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Brain functional model of natural language understanding

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Abstract- The present paper highlights a Cognitive Model for language comprehension, which is developed for the sensory input of written language sentences, where visual sensor is activated. In the flow of the paper, the various functional areas of the brain, called as Brodmann Areas and their functionalities are studied and the model of sentence understanding has been developed. Though the process of complete meaning understanding involves other sensory inputs, the present paper focuses on only one aspect of sense, viz., visual. The Brodmann areas identified for meaning understanding also have other functionalities in addition. But, the model presented in this paper needs further support and evidence in terms of empirical studies and experimentation using NMR techniques.

1. State of the Art

Comprehension of a sentence consists of at least three levels viz. Syntax analysis followed by Semantic interpretation and lastly Pragmatic elaboration. Syntax analysis of a sentence is the order or rules for combining words and inflections of that language. Semantic describes the way in which the meanings of sentences are represented. Language comprehension is a complex behavioural process of human, which is the outcome of the coordinated activity of different brain regions. Each brain region has a specific role. The white matter serves as the pathway for interaction among those regions.

The human brain is broadly classified into four lobes that are involved in the Language Processing functions and are as follows:

i. Frontal Lobe: Broca's area and motor cortex are situated in this lobe [18, 22, 25] . Mainly involves in attention and conscious thinking, voluntary movement for process execution. Functions like cognition, language processing, comprehension, problem solving, planning etc. are executed here.

ii. Parietal Lobe [11, 26]: It integrates the information from different sensory organs and creates a coherent structure/picture. The Dorsal and Ventral stream of the Occipital lobe also integrate here. Important functions involved are like spatial attention, visuo-spatial processing, taste, touch.

iii. Temporal Lobe: Wernicke's and Hippocampus area [18, 22, 25] are situated in this lobe attributed with functions of recognition, perception, language comprehension, learning and memorising. This lobe also takes part in audio, visual, verbal information processing and used as Long Term Memory (LTM) for memorising.

iv. Occipital Lobe [22, 11, 26]: This is the primary visual area. Human perceives the visual stream through thalamus for processing colour, orientation and motion information. Two streams originate from this lobe, one dorsal pathway towards parietal and other ventral which reaches temporal lobe respectively.

Korbian Broadmann was the first person who provided a cyto-architectonic [20, 24] description of the human brain cortex. According to functional localization, human brain is numbered in the range [1 – 52] referred to as Brodmann areas, BA **n** and further subdivided into **na, nb** etc.

Based on functions, the cognitive model of the brain consists of four different types of memory components. The components [23] are The Sensory Buffer Memory (SBM), The Short Term Memory (STM), The Long Term Memory (LTM) and The Action Buffer Memory (ABM). The SBM is an input buffer; it receives the inputs from the environment by using sensors like eye, ear, nose, tongue etc and passes them onto STM for further processing. In STM, it will store for a few minutes and the collected and processed information is then transferred to the LTM and ABM, for permanent storage and future use and for actuation (speak, write, walk) respectively [7, 8].

2. Computational Model

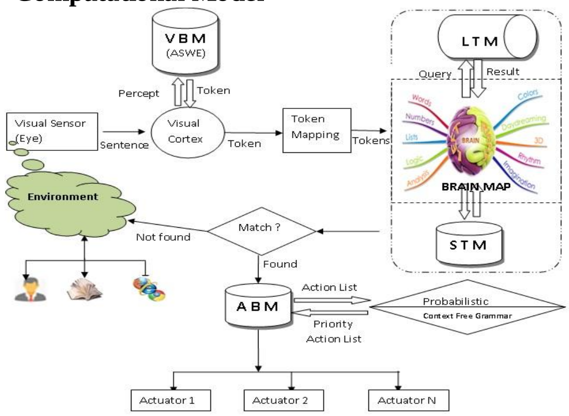

Fig1. Sentence Comprehension Process: [Source: 7]

3. Methodology

The Literature Study and Hypothesizing the BAs involved by Qualitative Analysis of the language comprehension process; which can be validated using NMR techniques.

4. Contributory work

The process of language comprehension is hypothesized to constitute of the following processes, which are mostly in a sequence: Perception, Filtration, Analysis, Token-meaning extraction, Association, Overall meaning extraction, Matching, Error correction, Concept updation and Action. The input signal is constrained to be a written sentence, albeit, a heard one. Hence the areas covered by such signal propagation would be different from other input signal types.

4.1. Perception: From the environment, eye perceives the visual stimuli, in our case a written sentence, through the thalamus, which directs the visual signal to the occipital lobe [26]. The lobe consists of 2 regions viz., primary and secondary visual cortices encompassing 3 different Brodmann areas 17, 18, 19[13, 15]. The primary visual cortex V1 (BA 17) [13, 25, 26] region of the occipital lobe receives the visual signal and is responsible to process it.

4.2. Filtration: Depending upon the type of information to be processed, V1 sends the signals in two different directions.

Dorsal stream: This is the spatial and visual pathway. This stream travels up into the posterior Parietal cortex through secondary visual cortex V2 (BA 18, 19) [26, 11]. The roles associated with the dorsal stream are to get the information required to locate the object, also to detect its motion and to answer - "Where" and "How" questions.

Ventral stream: This is the object recognition pathway. The other stream travels from the V1 through secondary visual cortex V2 (BA 18, 19) into the inferior temporal cortex. The roles associated with this stream[26,11] are to get information that is required for identifying or detecting objects, attributes to be processed for information about the shape and colour of the objects and to answer - "What" questions.

4.3. Analysis: In Short Term Memory (STM), tokens are annotated with their morphological features. STM is used to retain the newly acquired information from the environment as well as the retrieved information from the Long Term Memory (LTM); that are previously stored but presently required to process the current input. This information is valuable for goal-directed cognitive activities like Language comprehension, Reasoning, Learning and Planning. While comprehending a complex sentence, it is required to preserve the order of words in the entire sentence (especially, for fixed word order languages like English of the present context). In addition to this, to understand the context of a sentence, discourse integration also is required; which correlates the present sentence/phrase to the previous, to resolve anaphora, for example.

4.4. Token-meaning extraction: The syntax of English language sentences effect the meaning while comprehending it. The Broca's area of the brain is responsible for the syntactic analysis. It has been assumed by Geschwind (1972), Goodglass (1993) [28] that the posterior superior temporal cortex in Left Hemisphere (LH) is responsible for language comprehension. The junction of temporal, parietal and occipital is known as Wernicke's area (BA 22), which takes these parts in accomplishing a vital role of integration of all sensory information like visual, auditory and somatic. Each sensory cortex has its respective associated areas for pre-processing and redirection towards the receptors. According to Wernicke's model, initial processing of a sentence read, takes place in the visual, uni-modal cortex that is associated with primary visual cortex.

4.5. Association: The processed information from the previous phase is then conveyed to the angular gyrus (BA 39) [18] which serves as the connection between language centres and the visual cortex. Here the word meanings are transformed into a regular neural representation. For comprehension of a sentence, the meaning of each word is required. Thus neural representations are transferred to Wernicke's area where the meaning to each word is associated [15].

4.6. Overall Meaning Extraction: The associations established in the previous phase are used to obtain the meaning of the total sentence. Working memory is intermediary between the STM and LTM. The neural signals of meanings are passed to the Broca's area through arcuate fasciculus. Arcuate fasciculus is the area which connects the Broca's area (BA 44/45) with Wernicke's (BA 22) area. The anterior temporal lobe is considered as a region that involves the combinational processes both in the syntactic and the semantic analysis of a sentence [2]. The syntactic information and the verb-argument-based information are integrated in left posterior (Superior Temporal Gyrus) STG /STS (Superior Temporal Sulcus) [2, 9].

The interior frontal gyre (IFG) sub-regions of Broca's area have been allocated to different aspects of language processing. The BA 44 [2] supports the syntactic structure building, BA 44/45[2] has the role in thematic assignment and the syntactic movement and BA 45/47 [2, 9] take part in semantic processing. Thus Broca's area is involved in the processing of syntactically complex sentences that need space and further processing in working memory (WM). The final integration of syntactic and semantic information takes place in the activation of both the IFG (interior frontal gyre) and the STG (Superior Temporal Gyres) [2, 9]. Nobre et al. [2] shows that posterior inferior temporal cortex differentiates letter strings from non-linguistic complex visual objects. Rogalsky et al. reported that BA 38 is activated at the time of semantic analysis of an incoherence sentence[2]. According to Cohen & Dehaene (2004) [1], a functionally specialized processing stream exists within inferior temporal cortex for visual word recognition. Marslen-Wilson & Tyler (2007) [1] show that brain activities are more in anterior inferior temporal cortical regions, while distinguishing words from non-words and is affected by the semantic context of words. This indicates that anterior inferior temporal cortex holds more elaborate linguistic representations [1].

As stated by Bench et al. 1993 and Awh et al. 1996 [1], the Broca's area is often activated in working memory tasks where sub-vocal rehearsal is the main strategy for maintenance of information in LTM. Positional information might be represented in oculo-motor coordinates, where the memorized location might be maintained in terms of a saccade vector that acquires the target [1].

4.7. Matching and Error correction: The computed action and the expected/intended action are matched resulting in a difference; which, depending upon its magnitude can sometimes become incomplete/partial understanding (for low positive values) or completely misunderstood (high positive values). The objective of any human-human communication is complete understanding of the intention of the speaker or writer. Hence a feedback loop operates in co-ordination with the environment, so as to achieve the goal of optimizing this difference error and finally achieving complete understanding.

4.8. Concept Updation: Storage of STM is temporary; the information stored is lost in a few seconds when the attention is diverted from one task to another. As compared to STM, the space and durability of Long Term Memory (LTM) is much more. After the initial acquisition, as more and more information is retrieved and used from LTM, the more stable, it becomes. The connections among neurons will be consolidated for the sake of reliability of the information that is stored redundantly in different regions. If one path becomes unavailable, alternate paths are used for retrieval. According to Karl Lashley and Wilder Penfield (1950-60) [27], LTM is widely distributed throughout cerebellum. The storing in LTM is an ongoing process, establishing itself on every sleeping event. Hippocampus, located in the inner fold of temporal lobe, is considered as the centre for LTM. Multiple times, the facts (have) or information has to pass into this area for memorization, so that the association among the object and properties become well-built. Science Direct [11] quotes that new researchers suggest that information is encoded in the cerebral cortex [4] and the motor cortical circuits, used as LTM.

4.9. Action: Depending upon the past experience and knowledge, the current prioritized list of functions is generated in anterior association areas of frontal lobe. The planned information is then sent to pre motor cortices (BA 6) [13] for execution. After pre-processing, to trigger actions, it is directed to primary motor cortices (BA 4) [13] to instruct the corresponding actuator.

5. Proposed Model

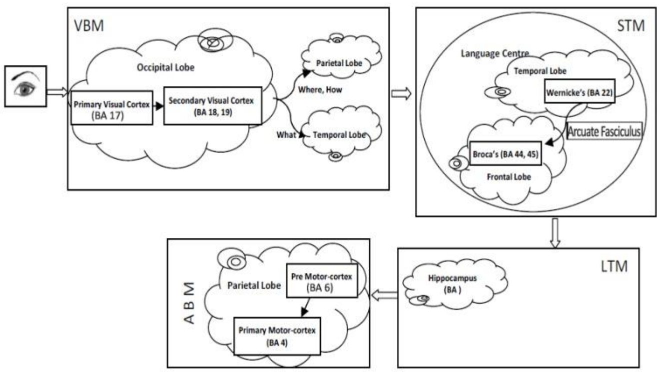

Fig. 2: Brodmann Areas Involved in Language Comprehension

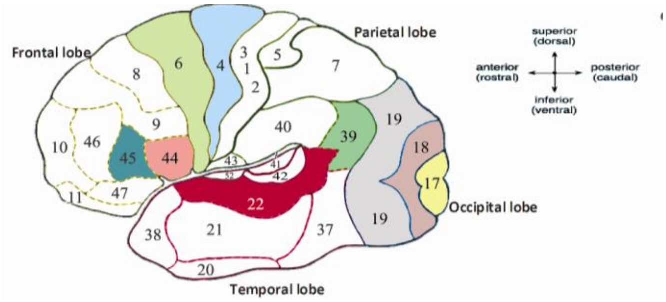

Fig. 3: BAs of Brain indicating the areas that involved in Language Comprehension

6. Conclusion

The process constitutes the following steps (mostly) of a sequence: Perception, Filtration, Analysis, Token-meaning extraction, Association, Overall Meaning Extraction, Matching, Error correction, Concept Updation & Action.

The Brain areas involved are: the Occipital Lobe regions (BA 17, 18, 19), which perceive and forward to Dorsal & Ventral side, the Frontal Lobe areas involved are (BA 44, 45), Broca's area and motor cortex, the regions of Parietal Lobe (BA 4, 6) which integrate the Occipital lobe streams and the Wernicke's and Hippocampus and of the Temporal Lobe (BA 22) involved in language comprehension.

7. Future Work

The Brodmann areas hypothesized to be involved in Language Processing are validated using any of the Nuclear Magnetic Resonance techniques. In this paper, only the visual sensor is used and only visual signals are considered as the input. Taking into consideration other sense organs, the BAs involved may differ. Hence, multi-modal sensory input could be experimented and the varying BA paths of language comprehension could be recorded using NMR techniques.

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