Visual binding, reentry, and neuronal synchrony in a physically situated brain-based device

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Abstract

By constructing and analyzing a physically situated brain-based device (i.e. a device with sensors and actuators whose behavior is guided by a simulated nervous system), we show that reentrant connectivity and dynamic synchronization can provide an effective mechanism for binding the visual features of objects.

The mammalian visual system contains a variety of cortical regions specialized to respond to different features such as shape, color, and object motion, and no single region has superordinate control. This poses the so-called 'binding problem': How do these functionally segregated regions coordinate their activities in order to associate features belonging to individual objects and distinguish among different objects? Most proposed mechanisms for solving the binding problem fall into one of two classes (i) binding through the influence of 'higher' attentional mechanisms and (ii) binding through selective synchronization of dynamically formed neuronal groups. It has been suggested that parietal or frontal areas could bind and select objects by means of an executive mechanism, for example, a spotlight of attention that would combine visual features appearing at a single location in space. Advocates of neural synchrony, by contrast, suggest that binding is an automatic, dynamic, and pre-attentive process enacted by low-level neural dynamics such as the linkage of neuronal groups by selective synchronization. These synchronized neuronal groups form into global patterns of activity, or circuits, corresponding to perceptual categories. A fundamental question for proponents of neural synchrony is how such emergent circuits contribute to an organism's rich and variable behavior, especially in cases that require preferential behavior towards one object among many in a scene.

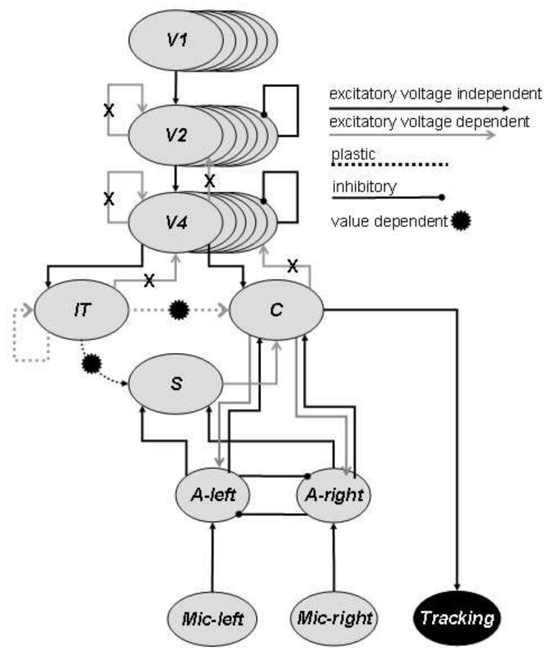

Figure 1: Neuroanatomy of Darwin VIII. The simulated nervous system contained 28 neuronal areas, 53,450 neuronal units, and approximately 1.7 million synaptic connections. Voltage dependent connections represent the contribution of receptor types (e.g. NMDA) that require postsynaptic depolarization to be activated. Changes in the strengths of value dependent plastic connections are modulated by activity in the value system (area S). Tracking commands were issued based on activity in area C. Areas *A-left/A-right* respond to auditory signals in Darwin VIII's environment.

A previous computational model of visual binding (Tononi et al., 1992) learned to make simulated saccades to preferred visual objects. This model included nine simulated cortical areas of the visual system, as well as reward and motor systems, and its performance showed that reentrant connections within and among areas facilitated the recognition and discrimination of multiple objects in a scene. However, despite its success in showing the capabilities of reentrant circuits, the model had several limitations. The stimuli used were taken from a limited set and were of uniform scale. Furthermore, its behavior did not emerge in a rich and noisy environment of the kind confronted by behaving organisms.

Here, we address these limitations by embedding a simulated nervous system in a real-world behaving device capable of engaging in rich exploratory and selective behavior. We describe the construction and performance of Darwin VIII, the latest in a series of brain-based devices (Krichmar and Edelman, 2002), in which, as a result of reentrant connectivity, synchronously active neuronal circuits are dynamically formed as the device engages in visually guided behavior and participates in a discrimination task. Darwin VIII contains simulated neural areas analogous to the ventral stream of the visual system (areas *V1, V2, V4, IT*), areas that influence visual tracking (area *C*), and a value system (area *S*). Value systems are neural structures that signal the occurrence of a salient cue from the environment and modify the brain-based device's behavior by modulating synaptic plasticity. These simulated areas are reentrantly connected and, to represent the relative timing of neuronal activity, each neuronal unit in each area is described by both a firing rate variable and a phase variable, where similar phases reflect synchronous firing. A high-level schematic of Darwin VIII's neuroanatomy is shown in Figure 1.

In our experiments, Darwin VIII autonomously approaches and views multiple objects which share visual features. After some time, it becomes conditioned to prefer one target object over multiple distracters, by association of the target object with an innately preferred auditory cue. Darwin VIII demonstrates this preference behaviorally by orienting toward the target object. Reliable discriminations are achieved by Darwin VIII despite the continual changes in the size and position of visual stimuli that result from self-generated movement in a rich real-world environment.

We were able to observe Darwin VIII's overall behavior while simultaneously recording the state of its simulated nervous system at all levels. Specifically, we observe the formation of synchronously active neuronal circuits for each object in Darwin VIII's visual field (Figure 2). These circuits, which are enabled by reentrant connections within and between neural areas, give rise to biases in motor area activity which in turn evoke discriminatory behavioral responses. By lesioning certain reentrant connections at different stages of the experimental paradigm, we show that reentrant connectivity and dynamic synchronization among neural areas are necessary for success in the discrimination task.

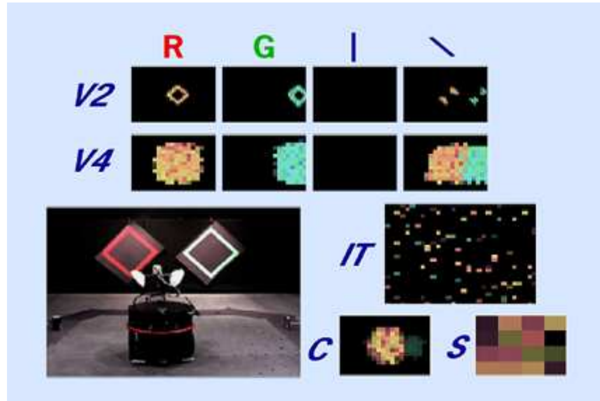

Figure 2: Snapshot of Darwin VIII's neuronal unit activity during an approach to a red diamond target (left) and a green diamond distracter (right). The panels next to Darwin VIII show the activity and phase of selected neural areas (sub areas in *V2* and *V4* are specialized - from left to right - for red, green, vertically, and diagonally oriented stimuli). Each pixel each area represents a neuronal unit, the grayscale represents a combination of activity and phase. The units responding to the attributes of the red diamond share a common phase, whereas those responding to the green diamond share a different phase.

Higher brain function depends on the cooperative activity of the entire nervous system, reflecting its morphology, its dynamics, and its interaction with the body and the environment. The development of Darwin VIII's nervous system was shaped by experience in a rich real-world environment, by the operation of value systems, and by the correlations on neural activity imposed by reentrant connectivity. As a result, Darwin VIII exhibited coherent interactions between local dynamics (i.e. activity in particular neural areas) and global dynamics (i.e. synchronously active circuits and broadly distributed neural circuits). In accord with theoretical views emphasizing the importance of binding through synchrony, we found that these interactions enabled Darwin VIII to solve the visual binding problem.

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References

Krichmar, J. and Edelman, G. (2002). *Cerebral Cortex*, 12(8):818–30.

Tononi, G., Sporns, O., and Edelman, G. (1992). *Cerebral Cortex*, 2(4):31–35.