Visual Binding Through Reentrant Connectivity And Synchronization In A Brain-Based Device

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Animals can effortlessly bind the attributes of stimuli to form coherent perceptual categories. Such categorization requires the activity of functionally segregated cortical regions each specialized, for example, to respond to features such as color, shape and object motion. Yet, there is no superordinate or single executive area binding these features across such specialized regions. The solution to this "binding problem" requires a mechanism to not only associate features relating to each object in a scene but also to distinguish between distinct objects. Two general classes of proposals have been put forward to solve the binding problem (i) binding through the influence of "higher" attentional processes and (ii) binding through selective synchronization of dynamically formed neuronal groups.

The appeal to attentional or "top down" processes often focuses on parietal or frontal areas, the operations of which are distant from early stages of sensory processing, to bind and select objects in a visual scene by means of an executive mechanism. For example, a spotlight of attention that would combine visual features appearing at a single location in visual space. In this view, strict limits are placed on the number of objects that can be simultaneously bound by the limited capacity of the attentional mechanism. Advocates of neural synchrony, which is often characterized as a "bottom-up" process, 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.

We have previously presented a computational model to account for visual binding (1). This model emphasized the interaction between neural areas, and showed that reentrant connections between different visual areas were sufficient for recognizing and selecting multiple objects in a scene. The model was trained to prefer a particular visual object via simulated saccades. Its performance showed that binding and discriminative behavior could be achieved through the interaction of different neural areas via reentry. Despite this performance, 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 (2), in which, through reentry, synchronously active neuronal circuits are dynamically formed as the device engages in visually guided behavior and participates in a discrimination task. Darwin VIII autonomously approaches and views multiple visual shapes containing overlapping features. It becomes conditioned to prefer one of these shapes to the rest and demonstrates this preference behaviorally by orienting toward the preferred shape when confronted by a scene made up of pairs of these visual shapes. Because these pairs of shapes had shared features, successful discrimination required binding of the features belonging to each shape. Darwin VIII contained simulated neural areas analogous to the ventral stream of the visual system (i.e. *V1*, *V2*, *V4*, *IT*), areas that influenced visual tracking (i.e. superior colliculus), and areas analogous to the frontal cortex and reward systems. These reward or 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.

We show that reentrant connections and dynamic synchronization between neural areas are necessary for success in our discrimination task. Instead of relying on only "top-down" or "bottom-up" processes, Darwin VIII exhibited coherent interactions between local dynamics (i.e. activity in each neural area) and global dynamics (i.e. synchronously active circuits distributed across the nervous system). These patterns of activity were dynamic and degenerate: structurally different circuits could mediate similar recognition and discriminative behaviors. Thus, successful performance in exploring a rich, dynamic real world environment required a combination of synchrony, and value-dependent modulatory activity that constrained the interactions among local and global neural processes.

This work was supported by the W.M. Keck Foundation and the Neurosciences Research Foundation.

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2. Krichmar, J. L. & Edelman, G. M. (2002) *Cereb Cortex* **12,** 818-30.