Statement of Research Achievements – Earl K. Miller

Earl K. Miller has published over 150 papers (H-index = 77) relating neural activity in non-human primates to a wide range of cognitive functions including executive control, working memory, attention, categorization, learning, 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 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 neurobiology 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 long series of investigations, Earl’s lab showed that the activity of higher cortex neurons reflects 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 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 a body of evidence that higher cortical neurons are multifunctional. They signal different information in different tasks, as if they participated in different neural ensembles in different contexts. 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. By contrast, top-down signals feed back via 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. This includes evidence that the interplay between the alpha/beta (top-down) and gamma (bottom-up) frequency bands gate information in and out of working memory. This insight can explain working memory’s most important feature, that it is under volitional control. Earl has recently extended this work to explain a fundamental cortical function, predictive coding. Deficits in predictive coding are thought to underlie the sensory overload seen in autism. Imbalance between the frequency bands may explain that.

Brain waves and cognition. For a long time, it was assumed that what mattered was which neurons are activated, exactly when was not seen as critical. Earl’s lab has published a large and growing body of work suggesting that brain rhythms play a central role in cognition. This includes discoveries that oscillating "brain waves" control the timing of shifts of attention. They also found that different items simultaneously held in working memory line up on different phases of each brain wave. This can explain the limitation of cognitive capacity; we can only think about a very few things at the same time.