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Towards Computational Model of Human Brain Memory

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Abstract. Brain informatics intends to facilitate the research on brain by applying advancements of computer science for the collection, transformation and organization of the brain data. In this paper, we proposed a conceptual model of human memory and its formal specifications. The proposed model takes the structure-to-function approach. The proposed model is also formally evaluated with one of the existing model for the possibilities of temporary memory. And we proved that our proposed model encapsulates more information and it is more appropriate to handle memory related brain data as compared to the existing biological models.

AMS (MOS) Subject Classification Codes: 03E72, 54A40, 54B15
Key Words: Brain informatics, brain computational model, intuitionistic fuzzy closure/topological/sum intuitionistic spaces.

1. Introduction

Current research on human memory covers the broad perspectives of psychology, physiology, neuropathology and bio chemistry etc. And it has resulted in variety of biological memory models that cover different aspects of memory mechanisms which include learning, recalling, thinking etc. The ultimate purpose of this research is to comprehend and recognize the general brain processing that involves memory and also earlier detection of diseases like Alzheimers and Dementia. However, most of the existing memory models suffer from lot of limitations like, type specific, contradicting concepts, limited to experimental conditions, inadequate modeling of data etc. In recent years, Brain informatics [2][20][4] defines itself to facilitate the study of brain by applying advancements of computer science. It mainly emphasis on developing full of meaning and efficient techniques for collecting & measuring the biological brain data, conducting experiments, transforming and managing the brain related data etc. In this paper we are particularly focusing on modeling of human memory using prototype based object modeling technique. Our proposed model intends to provide more efficient storage, retrieval and manipulation techniques for handling of memory related brain data. We also report on applying formal techniques for their potential benefits as discussed in [20][4][29]. The remainder of this paper is organized as follows. In Section 2, we present a review of some of the existing biological models from both micro and macro level points of view. In Section 3, we propose the conceptual model of human memory to actually transform biological brain data in computer science using structure to function approach. To exemplify the possibilities of working memory processing, we present an example in Section 4. Finally, in Section 5, we present our discussion on the studied example. And finally gives our concluding remarks and future directions in Section 6.

2. Literature survey

Human memory is defined as a property and natural outcome of particular brain activities and current research rejects the ideas of memory as dedicated regions in brain [22]. Research at micro level found evidences of cellular and molecular substrate changes as a result of some experience in brain that carries memory activity[10][24][27] , and current macro level research concludes memory as multi memory system and considers it as an integral part of current information processing [9][14]. In [9] also identify the need to combine the ongoing micro and macro level research (that is to relate substrate or molecular level changes with the multi memory system processing) for their potential benefits which includes the identification of dementia, distinction among various types of memory and to recognize a particular change at cellular and molecular level as a result of some activity. The modern classification criteria for the memory systems on basis of psychological and neural characteristics are elaborated in [9]. Here, we will briefly overview some of the famous micro and macro level studies particular to working memory. Many experiments related to micro level research were conducted in identifying the activation of different regions of the Cerebral Cortex (specifically the prefrontal cortex) while performing different working memory tasks [16] For example, scientist found the distinction between dorso lateral and lateral region activation of prefrontal cortex in conscious and words retrieval tasks [16]And they suggested that lateral portion is activated more in retrieval task for verbal and visual processing. The first remarkable step towards modeling of human memory at macro level was made by Atikson & Shiffrin Model [28]. It gave the more generalized form of memory processing levels. Later on, development of memory models like Search of Associative Memory (SAM)[28] , Retrieving Effectively from Memory (REM) [25] and Complementary Learning System (CLS)[11] were mostly related to identification and recall processes from Long term memory whereas Temporal Context Model [11] tried to illustrate the gradual change in attention with time. We summarize some of famous existing memory models in Table 1. Current macro level research is focusing more on understanding emerging concept of memory systems with experimental findings. There is also a need to investigate the differences among memory types to gain clear ideas about the memory storage and representation as mentioned [22].After describing the salient features of existing models, we now list down some of major short comings associated with them. These are as follows:

i) Most of the macro level models take functional approach based on the results of their respective studies/ experiments.
ii) These models are type specific, for example, REM is for the retrieval of information, TCM deals with the change of attention with time etc.
iii) These models are limited to the experimental conditions applied thus covering limited field of view.
iv) All these models carry valuable information that needs to be properly managed to make best use the data

Model	Category	Main Features	Type
The Atkinson-Shiffrin model (A & S)	General	STS & LTS	General relationship
Temporal Context Model	Episodic Memory	Reconsolidation	Temporal context learning
Search of Associative Memory (SAM)	Recall & Recognition	Memory images, cue dependent processes	attention, word frequency etc
Complementary Learning Systems (CLS)	Recognition	Memory Patterns	Episodic memory data
Layered Reference Model of Brain (LRMB)	Psychology & physiology	Subconscious & Conscious	Learning, decision making, comprehension
Retrieving Effectively from Memory (REM)	Recognition	Improvement over SAM Memory images features	Word frequency, memory interferences
MINERVA 2	Episodic Memory	Memory trace as vector, Retrieved vector is the sum of all trace vectors.	De-blurring, Simple abstraction, frequency judgments, recognition, absolute judgments.
Adaptive Control of Thought Rational (ACT-R) Model	declarative procedural memory	Activation of network, Fan effect, Cue, Target	Learning.

TABLE 1. Comparison of Existing Biological Memory Models

v) Analysis of the information covered by any two models of the same type tends to give conflicting and unreliable results because of different experimental tasks and conditions.

3. PROPOSED MEMORY MODEL

In this Section, we proposed a formal model of human memory using the prototype based object modeling technique. This model generalizes biological concepts of the classification of memory with respect to the brain regions , relationships among them and integrates the studies done at micro and macro levels. In Fig. 1, we present that human memory model is composed of three major functional modules, Input, Central and Effecter. Let Mmem be the Memory Model and Mip, Mcent and Meff be the modules of the model, then we write Fig 1 as follows

$$Mmem = \{Mip, Mcent, Meff\} \tag{3. 1}$$

(1) Equation (1) shows that Memory Model corresponds to the property of Set and initially it is defined as the collection of three elements; Mip, Mcent and Meff. These elements are the subsets of Mmem and are described in Eq. (2), (3) and (4).

$$Mip\underline{C}Mmem \tag{3. 2}$$

$$Mcent\underline{C}Mmem \tag{3. 3}$$

$$Meff\underline{C}Mmem \tag{3. 4}$$

Now we elaborate the functionality of Mip and Mcent subset/module.

3.1. **Input module/subset (Mip).** The Input module/subset handles the signals received from the environment analyzes and transformed them in a form that is perceived by the brain for memory involved processing. This module/subset basically corresponds to the Sensory Registers of the brain that participate in scanning, processing and passing the signals to the sensory cortical areas for further processing.

$$Mip = \{x|Pip\,(x)\} \tag{3. 5}$$

Eq. (5) gives the formal description of this module/subset and it says that set Mip is the collection of all those elements x which get activate and operate on the incoming signal, isig, and satisfy the property Pip (x). Pip (x) corresponds to the electro-chemical activity constraints of neurons when they receive the signal isig from the stimulus. The input module/subset also incorporates other control factors that interfere in selecting and transferring the processed signals to the Central Module/Subset. Let Isig be the set of all the sense signals that are identified by the brain at time instances, t1, t2, t3...

$$Isig = \{isigt1, isigt2, isigt3, \cdots\} \tag{3. 6}$$

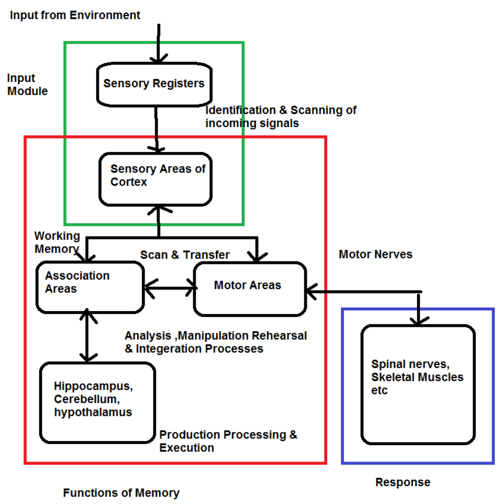

FIGURE 1. Proposed model of human memory)

Now we define the functionality, ϕ ip, of this module/subset.

$$\phi ip = \phi scan^{\wedge}\phi transfer^{\wedge}\phi decay \tag{3. 7}$$

The above Eq. (7) shows that ip functionality composed of three sub functions, which are scan, scan , transfer transfer and decay decay. In this Eq. (7) we also define the sequence operatorto show the sequence behavior among these sub functions. Each of the sub function follows the format which is defined in Eq. (8) as follows.

$$\phi = \{isig \times rsig \times mR\} \tag{3. 8}$$

The is the partial function from Isig to Mip and it takes input of type (isig , mR) and it returns (rsig, mR). The input, isig & mR are the identified sense signal(s) and the memory chunk(s) respectively where isig Isig and mR Mip. The Memory chunk, mR is the collection of participant neurons from different parts of the brain. The output of the function, (rsig , mR) is the controlled signal, rsig and the renovated memory chunk(s), mR.

3.2. **Central module/subset (Mcent).** The Central module/subset, Mcent is the collection of Cortical regions and their connections with areas like Hippocampus, Cerebellum, Thalamus etc which are specialized for the executive processing, learning, perception and other lower level complex functionalities.

$$Mcent = \{y|Pcent\,(y)\} \tag{3. 9}$$

Similar to Eq. (5), in Eq. (9) we give the formal description of this module/subset and say that set Mcent is the set of neuronal regions, y, which satisfies the property Pcent (y). This collection of y operates on the processed signals from the input module/subset. In Biology, Cerebral Cortex is usually described as composed of three interconnected functional components which are Sensory Cortex, Association Cortex and Motor Cortex. Based on this, we further divide the Central Module/Subset into three main sub modules/subsets; Sensory Cortex Module/Set (Csen), Association Cortex Module/Set (Cass) and Motor Cortex Module/Set (Cmot) as shown in Fig. 2. We also add one more module Supplementary Control Set (Cconn) to include the regions that are also involved in carrying out controlled functionality which is not covered by the former sub modules/subset. The composition of this module/subset is formally defined in Eq. (10).

$$Mcent = \{y|y\epsilon Csen, y\epsilon Cass, y\epsilon Cmot, y\epsilon Cconn\delta Pcent\,(y)\} \tag{3. 10}$$

These sub modules/subsets Csen,Cass and Cmot are defined in Biology as complex composition of four Lobes of Cerebral Cortex which are Temporal Lobe, Occipital Lobe, Frontal Lobe and Parietal Lobe. Each sub module/subset has its own specialized functionality and the choice of the execution of the functional components at certain time t is done by the set of controlled conditions. Let sens, ass, mot be the functions for Csen, Cass and Cmot respectively and is given below in Eq. (11).

$$\phi center = \lambda\,(\phi sens, \phi ass, \phi mot) \tag{3. 11}$$

Here defines the Piece wise operation on ϕsens, $\phi ass \& \phi mot.$ We have also noticed above that each module/subset of the model embeds an operation at every level to record a New Experience. This New Experience is defined as any electro- chemical change in neuronal level information of mR at some time t for duration $\wedge$ t. It is defined as overwrite operation in Eq. (12) as follow

$$\phi exp = updation \tag{3. 12}$$

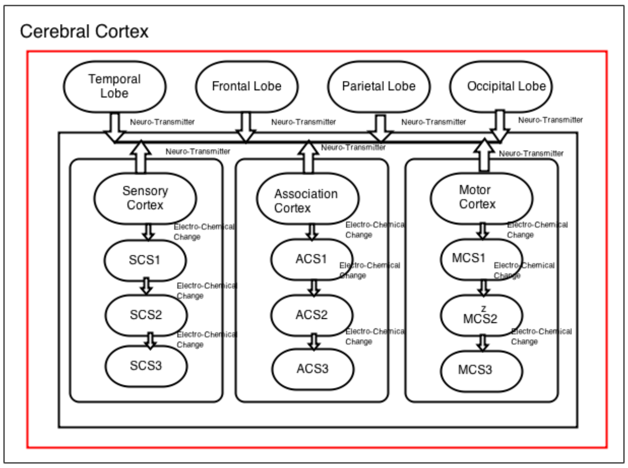

FIGURE 2. Elaboration of central module

The function ϕexp , returns the renovated information of a particular set of neurons mR and the control signal rsig. At any stage of information processing, we define mR as the set of all states of that particular module/subset.

$$mR = \{mR1, mR2, mR3, \dots\} \tag{3. 13}$$

The behavior of mR for every module/ subset corresponds to the prototype based object modeling in that with every new experience a new memory state, mR is defined.
Fig. 3 shows the structure of prototype object Sensory Cortex Module/Set (SCS) for Csen module. This object is defined within a particular Lobe at some time t with some Threshold Potential value. It contains aggregated information from participant prototype objects. This object also contains values related to resting and action potential (mV) of neuron, it synaptic strength, chemical bonding and other related cellular and molecular data. The addition of new prototype object in a particular cortex Set occurs as a result of some brain activity that defines some change (described in Eq. (12)) in neuronal activity of that cortex Set.

We now modify the Eq. (1) to Eq. (14) & (15) and define memory mechanism not as a collection of sub modules but as an outcome of the particular brain activities as mentioned in Section 2.

$$Mmem = Mip \times Mcent \times Meff \tag{3. 14}$$

$$Mmem = \{(x, y, z) \,|x\epsilon Mip, y\epsilon Mcent \& z\epsilon Meff\} \tag{3. 15}$$

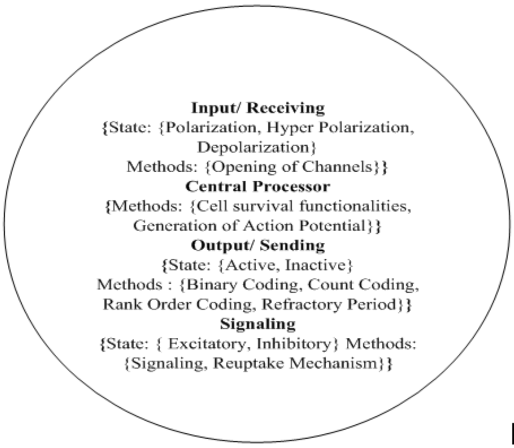

FIGURE 3. SCS prototype object

4. CASE STUDY

In this section, we take one of the existing models as case study, describe it in formal terms and try to show that the information represented by this model is a subset of the information covered by our proposed model.

4.1. **Baddeleys working memory model.** From the description available in [11, 25], we describe the Baddeleys Working Memory model in formal terms as follows in Eq. (16),

$$Mw = \{PL, VS, CE, EB\} \tag{4. 1}$$

Eq. (16) is showing that this model is the collection of four elements namely, Central Executive (CE), Phonological Loop (PL), Visual Sketch Pad (VS) and Episodic Buffer (EB). The CE, being the controller is responsible for the functionalities including transforming, managing and examining the information processing among and within the rest of the components [11, 12, 13, 25]. The overall controlled functionality of CE can be formally expressed as union of the sub controlled functionalities and it is expressed in Eq. (17) and (18).

$$\phi_{ce} = \{CE \longleftrightarrow PL, CE \longleftrightarrow VS \& CE \longleftrightarrow EB\} \tag{4. 2}$$

$$\phi_{ce} = \phi_f \cup \phi_{cvs} \cup \phi_{cpl} \cup \phi_{cep} \cup \phi_{bind} \cup \phi_{other} \tag{4. 3}$$

The Phonological Loop (PL) and Visuo$-$Spatial Sketch Pad (VS) subsets/modules were also described to hold processing of encoding, storing and maintaining of their respective information [11, 25] and is formally expressed in Eq. (19), (20), (21), (22) ,(23) and (24).

$$PL = \{Pstore, Acomp\} \tag{4. 4}$$

$$\phi_{pl} = P_{store} \longleftrightarrow A_{comp} \tag{4. 5}$$

$$\phi_{pl} = \phi_{cpl}\left(\phi_{ecod}, \phi_{st}, \phi_{mt}\right) \tag{4. 6}$$

$$VS = \{V_{comp}, Sp_{comp}\} \tag{4. 7}$$

$$\phi_{vs} = V_{comp} \longleftrightarrow Sp_{comp} \tag{4. 8}$$

$$\phi_{ps} = \phi_{cvs}\left(\phi_{ecod}, \phi_{st}, \phi_{mt}\right) \tag{4. 9}$$

In Eq. (19) and (24), the cpv and cvs are the representing the controled functionality of CE module/ subset that direct and examine the PL and VS modules/subsets. The fourth module, the Episodic Buffer (EB) put together the information from other modules, creates representations for the combined information and maintained it. The working of this module/subset is also controlled by the CE subset/module. In Eq. (25), we formally define its processing;

$$\phi_{eb} = \phi_{ceb} \left(\phi_{int}, \phi_{reh}, \phi_{tr}\right) \tag{4. 10}$$

Similar to cpv And cvs , the ceb is the function of CE module/subset that controls and examine the functionality for EB module/ subset. Suppose that P, is some processing and is recorded in both models Mw and Mmem then at any stage of processing Mmem covers more information related to P than information covered by Mw.

4.2. **Proof.** Since CE and Mcent are the core subsets/modules of Mw and Mmem respectively that operate on processing, P. The main role of CE is to control and manage the information flow for P in PL, VS and EB sub modules/subsets. And Mcent is proposed to cover the entire executive processing for P including the information of cortical regions involved for audio, visual and other activities, their connections, the retrieved information, external stimuli and other lower level complex functionalities. Thus, we can say that function ϕce is the subset of ϕcenter and it also corresponds that M center is the super set of CE, and is formally expressed in Eq.(25) as follows;

$$\phi_{ce}\underline{C}\phi_{center} \geq CE\underline{C}M_{cent} \tag{4. 11}$$

In a similar way, we can also prove that Information processing handled by the PL and VS is corresponding to the partial role of Csen and is expressed by following Eq.(27) to Eq.(29) . The functionality of the EM is covered by the role of Cass.

$$\phi_{pl}\underline{C}\phi_{sens} \geq PL\underline{C}C_{sen} \tag{4. 12}$$

$$\phi_{vs}\underline{C}\phi_{sens} \geq VS\underline{C}C_{sen} \tag{4. 13}$$

$$\phi_{em}\underline{C}\phi_{ast} \geq EM\underline{C}C_{ast} \tag{4. 14}$$

From Eq.(27), (28) and (29), we can evaluate that Mw covers part of the information processing covered by Mcent , thus we can say that Mcent is the super set of Mw.

$$M_w\underline{C}M_{cent}\underline{C}M_{mem} \tag{4. 15}$$

$$M_w\underline{C}M_{cent}\underline{C}M_{mem} \tag{4. 16}$$

5. Result and discussion

In Section 4, the case study was selected so that Working Memory possibilities can be tested in our proposed model. As observed by the information processed by the modules of proposed model, we may safely say that our model works as intended. Also, we have formally proved that our Proposed Memory Model covers more information and is more generalized as compared to the Baddeleys Working memory Model. From the results of the case study and discussion in Section 2, we summarize the comparison of the main characteristics of our proposed model with the existing models in Table 2.

Parameters	**Proposed model**	**Existing models**
Modeling Approach	Structure to Function Approach	Function based
Focus	Generalized mutli- memory system	Type specific
Understandability	Easy to understand - consensus of information	Conflicting descriptions oftypes of memory
Areas Covered	Incorporate broad perspective of experiments like psychology, physiology, psychiatry, biochemistry etc	Experimental conditions & objectives dependent
Field of View	Larger field of view (change from macro to neuron level)	Limited to experimental conditions
Data Techniques	Simple & efficient collection, measuring and management of complex information(using advancements of computer science)	Scattered information, varying parameters and difficult to make complex inferences

TABLE 2. Comparison and analysis of the feature of the proposed model and the existing models

6. Conclusion and future works

In this paper we mainly focused on transforming the memory mechanism of human brain in computer science in order to overcome the short comings of existing biological models discussed in Section 2. Based on the identified nature of human memory we first categorized the underlying structures of the human brain responsible to carry out the memory related activities and then tried to present the generalized multi memory system using the structure to function modeling approach. We also report on applying formal and computational techniques to model human memory.

6.1. **Future works.** At this level, the proposed model is limited to handle the high level features of memory mechanism. It also provides the base for many interesting future works in research, implementation and reusability perspective. We have in mind to provide the simulation of the model and other future tasks as given below;

1) To verify and evaluate the working of the model for other possible memory related tasks.
2) Elaboration & implementation of operators and techniques specific to our proposed model in order to record neuronal activities related and relationships among different regions of the brain while performing particular memory related tasks.
3) This model can be further extended to incorporate micro level empirical investigations as discussed in Section 2.
4) Introduce the parameters for the safety and security of the data.
5) Extend the model to include other activities related to brain information processing.

In our opinion, this work provides a very promising future for computer scientists and biologists to work together, and holds a lot of potential for research. It laid the foundation to look at the brain in a new way with the benefits of computer science technology. We believe that incorporation of formal methods and use of new technology in such sort of work will lead to an eventual success.

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