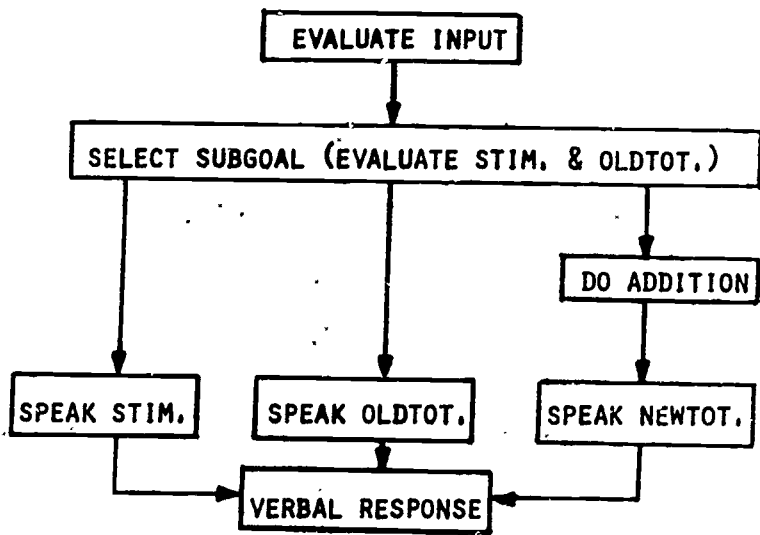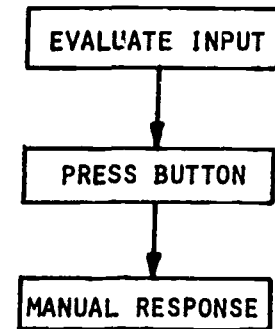
Figure 1

Figure 2
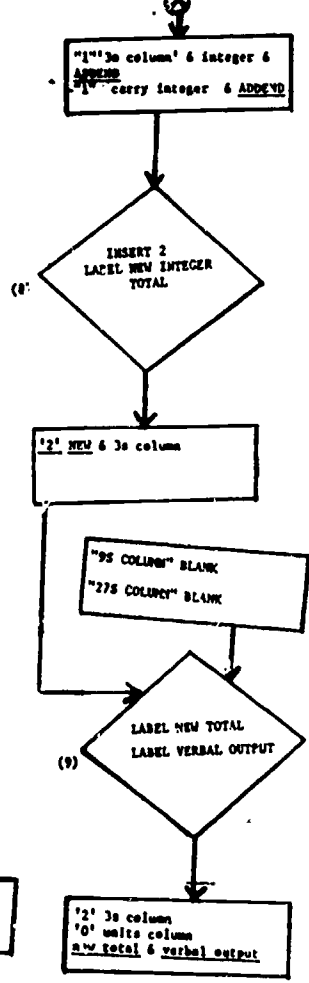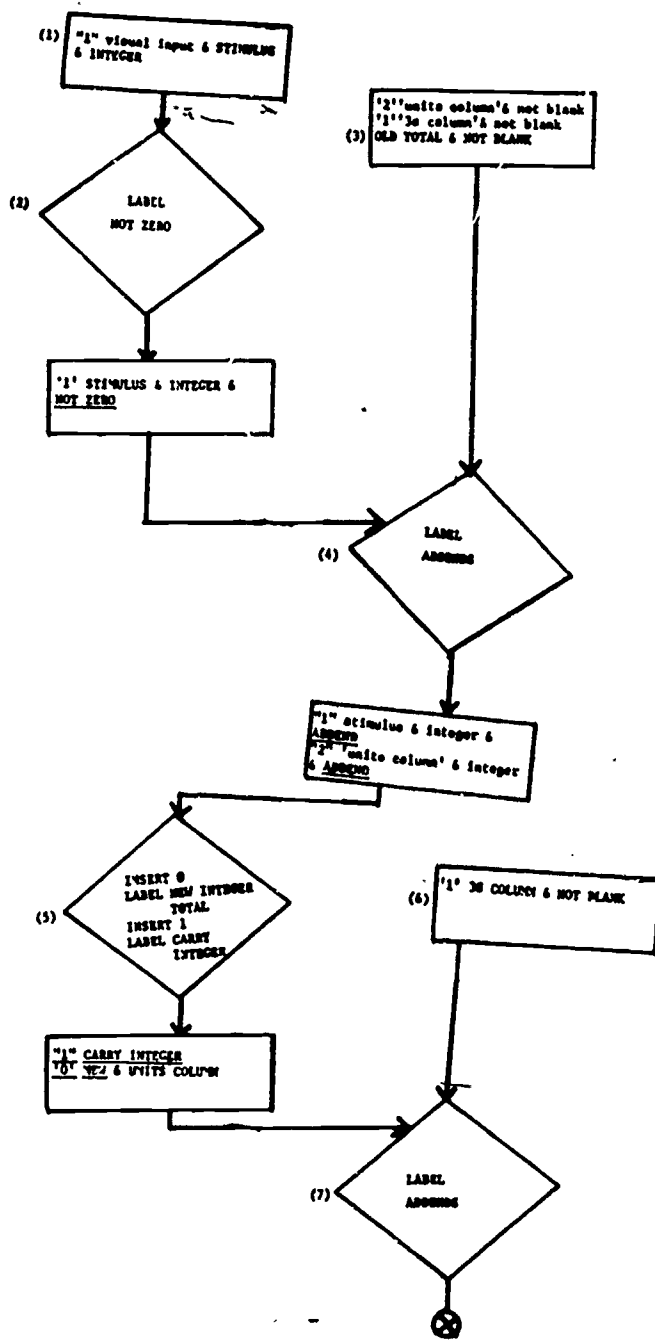
Figure 3

Figure 4

Labels in input concepts are all uppercase

Labels in output concepts are underlined

Labels otherwise are lower case and included to improve readability

Objects in input concepts are in double quotes

Objects in output concepts are underlined

Objects otherwise are in single quotes and included to improve readability

Figure 5

53

54

Figure Captions

Figure 1. Structural components of the functional architecture and permissible flows between them.

Figure 2. An abstract example of a dataflow graph.

Figure 3. Block diagram of the addition task submodel.

Figure 4. Block diagram of the auditory probe task submodel.

Figure 5. A dataflow graph for a specific example of the addition task submodel processing a single trial.

Table 1

Participant's Errors and Mechanisms in the Model for Simulating Them

Error Type	Occurance In Participant's Data	Trapped By Participant's	Mechanism In Model
1. Speaking the Stimulus	24 (.41)	Yes	Priming of Production From Previous Trial.
2. No Probe Response	13 (.22)	Yes	Decay of Probe, Competition Between Tasks.
3. Probe Response After Addition Response	9 (.16)	Yes	Competition Between Tasks.
4. Addition Fact Errors	9 (.16)	No	Confusability of Addends.
5. Forgetting Stimulus or Old Total	4 (.07)	Yes	Decay of Integers.
6. Carry Errors	0	NA	Persistence of Pattern in k.i.
7. Transposition Errors	0	NA	Confusability of Integers.

Note. Proportion of total errors in parentheses.

Table 2

Median Reaction Times for Participants (in ms) and the Simulation (in time cycles)

Condition	Subject				Simulation
	1	2	3	4	
Probe -	451	662	594	712	6
No Carry	(137)	(138)	(133)	(136)	(1ɔ)
Probe -	462	768	620	765	7
With Carry	(60)	(62)	(57) .	(60)	(9)
Addition - No	586	695	809	964	9
Carry, No Probe	(404)	(412)	(396)	(397)	(48)
Additon - No	863	1156	1214	1344	11
Carry, With Probe	(137)	(138)	(133)	(136)	(16)
Addition - With	1578	1436	2027	2668	17
Carry, No Probe	(195)	(188)	(198)	(198)	(27)
Addition - With	2209	1660	2483	2814	22
Carry, With Probe	(60)	(62)	(57)	(60)	(9)

Note. Number of observations in parentheses.

Table 3

Scaled Reaction Times for Participants and the Simulation

Condition	Subject				Simulation
	1	2	3	4	
Probe - No Carry	1.0	1.0	1.0	1.0	1.0
Probe - With Carry	1.0	1.2	1.0	1.1	1.2
Addition - No Carry, No Probe	1.3	1.0	1.4	1.4	1.5
Addition - No Carry, With Probe	1.9	1.7	2.0	1.9	1.8
Addition - With Carry, No Probe	3.5	2.2	3.4	3.7	2.8
Addition - With Carry, With Probe	4.9	2.5	4.2	4.0	3.7

Note. Values for each participant and the simulation are scaled separately in terms of the median Probe- No Carry reaction times, which were in each case the shortest median times.