Solving Complex Problems Using Hierarchically Stacked Neural Networks Modeled on Behavioral Developmental Stages

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Abstract

Our work adds a new dimension to neural network models by creating hierarchically stacked neural networks. These stacked neural networks model how humans acquire complex behavioral sequences. We present a blueprint for designing neural networks that incorporate Commons' Model of Hierarchical Complexity (1998) and thus, more closely parallel the behavioral learning process in humans with its capacities to flexibly solve and respond to complex problems. Commons' Model is based on research showing that cognitive development in humans proceeds through a series of ordered stages. Actions and tasks performed at increasingly higher stages are built on each proceeding stage. Hierarchical stacked neural networks in our design parallel this process by being ordered in the same way as the developmental learning sequence outlined in Commons' model. Using our model, we present a system directing incoming customers' calls to correct departments in a large organization based on customers' oral statements and responses to questions asked by the system.

1. Introduction

Hierarchical stacked computer neural networks in this system use Commons' (1998) Model of Hierarchical Complexity: They model human development and learning; reproduce the rich repertoire of behaviors exhibited by humans; allow computers to mimic higher level human cognitive processes and make sophisticated distinctions between stimuli; and allow computers to solve more complex problems.

Traditional neural networks are limited because they only model neuronal function and relatively simple physiological structures in the brain. By failing to model the manner in which human cognition develops, these networks are unable to reproduce the more complex behaviors of humans and have limited problem-solving ability. As a consequence, they cannot solve many problems that humans solve easily.

1.1. Theoretical Underpinnings of Commons' Model

Humans pass through a series of ordered stages of development. Behaviors performed at each higher stage of development are always more complex than those performed at the immediately preceding stage. Movement to a higher stage of development occurs by the brain combining, ordering and transforming the behavior at the immediately preceding stage. This combining and ordering of behaviors is non-arbitrary.

1.2. Commons' Model of Hierarchical Complexity

The model identifies 14 stages of hierarchical complexity in development. It classifies tasks by their highest stage of hierarchical complexity. It deconstructs tasks into the behaviors that must be learned at each stage in order to build the behavior needed to successfully complete a task

2. Hierarchical Stacked Computer Neural Networks Based on Commons' Model

Hierarchical stacked computer neural networks based on Commons' (1998) Model recapitulate the human developmental process. Thus, they learn the behaviors needed to perform increasingly complex tasks in the same sequence and manner as humans. This allows them to perform high-level human functions such as monitoring complex human activity and responding to simple language.

They can consist of up to 14 architecturally distinct neural networks ordered by stage of hierarchical complexity. The number of networks in a stack depends on the hierarchical complexity of the task to be performed. The type of processing that occurs in a network corresponds to its stage of hierarchical complexity in the developmental sequence. In solving a task, information moves through each network in ascending order by stage

2.1. Design of Neural Networks Based on Commons' Model

The task to be performed is first analyzed to determine the sequence of behaviors needed to perform the task and the stages of development of the various behaviors.
The number of networks in the stack is determined by the highest stage behavior that must be performed to complete the task. Behaviors are assigned to networks based on their stage of hierarchical development.

3. Example: System to Answer Customer Calls and Transfer Them to a Department

3.1. Features

Answers calls and based on callers' oral statements and directs them to a department
Queries callers for more information
Achieves the language proficiency of a three year-old
Asks simple questions

3.2. Design of Network

Uses 4 neural networks, N2, N3, N4 and N5.
N2: Circular Sensory Motor Stage Network: Forms open-ended classes
N3: Sensory Motor Stage Network: Recognizes classes
N4: Nominal Stage Network: Identifies relationships between simple concepts and labels them
N5: Sentential Stage Network: Forms simple sentences, constructs complex relationships and orders relationships

Processes Performed at Each Stage

Input: Front-end speech recognition system
N2: Uses inter-word intervals to group words
N3: Maps words to pretaught words central to organizational environment
N4: Identifies relationships between words and links to concepts
N5: Maps relationships between concepts and makes simple queries to caller
Output: Chooses department and checks with caller to see if it is the correct place to send call.

Figure 1 illustrates a stacked neural network 10 in accordance with one embodiment of the present invention. Stacked neural network 10 comprises a plurality of up to 14 architecturally distinct, ordered neural networks 20, 22, 24, 26, ..., of which only four are shown. The number of neural networks in stacked neural network 10 is based on the number of consecutive stages needed to complete the task assigned. A sensory input 60 to stacked neural network 10 enters lowest stage neural network 20. The output of each of neural networks 20, 22, 24, 26, ..., is the input for the next neural network in the stack.

The highest-stage neural network 26 in the stack produces an output 62. Each of neural networks 20, 22, 24, 26, ..., except for the first in the stack, neural network 20, can provide feedback 30, 32, 34, 36, 38, 40 to a lower-stage neural network 20, 22, 24, ... Feedback adjusts weights in lower stage neural networks. Neural networks in the stack 20, 22, 24, 26 ... can send a request 50 for sensory input 60 to feed more information to neural network 20. A neural network can send this request when its input does not provide enough information for it to determine an output.

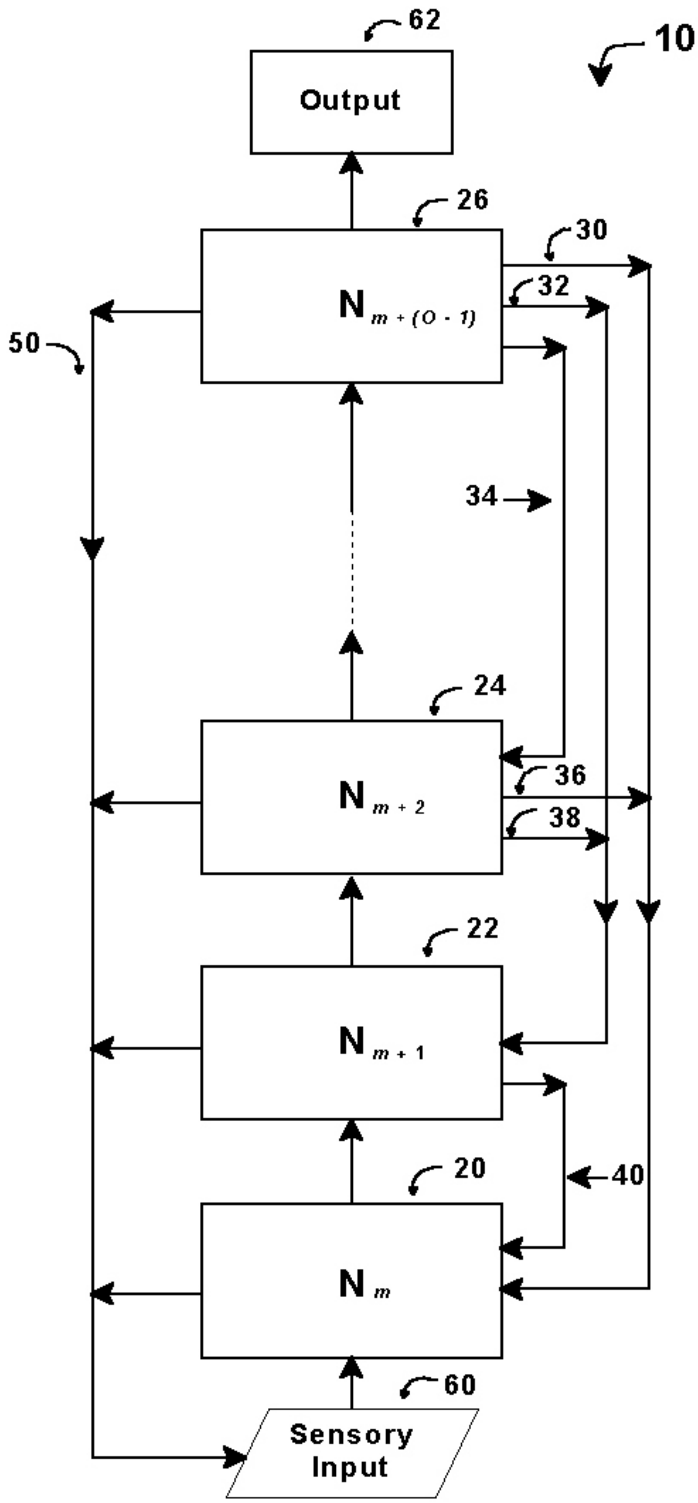

62
10
Output
26
30
32
N m + (O - 1)
50
34
24
36
N m + 2
38
22
N m + 1
20
40
N m
60
Sensory Input

FIG. 1

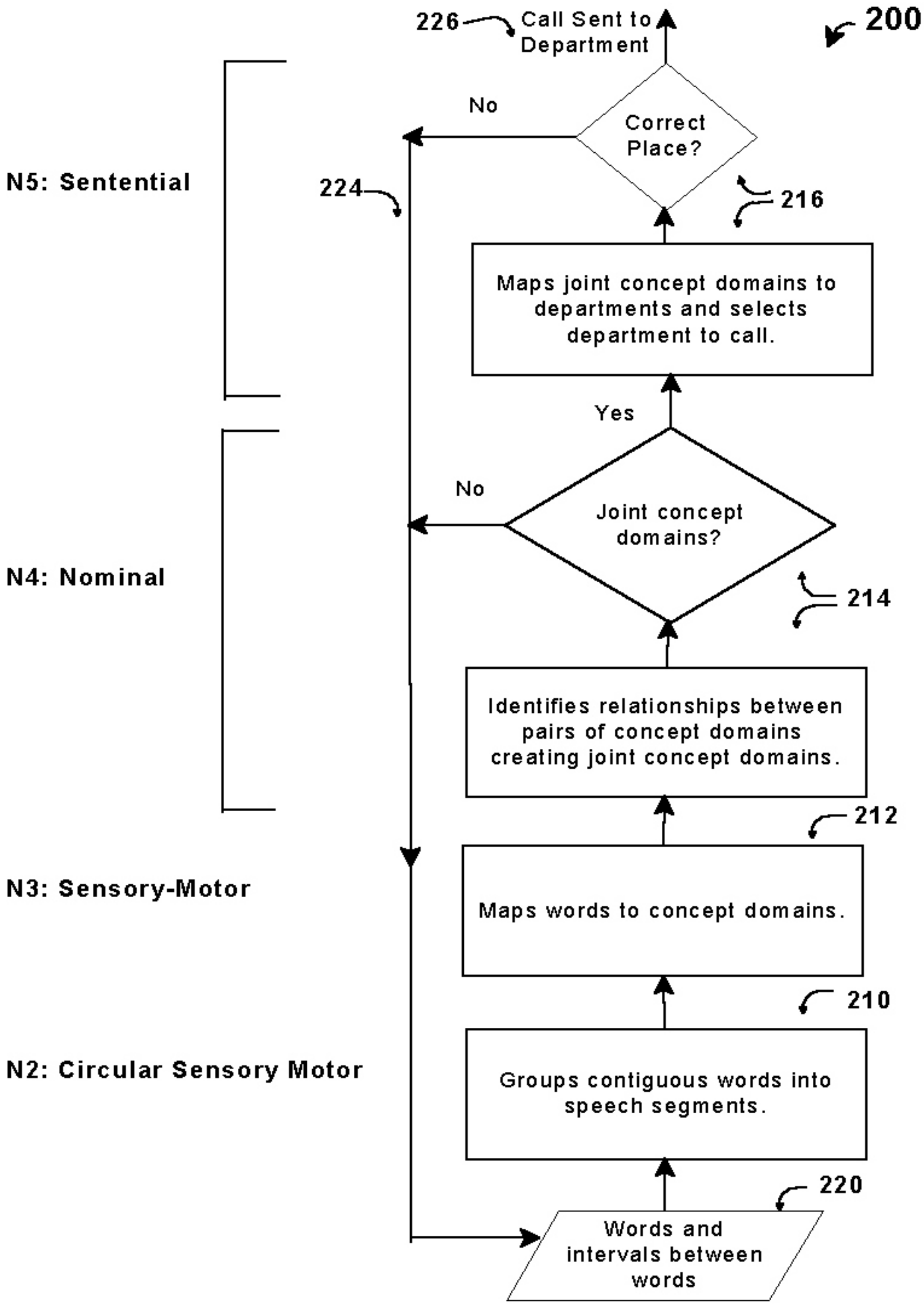
Figure 7 is a high level flow chart 200 that illustrates a series of four major processing steps 210, 212, 214, and 216 for the second embodiment of the present invention: An Intelligent Control System that Directs Customer Calls to the Correct Department in a Large Organization. A front-end speech recognition software system 220 translates customers' utterances into words, measures the time intervals between each word and removes articles, prepositions and conjunctions from the utterances. Words and time intervals between words are processed at a step 210 which performs tasks at the Circular Sensory Motor stage/order. At this stage/order, open ended classes are formed. In this step, time intervals between the words are used to break the word stream into contiguous word groups that reflect natural speech segments.

A next processing step 212, maps words in each group produced at processing step 210 into clusters called concept domains which represent concepts that are central to the company's functions. Processing step 212 uses tasks at the Sensory-Motor stage/order. At this stage/order, words are identified as belonging to meaningful classes.

A processing step 214, next identifies simple relationships between pairs of concept domains produced by process 212. Processing step 214 uses tasks at the Nominal stage/order. At this stage/order, simple relationships are formed between concepts. If processing step 214 is unable to identify any joint concept domains from the concept domains input from step 212, the customer is queried for more information. The customer's responses are sent to the front-end speech recognition system 220 and then processed at steps 210 and 212 before being processed at step 214.

Once step 214 identifies joint concept domains, then a processing step 216 maps the joint concept domains to clusters of neurons that represent relationships between company products and functions. This step operates at the Sentential stage/order. At this stage/order, simple sentences are formed, relationships between more than two concepts are understood and relationships are ordered. A department is competitively selected at this step based on the patterns of activation from the mapping of joint concept domains. The customer is queried to determine whether they would like their call sent to this department. If the customer answers affirmatively, a connection 226 is made to the department selected by the system. If they do not want this department, the customer is queried for more information. A response set of their utterances 224 is sent to the front-end speech recognition system 220. The words produced by the speech recognition system are input to processing step 210 and are processed in the same manner as the customer's initial utterances.

Commons ML, White MS. A complete theory of tests for a theory of mind must consider hierarchical complexity and stage: A commentary on Anderson and Lebiere target article, Behavioral and Brain Sciences, 2003.



200
226
Call Sent to Department
No
Correct Place?
N5: Sentential
224
216
Maps joint concept domains to departments and selects department to call.
Yes
No
Joint concept domains?
N4: Nominal
214
Identifies relationships between pairs of concept domains creating joint concept domains.
212
N3: Sensory-Motor
Maps words to concept domains.
210
N2: Circular Sensory Motor
Groups contiguous words into speech segments.
220
Words and intervals between words

FIG. 7

Figure 8 illustrates a stacked neural network 230 for the second embodiment of the present invention: An Intelligent Control System that Directs Customer Calls to the Correct Department in a Large Organization. Stacked neural network 230 comprises a stack of 4 architecturally distinct, ordered neural networks 240, 242, 244, and 246. Words and the time intervals between words are input into a neural network 240 from a front-end speech recognition system 220 that translates customer utterances into words, computes time intervals between words, and removes articles, prepositions and conjunctions.

Neural network 240 performs Circular Sensory Motor stage/order tasks that group words into contiguous word groups based on the time intervals between words that naturally segment speech. Output from neural network 240 is input into a neural network 242. Neural network 242 performs Sensory-Motor stage/order tasks that map words into concept domains that represent company functions. Output from neural network 242 is input into a neural network 244 which performs Nominal stage/order tasks that identify simple relationships between pairs of concept domains creating joint concept domains. If no joint concept domains are identified by neural network 244, then a query 252 is output to the customer for more information. This new information from the customer is sent to the front-end speech recognition system 220 and then processed by neural networks 240 and 242 before neural network 244 continues processing the customer's speech.

Once joint concept domains are identified in neural network 244, they are input into a neural network 246. It performs Sentential stage/order tasks that map the joint concept domains to clusters representing product/department relationships. Based on levels of department activation, a department is selected to be the department most likely to satisfy the customer's needs. A query 254 is then sent the customer to ask them if they would like to be sent to this department. If the customer responds "yes," then the call is sent to the department selected by neural network 246. If the customer responds "no," then the customer is further queried. A set of the customer's responses 254 are sent to the front-end speech recognition system 220 and then processed by neural networks 240, 242 and 244 before being processed by neural network 246. A group of feedback adjustments 256 are sent to neural networks 246 and 244 to adjust their weights based on the success or failure of the stacked neural network in selecting a department for the customer.

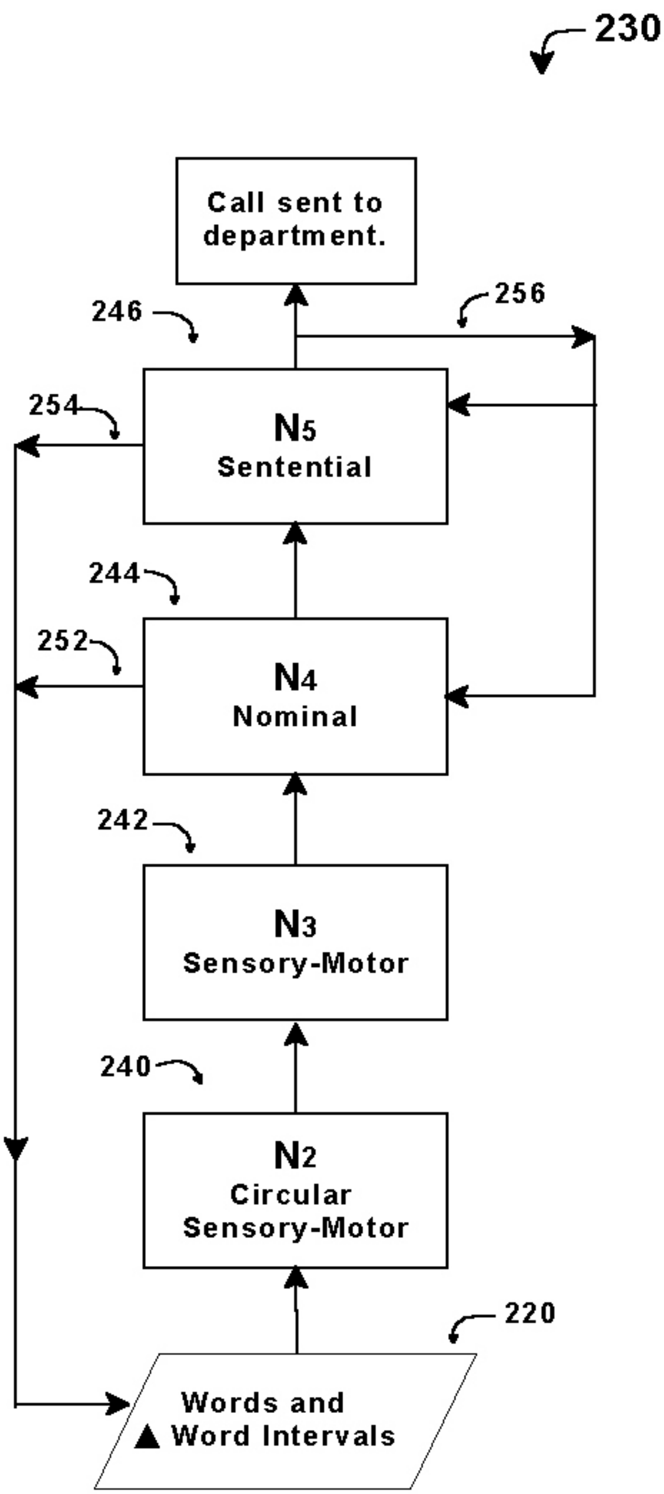

230
Call sent to department.
246
256
254
N5
Sentential
244
252
N4
Nominal
242
N3
Sensory-Motor
240
N2
Circular Sensory-Motor
220
Words and
▲ Word Intervals

FIG. 8