Humans are capable of an impressive repertoire of motor skills that range from simple movements, such as looking at an object of interest by turning the head and eyes, to complex and intricate series of movements, such as playing a violin or executing a triple somersault from a balance beam. Most movements are not performed perfectly the first time around, but instead require extensive periods of practice. During practice, we detect errors in motor performance and then modify subsequent movements to reduce or eliminate those errors. The iterative process of improving motor performance by executing movements, identifying errors, and correcting those errors in subsequent movements is called motor learning.

Motor learning occurs in behaviors that range in complexity from simple reflexive movements to highly developed skills. The simplest form of motor learning is adaptation, in which muscular force generation changes to compensate for altered mechanical loads or sensory inputs. Adaptation can involve movements across either a single joint or multiple joints, and can occur in both reflexive and voluntary movements. The best understood example of this type of motor learning is in the vestibulo-ocular reflex, in which eye movements normally compensate for motion of the head such that images remain stable on the retina during head movements. If subjects experience persistent image motion during head movements (e.g., after vestibular trauma or when wearing new corrective lenses), motor learning produces adaptive increases or decreases in compensatory eye movements that restore image stability during head movements.

Motor learning is not a unitary phenomenon, but can affect many different components of sensory and motor processing. Motor control involves both simple movement trajectories and complex series of movements in which multiple muscles and joints must be controlled in precise temporal sequence. Motor learning refines simple movements by altering the magnitude and timing of muscular force generation. For complex movements, motor learning is required to select and coordinate the appropriate muscular contractions, to link together motor subroutines, and to create new motor synergies by combining forces generated across multiple joints in novel spatial and temporal patterns.

Sensory processing is intimately linked with motor learning. Sensory information about the outcome of a movement is used to detect and evaluate errors in motor performance. The nature of the sensory information used can vary and depends on the movement being learned. For example, when learning to hit a tennis ball, vision provides the most salient information about the accuracy of the shot, but somatosensory information about the angles of the elbow and wrist and the feel of the ball against the racket also provide important cues. A violin player evaluates her performance with the auditory system, by listening for mistakes, and also by monitoring the pressure of strings against fingers. As subjects attempt new movements and refine existing skills, they develop expectations of the sensory consequences of their movements. During motor learning, the expected sensory outcomes of a movement are compared with the actual outcomes, and the difference between what was expected and what actually occurred is used to drive changes in subsequent movements.

The sensory inputs used to detect and correct errors in motor performance can change with practice. At the initial stages of motor learning, a subject may attend to a variety of sensory stimuli, but as learning proceeds, attention becomes restricted to salient sensory stimuli until eventually, as the movement becomes perfected, the reliance on sensory cues can disappear altogether.

The memories formed during motor learning are not accessible to conscious recall, but instead are expressed in the context of motor performance. This type of subconscious recollection of
gradually learned skills is called “procedural” (or “implicit”) memory and is also a feature of the expression and formation of mental habits. In contrast, the memory of facts and events, which can be learned in a single trial and are subject to conscious recall, is termed “declarative” (or “explicit”) memory [see IMPLICIT VS EXPLICIT MEMORY SYSTEMS, MEMORY]. The distinction between procedural and declarative memory was prompted by studies of patients with amnesia caused by dysfunction of the part of the cerebral cortex called the medial temporal lobe. Despite a profound inability to remember the training sessions and other events and facts, amnesic patients could be trained to learn new motor skills or to improve existing skills with practice. This finding indicates that procedural and declarative memory involve distinct brain areas and mechanisms.

Our knowledge of the brain regions involved in motor learning and memory derives from clinical studies of patients who have neurological diseases, stroke or other localized brain dysfunction, from brain imaging studies in humans, and from neurophysiological recordings in animal models. A number of distinct brain regions are involved in motor learning. The CEREBELLUM is required for adaptation, for conditioning, and for the learning and coordination of movements that involve multiple joints and muscles. The basal ganglia are involved in learning sequences of movements, and are also critical for habit formation. Although the studies of amnesic patients indicate that the medial temporal lobes are not required for motor learning, other cortical regions are clearly involved in the learning of motor skills and the associations of sensory cues with appropriate motor programs. These include primary motor cortex, somatosensory cortex, prefrontal cortex, and the supplementary motor areas. As learning proceeds and motor memories become consolidated, the relative contributions of neuronal activity in the various brain regions involved in motor learning can vary. The precise roles of distinct brain areas in motor learning and the neural mechanisms that underlie the acquisition and retention of motor skills are areas of active investigation in neuroscience.

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References


