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A central pattern generator for controlling sequential activation in a neural architecture for sentence processing

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ABSTRACT

The neural architecture for sentence processing is a model of a neural 'blackboard' capable of temporarily storing both semantic and syntactic information. Retrieving information from the neural blackboard requires a sequence of activations that is controlled by a central pattern generator. We implement a central pattern generator that controls the sequence of activation. To ground the implementation in a biological context, the implementation is based on a model of the escape swim network of *Tritonia diomedea*, a marine mollusk. A central pattern generator is developed to meet the specifications required to successfully control the sequence of actions and activations needed to retrieve information from the neural blackboard in response to a question. The model is an existence proof for a biologically plausible implementation of a neural blackboard central pattern generator. The role of the central pattern generator in this neural architecture of sentence processing illustrates the potential relation between controlling movement processing and cognitive processing.

1. Introduction

The role of Central Pattern Generators (CPGs) in motor control is well established (e.g., [19]). Motor control with CPGs is found in organisms ranging from mollusks (e.g., [18,35,44]) to control of locomotion speed in humans [8]. Based on the role of CPGs in motor control, CPG models have been used in controlling the motor behavior of robots (e.g., [45]), ranging from snake-like robots (e.g., [30]) to humanoid robots (e.g., [29,36]).

Here we want to investigate a role of CPGs in controlling higher level cognitive processing. The basis for such a role of CPGs is twofold. On the one hand, there are similarities between the microcircuits underlying CPGs in motor control and microcircuits observed in the neocortex (e.g., [46]). On the other hand, there are functional similarities between motor control and control of higher level cognitive processing. In this respect, Llinás [27] discussed the motor primacy in the organization of the brain and identified thinking as internalized movement. So, one would expect CPGs to play a role in this internalized movement as well.

An illustration of how cognitive processing could be related to motion control is found in the notion of cell assemblies formulated by Hebb [20]. Hebb identified three organizational principles by which cognitive processing could be related to brain processing. The first one is the well-known principle of Hebbian learning. Connections between neurons are modified when these neurons are concurrently active in a given process. In this way, information based on experience is learned. The second principle is the cell assembly that can result from Hebbian learning. When a given process is repeated over time, the neurons involved in that process will be stronger connected to each other, forming an assembly of cells. As a result, the assembly can be reactivated when only a part of its neurons are activated by a stimulus, because the assembly structure ensures that the other neurons are activated as well. Assemblies could be local, but they can also be global, interconnecting groups of neurons in different parts of the brain (cortex). These more global assemblies can be expected to occur in higher level cognitive processing (e.g., concept formation) because different forms of information will be combined in these processes (e.g., [32]).

Hebb's third principle is the "phase sequence" of assemblies that underlies thinking. In this view, a cognitive process typically results from a sequential activation of the assemblies (e.g., concepts) involved in the process (e.g., [5,24]). This sequential activation can be controlled by a stimulus, but it can also be controlled internally, e.g., when the activation of one assembly initiates the activation of another. Here, one can already see the relation with motion control. In sequential activation of assemblies, one assembly needs to be inactivated when another is activated, just as one

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set of muscles needs to be inactivated when another set is activated in movement control. So, as in movement control, CPGs could play a role in the sequential activation of assemblies underlying higher level forms of cognitive processing.

We will illustrate a role of CPGs in our neural architecture of language processing [38–41]. In this architecture, words are indeed implemented as cell assemblies proposed by Hebb. Sentence structures are then formed by temporarily connecting cell assemblies representing words (or word assemblies for short) in a 'Neural Blackboard Architecture' (NBA). The NBA allows sequential processing to occur, as for example the process of answering a question when a sentence is stored in the NBA. So, when the sentence *cat chases mouse* is stored in the NBA, the question "What does the cat chase?" results in a sequential activation of assemblies in the NBA, finally resulting in the activation of the assembly for *mouse* as the answer to the question. This process was simulated in [39]. In the simulation it was assumed that a CPG would control the sequential activation of assemblies, needed to produce the answer. However, the CPG was set by hand. Here we will develop and simulate a CPG that can be used to control this process. Before we discuss this CPG, we will first briefly outline the NBA and the role of control of sequential activation in this architecture.

2. Neural blackboard architecture for sentence structure

The NBA described by van der Velde and de Kamps [39] allows sentences to be processed and stored (temporarily). In the architecture, words are encoded as neural 'word' assemblies [31]. Such neural assemblies can be distributed over several parts of the brain. For example, assemblies referring to visible objects can be partially represented in the visual cortex and assemblies referring to verbs can be partially represented in the motor cortex. 'Fire engine' could be partially encoded by 'red' in the visual cortex and by 'loud' in the auditory cortex.

To form a sentence structure, word assemblies are temporarily bound to a neural 'structure' assembly in the blackboard (this can occur because each word assembly has a part that is connected to the NBA). Structure assemblies encode the relations between the word assemblies. Word assemblies can be simultaneously bound to several structure assemblies, allowing for unambiguous encoding of multiple instances of the same word.

Fig. 1 illustrates the representation of the sentence *cat chases mouse*. As illustrated in Fig. 1A, the word assemblies for cat, *chases* and *mouse* are distributed over the brain. Fig. 1B illustrates how structure assemblies of a specific type selectively bind word assemblies to form a sentence structure. So structure assemblies related to nouns (or noun assembles for short) bind to nouns and structure assemblies related to verbs (or verb assembles for short) bind to verbs. Furthermore, each structure assembly consists of a main assembly and subassemblies of a specific type. Subassemblies of the same type are used to bind structure assemblies to each other, in line with the structure of the sentence.

In Fig. 1B the structure assemblies N_1 (for *cat*) and V_1 (for *chases*) are bound by their agent sub-assemblies. This binding thus encodes that *cat* is the agent of *chases* in this sentence. Several structure assemblies bound in this manner can encode the syntactic structure of a sentence. Binding and control of activation in the architecture result from the selective activation of gating and memory circuits. These gating and memory circuits control the flow of activation within and between structure assemblies.

Fig. 1C illustrates a gating circuit that controls the flow of activation between the assemblies X and Y. The circuit is based on disinhibition. If assembly X is active, both neurons i_x and X_{out} will receive excitatory activation from this assembly. X_{out} will also receive inhibitory input from i_x when i_x becomes activated. This inhibition will prevent X_{out} from becoming active for as long as X_{out} and i_x are both activated. However, when I_x is driven to activation by an external input (given by a control signal) it will inhibit i_x. As a result, i_x will no longer inhibit X_{out} and activation can flow from assembly X to assembly Y.

The gating circuit illustrated in Fig. 1C also forms the basis for a memory circuit by which assemblies are bound. The only difference is that the external control signal that initiates the activation of I_x is replaced by a 'delay' assembly. The activity in the delay assembly is similar to the maintenance of activation found in experiments on working memory (e.g., [10]). The delay assembly is activated in the processing of the sentence. As long as it remains active, the assemblies it connects are bound because activation can flow from one to the other (for further details see [39]).

Using assemblies, gating circuits and memory circuits, a representation of a sentence can be made in the NBA. When a word is processed, a structure assembly will be activated in the blackboard. The type of structure assembly activated depends on the processed word. For example, a processed noun will activate a noun (N_i) structure assembly and a verb (V_j) assembly will be activated when a verb is being processed. Which specific structure assembly is activated is irrelevant as long as that assembly is free – none of its memory circuits are activated – and it is of the correct type.

When the sentence *cat chases mouse* (see Fig. 1B) is processed, the word assembly for *cat* is bound to N_1 by the activation of the memory circuit that connects these assemblies. *Chases* is bound to V_1 in a like manner. The binding between *cat* and *chases* is accomplished by binding the agent sub-assemblies of N_1 and V_1. To achieve this binding the two agent sub-assemblies have to be activated. Activating the gating circuits between the main assemblies N_1 and V_1 and their respective agent sub-assemblies allows activation to flow from the main assemblies to the sub-assemblies, thereby activating the sub-assemblies. Activation of the gating circuits is controlled by neural control circuits. Neural control circuits instantiate parsing operations based on the activation state of the neural blackboard and on which word assemblies are active (for details, see [39,40]). The subsequent binding between *chases* and *mouse* proceeds along similar lines.

The model illustrated in Fig. 1 is not the only neural model of sentence processing. Alternative models are models based on dynamics systems (e.g., [12]), reservoir computing (e.g., [21]) or recurrent neural networks (e.g., [37]). But these models do not produce information (e.g., answering questions) based on the sentence structure. By contrast, in the model in Fig. 1 a sentence structure is created in which the word representations given by the neural assemblies remain grounded. As a result, these assemblies can be used to retrieve information from the sentence or sentences parts. Recently, Sagara and Hagiwara [34] presented a neural model that can answer questions about sentences. But sentence processing in the model is based on a symbolic parser and sentences are represented as single nodes, associated to the nodes representing their words. Answers are derived from these associations, which do not give the ability to take the sequential (syntactic) nature of the sentence into account. Below we outline a dynamic process by which information from a sentence representation as illustrated in Fig. 1 can be retrieved in a sequential manner, based on the sequential and syntactic representation of the sentence. A CPG is then needed to control the sequential activation occurring in this process.

2.1. Answering binding questions

Once a sentence is stored, the information contained in the sentence is available in the NBA. Retrieval of this information is