Moving rhythms

Eve Marder

One hundred years ago, neuroscientists watched children and cats walking, jumping and running, and realized that these and other rhythmic movements require the orderly and progressive activation of many different muscle groups. How does the nervous system achieve alternate contraction of extensor and flexor muscles, timed correctly so that the skipping child does not trip or the flying locust fall from the sky?

On first principles, you, like the early neuroscientists, might propose two different classes of models to explain the generation of rhythmic movements. First, you might suggest that sensory receptors would continuously monitor the position of all limbs and joints, thus activating reflexes to trigger the next appropriate movement. Second, you might suggest the existence of an oscillatory circuit in the brain stem or spinal cord in vertebrates, or in central ganglia in invertebrates, to provide the essential timing for the sequential activation of the muscles needed to produce the desired repetitive movement. The former mechanism has been termed 'chain of reflexes' and the latter 'central pattern generator'.

Many neuroscience textbooks and almost all general biology books introduce the myotactic or stretch reflex. Consequently, it is often mistakenly assumed that the stretch reflex is the basis of rhythmic movement. For historical reasons, biology books and many neuroscience courses give little or no treatment to the large body of experimental work showing that rhythmic movements are organized by oscillatory central pattern-generating circuits in invertebrates and vertebrates.

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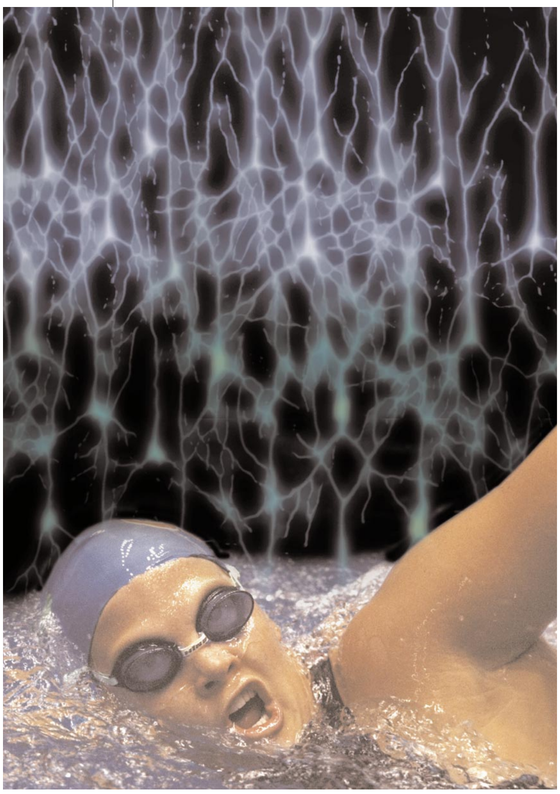

Today, we define central pattern generators as circuits that can produce rhythmic motor patterns in the absence of phasic drive, either from a sensory input or a descending control pathway. In other words, a central pattern generator is present when the existence of a rhythm does not depend on specific timing cues from peripheral or higher centres in the animal, although these inputs will certainly alter the motor patterns produced by the central pattern generator.

The existence of central pattern-generating circuits was first demonstrated by experiments showing that rhythmic movements are still produced after all the sensory feedback from limbs is removed. Today, we study 'fictive' motor patterns produced by pieces of the nervous system removed from the animal, similar to those that would drive movement if the muscles were attached, but termed fictive because the nervous system is no longer attached to its target muscles and sensory inputs. In many invertebrate animals, isolated ganglia produce fictive motor patterns. Spinal cords isolated from rats, mice, lamprey and chicks are all able to generate them, and slices of vertebrate brain stem generate fictive respiratory rhythms.

How does a group of neurons produce oscillations driving different motor neurons to fire rhythmically out of phase with one another so that the left and right legs can step in alternation? There are two general strategies for producing rhythms. Some are driven by neurons that are themselves oscillators, and that act as pacemakers. These neurons are similar to the pacemakers in the heart, and have specific combinations of voltage-dependent ion channels causing them to fire rhythmically in bursts of action potentials in the absence of rhythmic synaptic drive. It is thought that the circuit controlling respiration in vertebrates depends on such pacemaker neurons.

Other rhythms result from synaptic interactions among neurons that are not themselves rhythmically active. In this case, the rhythms are considered to be an emergent property of the circuit, resulting from interactions among the neurons of the circuit and the properties of individual neurons. In all cases, the specific timing of the circuit elements results from the synaptic connectivity among the circuit neurons.

Central pattern generators

How the nervous system achieves alternate, correctly timed contraction of extensor and flexor muscles.

Does the existence of central oscillatory circuits mean that reflexes and sensory feedback are unimportant for movement? Emphatically not. Sensory input is clearly important in shaping rhythmically generated movements so that they are appropriate to what the animal is doing at the time. Walking and swimming call into play neurons found in many brain regions, as well as the spinal-cord circuits and peripheral sensory neurons. It is the interplay among all these different structures that allows both relatively simple movements, such as walking over level terrain, as well as complex sequences of movements, such as in dancing or mountain climbing. All central pattern-generating circuits are subject to modulation by neurotransmitters and hormones, which can alter the frequency and intensity of the motor patterns produced by acting on specific subsets of circuit neurons.

New therapies to improve recovery after damage to the spinal cord could depend crucially on an appreciation that the spinal cord contains circuitry important for the generation of rhythmic movement. In principle, some rhythmic movement could be re-established below sites of spinal-cord lesion if the appropriate neuromodulatory environment were supplied to the central pattern-generating circuitry in the spinal cord. There are hopes that treadmill training will help to maintain the integrity of the neural circuits below lesions and facilitate functional recovery.

Rhythms are found in many areas of the brain, although their roles are not always clear. This makes it all the more important to understand the neuronal mechanisms by which rhythms with clear behavioural meaning are generated. ■

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FURTHER READING

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