Tall buildings, bridges, and many other artifacts possess oscillatory and resonant properties that rarely serve a purpose, and most often these properties are outright detrimental to function. These everyday examples automatically pose a thorny question: are oscillations an essential ingredient of the brain "design," or are they simply an inevitable byproduct of the opposing forces that are so ubiquitous in neurons and neuronal networks? Throughout this volume, I have tried to convince the reader that oscillations in the brain serve useful functions and that, without understanding these rhythms, the brain cannot be fully understood. However, I postponed addressing the difficulty involved in providing a definite answer to this difficult question. I also claimed that evolution took advantage of the ease with which synchrony can be brought about by oscillations at multiple temporal and spatial scales. However, I have not addressed the tough question of whether oscillations are critical for the emergence of the most complex brain operations, as well. Because oscillations and complex systems have been extensively discussed in the consciousness debate, it would be unfair to finish a book on brain rhythms without bringing up this much-debated issue.[2] Below are my thoughts, without pretending that I have the right solutions to these difficult problems.

Brain without Oscillations?

Most experiments discussed in the preceding Cycles dealt with correlations between some overt or covert behavior and oscillations. Providing only correlations, as supportive evidence for a function, is usually viewed with skepticism. In general, there are two types of objections presented against the case for brain oscillations. First, "I do not see them in my experiments; therefore, they do not exist or are not essential." Second, "My intervention eliminated the oscillations but did not affect behavior." These objections are relatively easy to dismiss on logical grounds. For example, the absence of evidence (not seeing it) is not sufficient evidence against the existence of a rhythm. One should look harder and use higher resolution methods. Furthermore, elimination of the rhythm may not have been complete, or the behavior under investigation may not have depended on the network examined. Arguments in favor of rhythms are similar and equally vulnerable. First, "In my experiments, a specific behavior is always accompanied by a

2. Crick and Koch (1990) suggested gamma oscillation as a carrier of conscious experience, although they subsequently rejected it in favor of a special type or group of neurons with hitherto undisclosed features (Crick and Koch, 2003; Koch, 2004). More recently, they pointed to the claustrum as the critical structure in consciousness because of its widespread cortical and subcortical connections (Crick and Koch, 2005). Rodolfo Llinás conjectured that consciousness is the product of a resonance between the specific and nonspecific thalamocortical systems in the gamma frequency range (Llinás et al., 1994). Freeman (1999) describes consciousness as a two-step process, led by the intentional causation self and followed by the awareness of the self and its actions. The two steps are realized through hierarchically stratified kinds of neural activity, but the functions and nature of neuronal activity of these processes are not detailed.

particular oscillation." Second, "Whenever my intervention affects oscillations, behavior is always impaired." These arguments can also be easily dismissed. First, correlation is not causation. Second, the intervention may not have been selective enough, and the behavioral impairment may not have been caused by the absence of oscillations but by some unwanted and unobserved side effect of the perturbation.[3]

The acid test for providing a definite proof for the essential role of brain rhythms in computation and brain function would be to selectively eliminate them and examine what is left after the complete lack of oscillatory timing. Unfortunately, this test in its pure form cannot be performed for reasons I discussed in previous Cycles. I briefly reiterate those arguments here. Most oscillations in the brain are not driven by an independent pacemaker but emerge from nonoscillatory constituents. Even when a pacemaker is identified, it is typically embedded in large networks with a complex feedback to the rhythm-generating neurons. As a result, oscillations are not a product of some independent function or structure that can be physically removed or selectively manipulated, leaving the rest of the brain patterns invariant. In fact, there is a logical absurdity in the quest of expunging oscillations selectively. Oscillation is an emergent property; that is, it reflects an order parameter that, in turn, affects the parts that gave rise to it. Thus, there is nothing "extra" to eliminate without fundamentally interfering with the elementary properties of the parts. Oscillations and other emerging collective patterns do not have "receptors" that can be affected by drugs or other means; only individual neurons do. It is not possible to selectively eliminate a rhythm without altering membrane channels, synapses, firing patterns of individual neurons, or their temporal interactions.[4] The problem in the quest for selective elimination of an order parameter lies in the reciprocal causal relationship between parts and the whole of an emergent quality, such as an oscillation.

Given the difficulty in providing an acid test, the baffling question naturally arises of whether a brain without oscillations can function properly. In principle, the answer is yes, as long as synchrony of neuronal assemblies can be brought about by some other mechanism(s) at the right time scales. In other words, what may not be essential is the rhythmic aspect of synchrony. As discussed in Cycle 5,

3. A scientific hypothesis or theory, of course, cannot be proven. A proof can be provided only when the rules are known, as is the case in mathematics. But in science, the rules are not known. Hypotheses and theories are constructed to guess what those rules might be. Good theories are not proven but rather are not (yet) replaced by more universal theories.

4. Nearly all interventions that affect oscillations are associated with gross changes of firing rates and/or alteration of the balance between excitation and inhibition. Our laboratory found a notable exception to this general rule. Activation of cannabinoid receptors, the brain targets of marijuana, preserved the firing rates of both pyramidal cells and interneurons in the hippocampus. Nevertheless, it reduced or eliminated theta, gamma, and ripple oscillations. The effect is due to a balanced reduction of presynaptic release of both GABA and glutamate and the ensuing reduction of population synchrony. While individual neurons keep emitting the same numbers of action potentials under the drug's influence, the spikes are no longer associated with assembly behavior (Robbe et al., 2005). The impairment of oscillation and synchrony may explain the detrimental memory effects of marijuana.

computers, TV sets, and other devices can also run, in principle, without oscillatory clocks, provided that some other mechanisms do the necessary temporal coordination across all levels of computation. If proper timing can somehow be provided by a nonrhythmic solution, the same brain hardware could perform all functions. However, this imaginary brain has to deal with further problems. First, it has to eliminate or randomize all time constants of its constituent neurons and their connections, because such constants are natural sources of oscillations. Second, it should eliminate the balance between opposing forces, such as excitation and inhibition or ion influx and outflux, because these opposing forces are also natural forces of oscillations. Alternatively, special mechanisms should be introduced for the annihilation of the emergent oscillations. Elimination of oscillations would also require introducing other mechanisms to keep track of time. In other words, avoiding oscillations and their consequences on the population behavior of neurons is much more complicated than exploiting the synchronization consequences of naturally emerging oscillations. Oscillations are ubiquitous in all brains, small and large; therefore, it is expected that such inherent features would be exploited by evolution. Rhythms naturally arise from the opposing forces that are so fundamental for brain operations, and oscillations are a "free" source of synchronization and timing. Understanding the utility of brain rhythms is possible only from this evolutionary perspective. On the other hand, the evolutionary argument also implies that oscillations play a role at all levels of brain function, from the simplest to the most complex, including the subjective character of brain computation.

Consciousness: A Function without Definition

What is the difference between a blink and a wink? The straightforward answer is that you must be conscious to execute a wink whereas blinking is a simple reflex. And what is the difference between declarative and nondeclarative memories? The answer is that we are aware of declarative memories; therefore, we can consciously declare them, which is not the case for nondeclarative memories. The explanatory power of these answers, of course, depends on the understanding of the hypernym "consciousness," which supposedly makes the distinction between the declarative and nondeclarative or voluntary and automatic clear. Consciousness is the crutch of cognitive neuroscience, perhaps the most widely used covert explanatory tool for the classification of mental phenomena. Yet, this frequently used hypernym does not even have a definition. Is it a product, a process, or a thing? There is not even good agreement what the theory about consciousness would be like.[5]

5. Stating that a wink is voluntary whereas the blink is involuntary faces the same linguistic problem since the hypernym "volition" remains undefined. Juarrero (2000) is a good guide for the philosophical debate about the voluntary vs. involuntary distinction. The compilation of essays on the self

Although definitions of c
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be helpful to list some of the
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about the brain is that its w
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are not.[7] Sagan's reductionis
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consciousness as

> a process in which informa
> perception is combined int
> the system and its environ
> the needs of the organism,
> to adjust the organism to it

This contextual definition ha
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ilar to that of humans. Giulio
defines the problem within th
ity to integrate and differen
consciousness.[10] In contrast
dualistic view that consciou
matter.

and soul by Hofstadter and Dennett
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the problem.

6. Sagan (1977), p. 26.

7. The "hard" problem of consc
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8. In common parlance, conscious
The word "consciousness" comes fro
which we know." However, in many l
tion" of a brain's output in light of res
Plum and Posner (1980) define consci
(p. 242). This medical definition only
ness." Faced with the difficulty of an
consciousness for granted ("Man, if y
strong) or ignore it ("If you can't expl

9. John (2005), p. 145.

10. Tononi's information theory m
perience is one and the same thing as