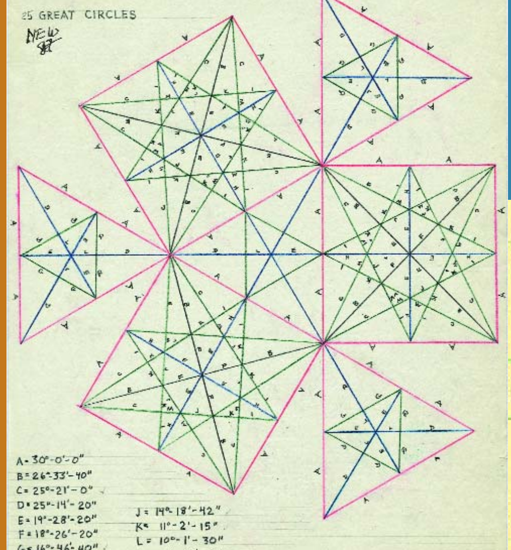
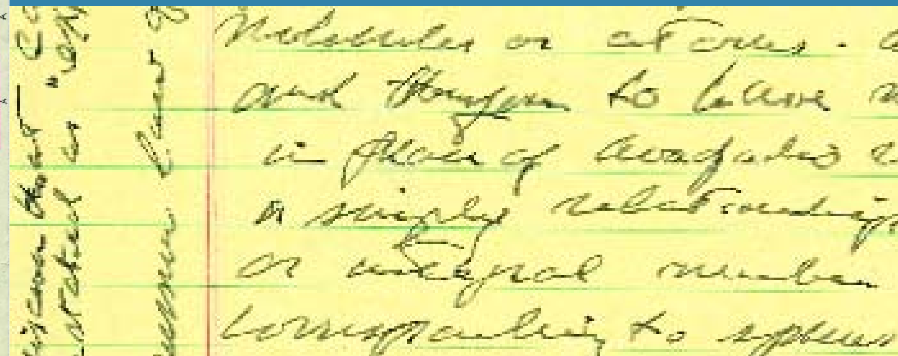




ROBERT DESIMONE
MCGOVERN INSTITUTE FOR BRAIN RESEARCH, MIT

How the Brain Pays Attention

Approximately 450 million people suffer from a mental disorder, and one in four families has at least one member with a mental disorder. The World Health Organization estimates that 30 percent of all lost workdays are due to neuropsychiatric conditions, which in developed countries costs between 3 and 4 percent of the gross national product. Robert Desimone, director of the McGovern Institute for Brain Research at MIT, emphasizes the need for neuroscience research—not just in terms of the public health effects of brain disorders, but also because of its potential impact beyond treating people with diseases, including, for example, how we teach our children and how we deal with the effects of aging. Research at the McGovern Institute is centered on systems neuroscience, which looks at how neurons function within larger brain systems to mediate complex behavior in both healthy and diseased states. Desimone's research focuses on attention and the mechanisms that allow us to filter out distracting information and accomplish the task at hand.

NOTEBOOK

It is crucial to our survival that our brains filter out an enormous amount of input. The question is, how does that filtering occur?

Our theory is that the neurons in the brain may be listening for synchrony in their input. That is, the structured information controls the neuron's output, enabling it to filter out the noise.

The greater the synchrony, the faster monkeys were able to respond to events. Indeed, we were able to use measurements of their neural activity to predict how fast they would respond—and did so at least half a second before the monkeys actually made a move.

If brain functioning depends upon neurons that essentially sing to one another in different frequency ranges, then how might experiences with music affect the brain's ability to process information?

The McGovern Institute for Brain Research

Founded in 2000, the McGovern Institute has a mandate to use neuroscience to help people with brain disorders and is committed to advancing human understanding and communication for all of humanity. Faculty at the institute focus on three interrelated research areas: perception, cognition, and action. As an example of how the brain integrates these three functions—without any apparent effort on our part—consider a train coming toward you:

Perception enables you to notice the sights, sounds, and vibrations of the train.

Cognition allows you to evaluate this information and form the emotional reaction of fear, the recognition of danger, the focused attention on the train, the calculation of its speed, and the decision to act.

Action, the behavioral result of perception and cognition, saves your life as you jump out of the way of the approaching train.

A serious dysfunction in any of these areas could keep you from responding appropriately. Indeed, many brain disorders involve problems in one or more of these functions. Autism, for example, causes dysfunctions in social cognition, such as in how to evaluate social input like a smile or a frown. Parkinson's disease manifests itself in motor difficulty. But autism can cause clumsiness, and Parkinson's may cause mentally diffuse thoughts, and both entail altered perceptual sensitivities. Unless we understand the whole system, we will design treatments that may address isolated symptoms but not necessarily the underlying disorder. Thus the research at the institute is undertaken from a systems perspective, which shows not just how individual neurons work, but how they work together with neighboring neurons to affect the brain functions involved in diseases and disorders, and in learning and cognition. Collaboration among researchers working from different disciplines is seen as the key to achieving common goals.

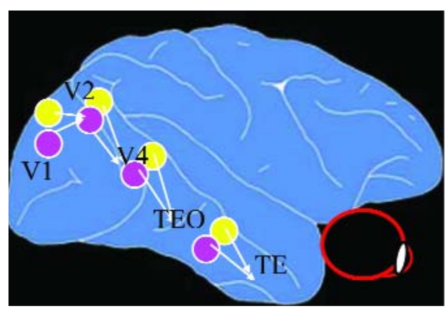
Attention and Executive Control

The influence of our brains' attentional mechanisms is profound. We are able to both ignore internal and external distractors and inhibit competing responses to situations in order to accomplish tasks. As we move about and look around throughout the course of our daily lives, we may think that we're processing everything, but in fact all kinds of information is coming into our sensory systems that we do not process. For example, if you're reading this now, sitting down, hopefully you're not paying attention to the seat cushion that you're sitting on. It is crucial to our survival that our brains filter out an enormous amount of input. The question is, how does that filtering occur? Typically, a neuron in the brain receives hundreds or even thousands of inputs from along its dendrites, yet it will send just one message out its axon and downstream to the next area of the brain. Figuring out how that one key message gets through all the others will shed light on the many impairments of attention and executive control that are common in mental disorders.

Our experiments focus on visual attention. As illustrated in Figure 1, the visual pathway in humans (and monkeys, on whom the initial experiments were conducted) begins in area V1, the primary visual cortex in the back of your head. The neurons there are sensitive to just small lines and spots. The pathway moves forward, increasing your visual processing, so that by the time it arrives at the temporal lobe just above your ear the neurons are firing and you see complex images of faces and other things—but not of *all* the stimuli that you were subjected to.

Figure 1.

The Visual Pathway



Area V1—where perception starts
Area TE—where perception ends

So how is the neuron, essentially, listening to some of its inputs and not others at any given moment in time? The answer has to do with the role of temporal processing in the brain. We know that neurons do not simply add up all the thousands of inputs they receive; rather, they are quite sensitive to the timing of the inputs. So, for example, if the activity of two neurons feeding another neuron further down the visual pathway is correlated in time, they might be more likely to control that neuron's response at that moment, and thus that information would pass down through the system.

Figure 2 shows digital pulses coming in to a neuron from a population of neurons feeding it. As you can see, the signals have no correlation in time; those neurons are simply sending information through as it comes in. It amounts to noise. Figure 3, on the other hand, shows a set of input neurons with some correlation in their structure. In an auditory demonstration of these signals, those in Figure 2 would sound like static, whereas the signals in Figure 3 would form a structured, synchronized tone.

Figure 2.

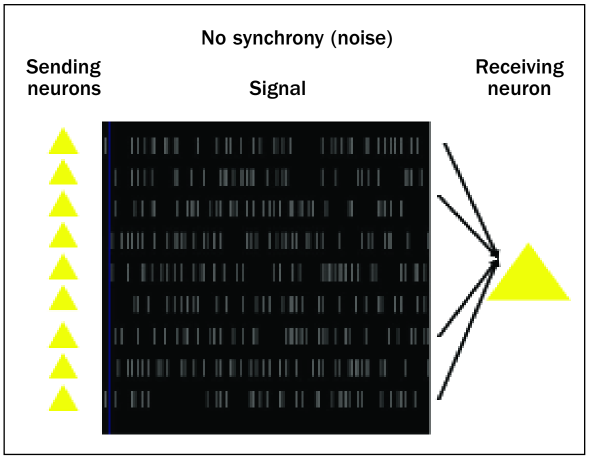
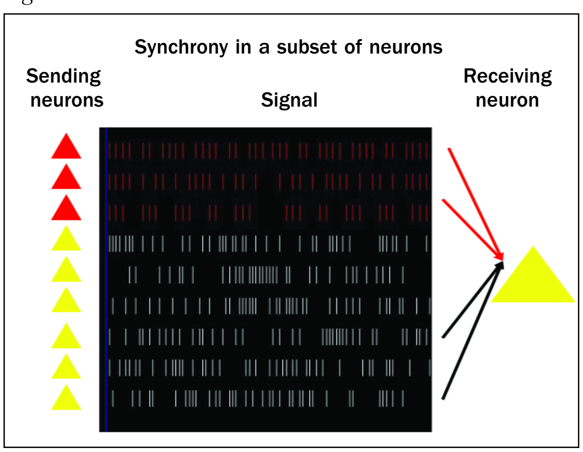


Figure 3.



Our theory is that the neurons in the brain may be listening for synchrony in their input. That is, the structured information controls the neuron's output, enabling it to filter out the noise. We tested this theory with experiments on monkeys trained to pay attention to a particular pattern on a computer screen while ignoring another. (They were looking for a small color change in the pattern they were attending to and would be rewarded for signaling it.) We recorded the monkey's brain activity based on what it was paying attention to, and found that synchronized activity was modulated based on where the animal was attending.

When the monkeys directed their attention toward a stimulus, their synchronous neural activity increased. The most common frequency of these neural interactions is around 50 to 60 hertz, similar to the line frequency of electrical systems. This seems to be a sort of fundamental frequency that the brain operates on.

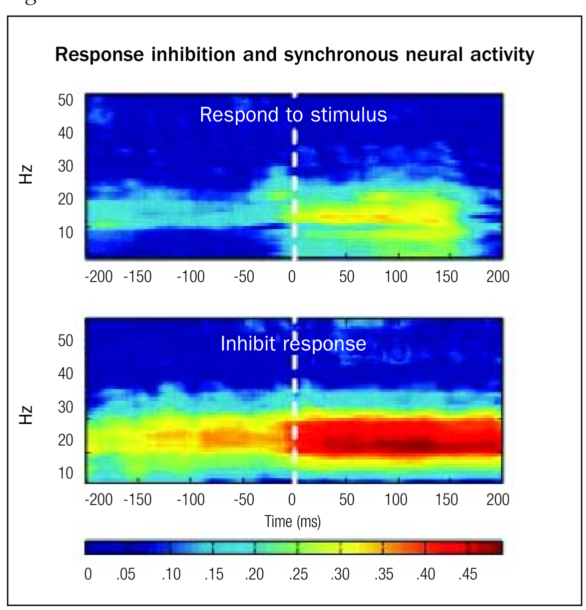
The greater the synchrony, the faster the monkeys were able to respond to events. Indeed, we were able to use measurements of their neural activity to predict how fast they would respond—and did so at least a half second before the monkeys actually made a move.

Our attentional system involves not just filtering out information, but also making sure that we don't respond inappropriately to stimulation that isn't important. To test this mechanism, we trained monkeys to respond (by pushing a lever) if one stimulus changed color but to ignore another stimulus that changed color. Figure 4 shows the difference in synchronous neural activity across these activities.

There is far more synchronized activity in the brain when the monkey is suppressing a response, which means it's working harder to do so. Notice that the inhibition activity, or executive control, occurs in a low frequency range, around 10 to 20 hertz. We know from research on the properties of neurons that they are tuned to different frequencies for their inputs, which presents a sort of multiplexing in the way the brain operates at different frequency levels.

We also noted that when the monkeys' neurons coding the distracting stimuli synchronized their activity, the monkeys completed their action far more slowly than when their neurons synchronized for the stimuli to which they

Figure 4.



were supposed to be paying attention. A similar process might occur when a child at school observes the birds outside the window instead of the teacher at the blackboard.

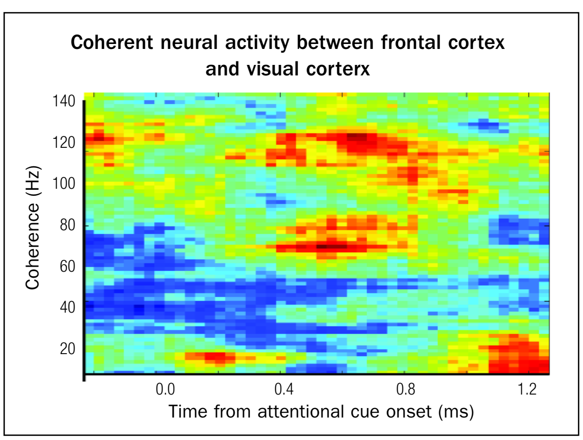
So we know that the visual pathway conveys information down to the temporal lobe, enabling us to recognize people's faces and other complex images, by synchronizing the activity of the neurons carrying the important information and filtering out the rest. This brings us to the next, fundamental question: What controls the synchronous activity in the brain's visual system?

To explore this question, we first used human subjects and functional magnetic resonance imaging (fMRI) scanners to pinpoint the areas of the brain involved in visual attention and, likewise, where the control occurs. However, although MRI and fMRI scanners show the *location* of brain activity quite well, they don't shed light on *how* the brain is working, at a fine temporal time scale. So we used a technique called magneto-encephalography (MEG), which detects the tiny fast changes in magnetic fields caused by neurons' digital pulses. MEG provides detailed data about the brain's temporal processing of signals—which our previous work had shown to be of key importance.

We measured human subjects' brain activity using MEG while they performed tasks quite similar to what we had the monkeys do (we didn't tell the human subjects that). That is, they focused on a screen and pressed a button when a certain object that came into view changed color, but not when a different object (a distracter) changed color.

The results were clear: the frontal cortex and the parietal region of the brain—the same attention controls regions localized by the fMRI studies—synchronized their activity with the visual processing areas of the cortex. Figure 5 shows the level of coherence (synchronized neural activity) between the two regions in different frequency bands (hertz).

Figure 5.



Higher degrees of synchrony are shown with colors at the red end of the spectrum. In the high frequency range, the frontal cortex has synchronized its activity with the visual system, presumably targeting the neurons processing the information from the attended object. For example, if the subject was confronted with objects A and B but was instructed to attend only to object A, then the frontal cortex would synchronize its activity with the neurons processing object A in the visual cortex. Those neurons would then be able to signal the color change, and would also cause the memory of object A to be passed on to systems for visual awareness and memory storage. In that way, subjects would be able to describe and remember object A, but not the irrelevant object B.

Conclusion

It has been widely believed that the attention and executive control problems common in mental disorders such as ADHD, schizophrenia, bipolar/mania, unipolar depression, and Parkinson's disease are a function of the *magnitude* of brain activity, and indeed drugs to treat these conditions are based on this premise. However, our research indicates that it is not the magnitude of activity that correlates to the ability to pay attention or inhibit inappropriate responses so much as the level of *synchrony* of neural activity. This finding has led us to consider whether entirely different drug compounds that might alter the timing of neural activity to increase the chances of synchrony may hold promise.

In addition to medical applications, our understanding of the brain's workings is also influencing our thinking about how we educate our children. For example, if brain functioning depends upon neurons that essentially sing to one another in different frequency ranges, then how might experience with music affect the brain's ability to process information? We have begun new experiments at the McGovern Institute involving children and musical training that build on what we now know about the brain's temporal synchrony. It may be that there's a symphony inside our brains, and it will take a symphony to lead us to understanding it.

ROBERT DESIMONE is director of the McGovern Institute for Brain Research at MIT, where he oversees a broad research program ranging from genetics in the worm to human cognition. Prior to joining MIT, he was scientific director of the National Institute for Mental Health. Desimone can be reached at desimone@mit.edu.