Statement of Research Achievements – Earl K. Miller

Earl K. Miller has published over 160 papers (H-index = 78, over 51,000 citations) relating neural activity in non-human primates to a wide range of cognitive functions including executive control, working memory, attention, categorization, and decision-making. Earl was an early innovator of techniques for studying the activity of many neurons in multiple brain areas simultaneously. This has provided insight into how different brain structures interact and collaborate. Earl’s work has established a foundation upon which to construct more detailed, mechanistic accounts of the neural basis of executive brain functions.

An Integrative Theory of Prefrontal Cortex Function. Earl (with Jonathan Cohen) published a highly influential and highly cited paper proposing a new neurobiological theory of prefrontal cortex function (Miller and Cohen, 2001). Prior to that, the dominant hypothesis was that the prefrontal cortex was involved in holding information in working memory. They instead argued that the prefrontal cortex serves a specific function in executive control: the active maintenance of patterns of activity that represent goals and the means to achieve them. They provide bias signals throughout much of the rest of the brain, guiding the flow of neural activity along pathways that establish the proper mappings between inputs, internal states, and outputs needed to perform a given task. This is now a dominant hypothesis guiding contemporary work on the neurobiological of the prefrontal cortex and executive brain functions. It is one of the most highly cited papers in the history of neuroscience.

Neural basis of categories, rules and concepts. In a series of investigations, Earl’s lab showed that the activation of higher cortex neurons reflects the abstract cognitive top-down processes. They showed that neural activity represents abstract rules such as "same vs. different", the category or quantity of visual stimuli, and that PFC activity reflects the flexible remapping of stimulus-response associations. Prior work treated prefrontal cortex as if it were high-level sensory cortex.

Multifunctional, mixed selectivity, neurons. For much of 20th century neuroscience, a doctrine held that each neuron is a processing unit with a specific function. Beginning in 2000, Earl and colleagues provided compelling evidence that higher cortical neurons are multifunctional. They signal different information in different tasks, each participating in different neural ensembles. More recently, with Stefano Fusi, Earl developed a model and further experimental evidence of how mixed-selectivity neurons provide the brain with the computational horsepower needed for higher cognitive functions. At first, the idea of multifunctional neurons was met with a good deal of skepticism. Now, it is widely accepted and studied.

Top-down vs bottom-up cortical processing in different frequency channels. In a series of papers beginning in 2007, Earl and colleagues showed that bottom-up sensory signals feedforward in the cortex via higher frequency (35-55 Hz) gamma synchrony between cortical areas. By contrast, top-down feedback signals are associated with lower frequency (22-34 Hz) alpha/beta synchrony. Thus, it seems that the cortex uses two different “spots on the FM radio dial” for these two major modes of processing.

The initial studies focused on top-down vs bottom-up visual attention. Over the years, Earl has expanded and extended this work. He has found evidence that the interplay between the alpha/beta (top-down) and gamma (bottom-up) frequency bands supports the gating of information in and out of working memory. This is one of the first insights that can explain the most important feature of working memory, that it is under volitional control. Earl has recently extended this work further to explain a fundamental cortical function, predictive coding. Deficits in predictive coding are thought to underlie the sensory overload seen in autism. An imbalance between the frequency bands may explain that.

Brain waves regulate neural communication. For a long time, it was assumed that what mattered was which neurons are activated, not their rhythms. Earl’s lab has published a large and growing body of work suggesting that brain rhythms play a central role in communication within the brain. This includes discoveries that show that oscillating “brain waves” may control the timing of shifts of attention. They also found that different items simultaneously held in short-term memory line up on different phases of each brain wave. This may explain why we can only think about a few things at the same time.