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Simulations of a columnar architecture for cortical stimulus processing*

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How does the brain, most notably the visual system, manage to process and ultimately "understand" the immense amount of data, that is picked up by our sensors in each second of everyday life? What strategies, what neural algorithms does it use to interpret the sensory input in terms of what it "knows", and how does it decide when to learn and memorize new content?

Questions like these still go largely unanswered, when we come to view brain function as a whole – in spite of the overwhelming amount of detailed neurophysiological data that is available, and in spite of our progress in modeling and explaining individual brain functions in specific areas of the brain. The brain is probably not just a collection of highly specialized neural circuits, which provide individual optimized solutions at the various stages of processing, but it re-uses the same set of generic and powerful processing strategies over and over again. Thus, answering the above questions based on the available physiological data is virtually impossible, without having a useful hypothesis of brain function, ranging from local circuitry to the brain as a whole. We aim to answer these questions, founding on a concisely drawn functional model of a reappearing cortical circuitry, which is the very basis of cortical stimulus processing and understanding.

In [3] we have put forward a hypothesis of computation in neocortical architecture. It bridges the gap between processing of signals at the single-neuron level, and the processing of cognitive symbols at the level of knowledge representation: This model proposes the *cortical column* as a basic, generic building block of cortical architecture. The same columnar circuit is reused all over the cortex, applying a generic algorithm to varying sensory data. This model gives a detailed functional interpretation of the six-layered columnar cortical architecture (fig. 1) and related sub-cortical (thalamic) structures. It hypothesizes three intercommunicating columnar processing systems at each stage of the cortical hierarchy: The "A-system" (including the middle cortical layers IV and lower III) accomplishes fast bottom-up processing. Computation in this bottom-up pathway is heavily based on a spike-latency code, which is able to reliably encode stimulus properties in the timing of individual spikes [4]. In the A-system, the first wave of spikes traveling upwards in the cortical hierarchy can activate a coarse initial "local hypothesis" on the contents present in the stimulus. In the "B-system" (superficial layers II and upper III), this initial hypothesis is refined by slower processes, involving iterative exchange of information between columns both at the same (horizontal connections) and at different hierarchical levels. Finally, the "C-system" (deep layers V and VI) represents the local interpretation of the input signals that results from the local integration of bottom-up, lateral, and top-down signals. The local interpretation of the C-system is then fed back to the B-system of a lower level, inducing expectations, predictions, and consequently revised interpretations of the input signals at this stage. Subsequently, input signals that match the local prediction are suppressed, and only differences between predicted and actual signals can reach the next higher cortical level (cf. [5]). Thus, stimulus content is effectively expressed in terms of previously achieved knowledge (*self-reference*). Learning of new representations is induced, if the remaining activity is too large, and if the difference signal reaches the highest level of cortical integration, the hippocampal formation.

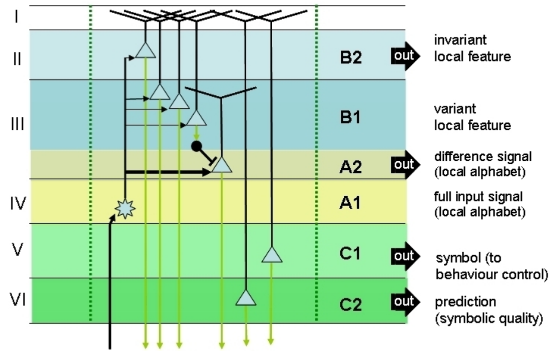

Figure 1: Layered model of a cortical column as proposed in [3]. Three different subsystems at different vertical locations (layers) are intertwined within each cortical column. The A-system (middle layers) accomplishes fast bottom-up processing of sensory signals. The B-system (superficial layers) represents the input from the A-system in a refined way by exchanging information with neighboring columns. The C-system (deep layers) develops representations related to action/behavior and predictions fed back to lower levels.

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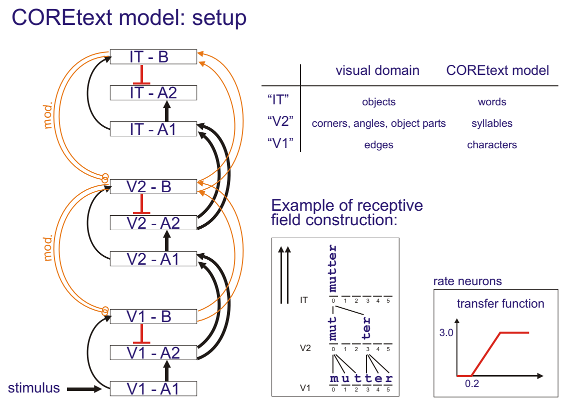

Figure 2: The "COREtext" model implements three cortical levels (denoted V1, V2, IT for convenience) including the columnar A and B subsystem to explore the neural activation dynamics and the "switching-off" mechanism (inhibition from B to A2), as proposed in [3]. We use text as a simplified input space, giving exact rules for the construction of receptive fields.

At the Honda Research Institute, we substantiate this model on several levels of detail. At the single neuron level, we investigate, under which conditions a spike-latency code can reliably be generated and maintained in the visual system [4], and we propose, how the visual system can immediately profit from the use of a spike-latency code, implementing *homogeneity detection* [1]. At the level of several cortical columns, we examine the information flow inside the column, and between columns of different cortical areas. We simulate a model prototype, that demonstrates the formation of a fast initial stimulus hypothesis, and its subsequent refinement by inter-columnar communication in a hierarchy of three cortical areas. In this reduced (but instructive) simulation, we implement word recognition from a string of characters (fig. 2). The three cortical areas represent letters, syllables, and words. Focusing on the intra- and inter-columnar dynamics, we show how the different processing systems interact in order to switch off expected signals and accomplish symbolic recognition of words, and how representations for new words can be constructed based on old representations (*self-reference*). At the level of the visual hierarchy, we implement a large-scale simulation of main parts of the visual system, involving several primary and higher visual cortical areas (V1, V2, V6, IT), as well as parts of the hippocampal formation (HF), and sub-cortical structures involved in generating eye saccades (fig. 3). In this model, we simulate the interplay of visual areas in object recognition. Area V4 exemplarily features the detailed columnar setup. It is embedded into the hierarchy of other visual areas, which are modeled as topographic feature maps and associative memories [2]. Using this model we can demonstrate trans-saccadic

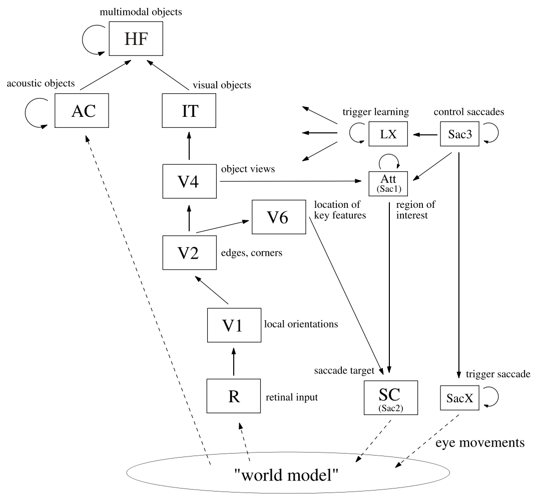

Figure 3: Layout of our visual model of saccadic object recognition. The model consists of various visual areas (R, V1, V2, V4, V6, IT), auditory areas (AC), hippocampal formation (HF), saccade related areas (SC, S1, S3), and some auxiliary areas triggering learning and the execution of saccades (LX, SacX). Currently only area V4 implements the full columnar model.

object classification and the learning of new object representations, based on the incremental refinement of an object hypothesis during a saccadic sequence.

In our contribution, we will give an overview of our different modeling approaches, ranging from the single-spike level, over investigations of the columnar dynamics, to a large-scale simulation of main parts of the visual hierarchy.

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