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The Neural Basis for Learning of Simple Motor Skills

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The vestibulo-ocular reflex (VOR) is a simple movement that has been used to investigate the neural basis for motor learning in monkeys. The function of the VOR is to stabilize retinal images by generating smooth eye movements that are equal and opposite to each head movement. Learning occurs whenever image motion occurs persistently during head turns; as a result image stability is gradually restored. A hypothesis is proposed in which the output from the cerebellar cortex of the flocculus guides learning; the locus of learning is in the brain stem, in VOR pathways that are under inhibitory control from the flocculus. Other, parallel VOR pathways do not receive inputs from the flocculus and are not subject to learning. Similarities among the VOR and other motor systems suggest some organizing principles that may apply in many forms of motor learning.

COMPLEX MOTOR PATTERNS SUCH AS THE PLAYING OF A Beethoven piano sonata or the fielding and throwing of a baseball are not executed correctly on the first attempt. Rather, initial efforts are corrected, refined, and finally (sometimes) perfected by a process that involves making errors, detecting them through sensory inputs and correcting the errors on subsequent repetitions of the movement. The process that improves motor performance through practice is called motor learning.

Much has been discovered about the neural and cellular basis for learning in invertebrate species (*1*), but little is known about how learning occurs in intact mammals. We think that motor learning provides a unique opportunity to understand learning in mammals, because motor activity generates a tangible output that can be measured in the laboratory. To identify the neural networks that subserve specific movements and to determine how and where each network is modified in association with learning, we have investigated the neural networks that mediate a simple example of motor learning in monkeys.

Eye movements as a model system for learning. Eye movements have a number of advantages that make them an excellent model system for investigating both normal brain function and learning in adult primates. Just a few muscles are used to move the eyes, and many of the neural networks that provide inputs for those muscles have been identified. Indeed, the past 20 years has seen a massive effort in the study of the neural basis for eye movement (*2*). The result is a strong conceptual and technical foundation for conducting experiments on learning in the oculomotor system of awake, behaving monkeys.

The primate oculomotor repertoire consists of several kinds of eye

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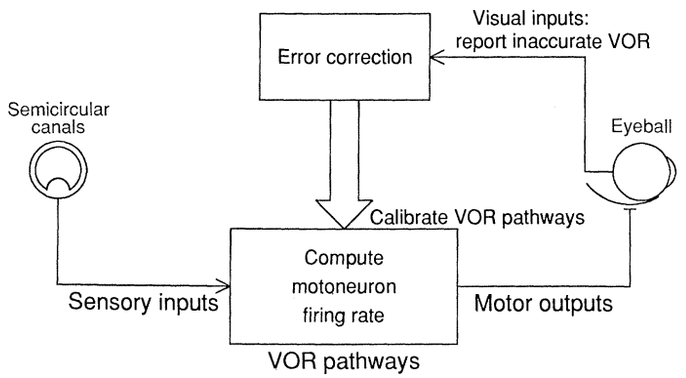


Fig. 1. Overview of the organization of the VOR. Sensory inputs arise in the semicircular canals on the left side of the diagram. They are transformed by VOR pathways in the brain stem and cerebellum to provide commands to move the eyes. Visual feedback originates from the retina and provides inputs to an error correction mechanism. The large arrow indicates the long-term effect of visual inputs in calibrating the VOR pathways.

movements, each subserved by a separate neural network. Each class of eye movement performs a clearly defined function and is tuned to provide accurate performance. In the past 10 years, it has become clear that motor learning is an important feature of eye movements. For every kind of eye movement, accuracy is regulated by a specific form of motor learning that is guided by identifiable sensory stimuli (*3*). In this article, we will focus on one eye movement subsystem, the vestibulo-ocular reflex (VOR), because it has been used extensively for investigation of the neural basis for motor learning.

Motor Learning in the VOR

The VOR is the principal mechanism that keeps visual images stable on the retina as we move our heads. During each head turn, the VOR automatically causes a compensatory smooth eye movement that has both a short response latency and remarkable accuracy. In rhesus monkeys, passive rotary head movement evokes smooth eye movements after a latency of 14 ms (*4*). Over a wide range of trajectories of passive head turns imposed in darkness, the eye movements remain opposite in direction and nearly equal in amplitude to head movement; the gain of the VOR, defined as eye speed divided by head speed is close to 1.0 (*5*).

An accurate VOR is important because we require stable retinal images for good vision. Visual acuity begins to degrade if images slip across the retina at speeds as low as 2° to 3° per second (*6*). Although image motion is actually sensed by the visual system, image stability can best be maintained through a reflex driven by vestibular inputs. Visual inputs are too slow and have too long a latency to maintain image stability at the speeds of most head turns.

We think of the VOR in the general terms outlined in Fig. 1. The sensory inputs originate in the semicircular canals of the vestibular apparatus and enter the brain over the eighth cranial nerve. VOR pathways in the brain stem and cerebellum transform the amplitude and dynamics (7) of the vestibular inputs to provide commands for motor outputs, via extraocular motoneurons. If the transformations applied by the VOR pathways are incorrect, then the VOR is inaccurate and images move across the retina during head turns. Image motion activates visual inputs that are used as feedback for two corrective mechanisms. One mechanism provides immediate visual guidance of eye movement with a latency of about 100 ms (*8*). The other mechanism operates through motor learning to gradually recalibrate VOR pathways so that subsequent head turns generate an accurate VOR (*9*). In engineering terms, motor learning provides long-term negative feedback that is critical because the VOR operates "open-loop" and must work correctly in the interval before there can be immediate guidance by visual feedback (*10*).

In the laboratory, we elicit motor learning in the VOR by fitting rhesus monkeys with spectacles that magnify or miniaturize visual inputs (*11*). For example 2× telescopic spectacles double both the size of visual images and the speed at which they appear to move when the head is turned. As a result, the compensatory eye movements produced by the normal VOR are too slow. Retinal images are stabilized only if the VOR is twice its normal speed; a perfect VOR would have a gain of 2.0. If monkeys view the world through telescopic spectacles while making active head turns in their cages, the VOR gets gradually larger. After several days, passive head rotations in darkness evoke a VOR with a gain as high as 1.8. A similar approach with 0.25× miniaturizing spectacles produces a decrease in the gain of the VOR to values as low as 0.3, near the optimal gain of 0.25.

Magnified and miniaturized vision cause motor learning by mimicking situations normally faced by the VOR. In real life, motor learning probably (i) establishes the initial performance of the VOR in infants; (ii) maintains good performance in the face of growth and changes in the mechanical properties of the orbital tissues; and (iii) compensates for the loss of neurons in the VOR pathways during aging. In addition, motor learning can help to restore good performance to the VOR after the pathological loss of the vestibular apparatus on one side, which deprives the VOR of half of its inputs and would, without motor learning, halve the gain of the VOR (*12*).

We think that motor learning is caused by changes in the efficacy of existing synaptic connections, and two facts suggest that there is a circumscribed site of changes. First, learning occurs only if retinal image motion and head turns occur together. In monkeys, the VOR does not undergo motor learning either during head turns in the dark, or during image motion with the head stationary (*13*). This implies that the site of modification must also be a site of convergence for visual and vestibular inputs that guide the learning process. It seems unlikely that the relevant visual and vestibular signals would converge at more than a few sites. Second, the changes are specific to the VOR. Of all the other kinds of eye movement, only a phenomenon called "optokinetic afternystagmus" (or OKAN) undergoes changes that are linked with changes in the VOR (*14*). This suggests that the site of learning is in the restricted set of pathways that are shared by OKAN and the VOR but not by other eye movement subsystems.

Neural Components of the VOR

Parallel pathways in the VOR. There are two sets of parallel VOR pathways—one that learns and one that does not (*15*). Figure 2 illustrates data on which this conclusion is based. We measured the VOR in the dark during a transient vestibular stimulus that imposes a rapid change in head velocity from 0° to 30° per second within 50 ms. Superimposing the eye velocity evoked by this stimulus before and after motor learning allows us to compare the responses in detail. The slow-sweep speed records in Fig. 2A suggest, and the fast-sweep records in Fig. 2B confirm, that the first several milliseconds of the VOR always follow the same trajectory, even though motor learning is clearly expressed in later parts of the responses.

The invariance of the first few milliseconds of the VOR suggests that one set of pathways (UNMODIFIED) causes the shortest latency component of the VOR and is not modified in association with motor learning. The total latency of the unmodified pathways, from the onset of the head turn to the onset of the compensatory eye

movement, is equal to the latency of the VOR, which is 14 ms. A second set of pathways (MODIFIED) contains the site of motor learning in the VOR and contributes to eye movement after a longer latency. To estimate the total latency of the modified pathways, we measured the time of divergence of the eye velocity records obtained before and after motor learning. The latency of the modified pathways averaged 19 ms and was the same for both increases and decreases in the gain of the VOR (*16*).

The waveforms of the eye velocity records in Fig. 2A suggest a further difference between the modified and unmodified VOR pathways–their vestibular inputs arise from different classes of primary afferents. When the gain of the VOR is low (G = 0.32), eye velocity during a rapid change in head velocity overshoots its steady-state level. In contrast, there is no overshoot when the gain of the VOR is high (G = 1.57). Recordings of the firing rate of single vestibular primary afferents revealed a possible basis for the change in the overshoot in the VOR (*17*). In response to rapid changes in head velocity, some afferents showed phasic responses with considerable overshoot in firing rate, while others showed tonic responses that followed the head velocity stimulus with high fidelity.

The change in overshoot in the VOR can be explained if the phasic afferents provide inputs to unmodified VOR pathways and the tonic afferents provide inputs to modified pathways (Fig. 2C). The vestibular inputs arise at the left side of the diagram, and the waveforms on the input lines show profiles of firing rate as a function of time for typical tonic and phasic afferents. The circle at the right is a summing junction that performs algebraic addition of its inputs from the modified and unmodified pathways. The box labeled G represents the site of motor learning and is placed in the central VOR pathways, because motor learning does not cause changes in the response properties of the primary afferents themselves (*18*). G acts as a multiplication factor for the inputs from tonic afferents (Fig. 2C). Thus, lowering the value of G to 0 prevents tonic afferents from contributing to the VOR but does not alter transmission through pathways from phasic afferents. The gain of the VOR is reduced (but not to 0), and the dominance of inputs from the phasic afferents causes the small remaining VOR eye velocity to have more overshoot. Increasing the value of G to twice its normal value allows the contribution from tonic afferents to overcome that from phasic afferents. The gain of the VOR is increased and eye velocity shows little or no overshoot. The scheme in Fig. 2C also accounts for our observation that the unmodified pathways dominate the first few milliseconds of the VOR. The phasic afferents, which project into unmodified VOR pathways, respond to the sudden onset of head motion 4 ms earlier than do the tonic afferents (*17*).

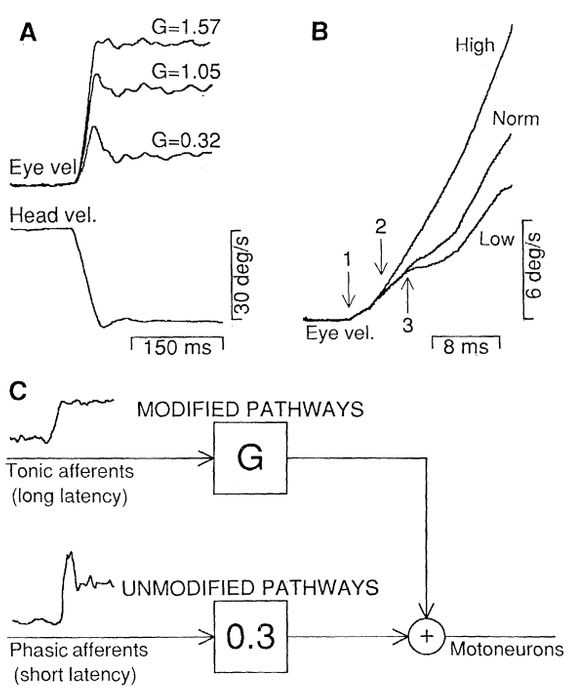


Fig. 2. A model of the VOR with two parallel pathways—one that learns and one that does not. (**A**) Slow-sweep records showing the trajectory of a rapid change in head velocity and the profiles of the eye velocity responses before and after motor learning induced by magnifying or miniaturizing spectacles. The values of G indicate the gain in the VOR. (**B**) Fast-sweep records showing the details of the eye velocity records at the initiation of the VOR. Arrow 1 points out the initiation of the VOR; arrow 2 points out the time when the high gain response deviates from normal; and arrow 3 points out the time when the low gain response deviates from normal. (**C**) Model of the VOR that accounts for the extra delay in the modified pathways and for the effect of motor learning on the overshoot in the VOR. Signals travel from left to right. Each input line is labeled with the firing of a tonic or phasic afferent in response to rapid changes in head velocity. The boxes act as multiplication factors for their input signals: the unmodified pathways have a fixed gain of 0.3 and the modified pathways regulate the gain of the VOR by changing the value of G. The circle with a plus inside it algebraically sums the inputs from the modified and unmodified pathways.

These behavioral data help to guide and interpret experiments in which we have recorded the firing rates of neurons in the VOR pathways. First, they tell us to look for at least two VOR pathways with different physiological properties. Second, they provide "fingerprints" for neuronal responses recorded from the modified and unmodified pathways. For example, neurons in the modified pathways must respond with latencies that are appropriate to contribute to eye movement after a total latency of 19 ms. Finally, the existence of unmodified VOR pathways implies that changes in the modified pathways must exaggerate the change in the VOR, to overcome the fixed contribution of unmodified pathways. Under the assumptions used in Fig. 2C, for example, the gain of the VOR could be reduced to 0.3 only if neurons in the modified pathway became unresponsive to vestibular inputs.

The neural network for the VOR. Current knowledge of the anatomical pathways that subserve the VOR is consonant with the idea that there are several parallel VOR pathways with different physiological properties (Fig. 3). The best studied pathway is the classical three-neuron reflex arc, in which a VOR interneuron receives monosynaptic inputs from vestibular primary afferents and projects directly to extraocular motoneurons (*19*). We will suggest below that this pathway is responsible for the shortest latency, unmodified component of the VOR.

A second VOR pathway includes the flocculus, which is a part of the vestibulo-cerebellum. We know that the flocculus is necessary for motor learning because bilateral ablation of the flocculus abolishes the ability to undergo learning without having major effects on the normal VOR (*20*). Purkinje cells (PCs) are the sole output neurons from the flocculus. They receive two classes of inputs: climbing fiber inputs, which cause complex spikes in PCs, and mossy fiber inputs, which cause simple spikes in PCs. Climbing fiber inputs to the flocculus transmit a visual signal that is sensitive to retinal image motion (*21*). Mossy fiber inputs transmit at least three major signals. The input pathway labeled 1 in Fig. 3 originates from the vestibular system and encodes the angular velocity of head motion (*22*). Input 2 originates from visual pathways that are sensitive to the speed and direction of moving retinal images (*23*). Input 3 encodes the angular velocity of smooth eye movement in the orbit and appears to be a copy of the final motor command sent to motoneurons (*24*). The flocculus both provides inputs that command eye movement and receives feedback about the commanded eye movement (Fig. 3). This arrangement is based on evidence that

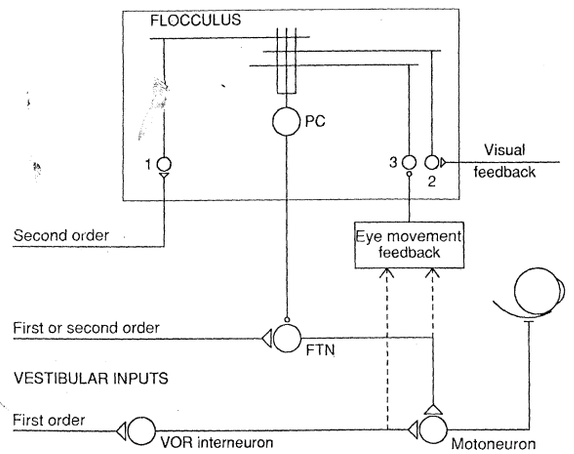


Fig. 3. Schematic diagram of the pathways subserving the VOR. The diagram includes a VOR interneuron, a flocculus target neuron (FTN), an extraocular motoneuron in the brain stem, and three mossy fiber inputs to a Purkinje cell (PC) in the flocculus of the cerebellum. Triangular synapses are excitatory and the circular synapses are inhibitory. The circuit has been simplified by showing only one side of the brain and by not including reciprocal inhibitory pathways to antagonist motoneurons. The inputs to the eye movement feedback are dashed to indicate that their anatomical substrate is not known.

the eye movement input to the flocculus is configured in positive feedback (*8*).

The dependence of motor learning on an intact flocculus provided the rationale for experiments that identified a third VOR pathway. We introduced recording microelectrodes into the brain stem and looked for cells that were inhibited when single shocks were applied through stimulating electrodes that had been implanted chronically in the flocculus. Because the monkey was awake during the recordings and had been trained to track a moving target, we were also able to evaluate each neuron's discharge in relation to eye movements. This approach identified a subgroup of VOR interneurons that we call flocculus target neurons (FTNs) (*25*). FTNs are in the vestibular nuclei in the same region as other VOR interneurons, but we treat them separately because they differ in two important ways. First, FTNs are inhibited at monosynaptic latencies after single electrical shocks applied to the flocculus; other VOR interneurons are not inhibited. Second, FTNs show qualitative differences from other VOR interneurons in the relation between firing rate and eye movement. Because intracellular recordings have shown that the flocculus inhibits direct brain stem VOR pathways (*26*), we assume that FTNs receive monosynaptic or disynaptic inputs from vestibular primary afferents and project directly to extraocular motoneurons.

Changes in Neuronal Firing with Learning

Of the neurons that have been examined, which include VOR interneurons and several classes of neurons in the vestibular nucleus (*27*), only FTNs and PCs show striking changes in firing in association with motor learning in the VOR (*25, 28*). Because we did not attempt to follow the responses of individual cells during learning, our experiments documented differences in the responses of populations of FTNs and PCs recorded before and after learning. We know that these differences reflect actual changes because each FTN and each PC has other response properties that reflect how it had fired during the VOR before motor learning. Figure 4 illustrates the firing rate during the VOR for two FTNs and two PCs that were selected to represent the population means before and after the gain of the VOR had been reduced.

FTNs fit one of the criteria suggested by our behavioral experiments for neurons in the modified pathway: the magnitude of the change in FTN firing exaggerates the change in the VOR. Before motor learning, FTNs showed increased firing during the leftward VOR evoked by rightward head motion. After the gain of the VOR had been reduced to 0.3, FTNs had lost the excitatory response and were inhibited during the small remaining leftward VOR eye movements. If FTNs provide some of the inputs that drive the VOR before motor learning, then the opposite sign of the response after a reduction in the gain of the VOR must act as a brake. This exaggerated change in FTN firing is presumably necessary to overcome the fixed contribution of unmodified VOR pathways.

A brain stem site of learning? One goal of our work is to identify the locus of the primary changes in synaptic efficacy, those which cause motor learning. The fact that FTNs and PCs undergo changes in firing implies that both are involved in motor learning. However, the evidence presented above does not reveal the primary site of learning, because the neurons are embedded in an interconnected neural network. Three plausible mechanisms could explain the changes in the responses of FTNs and PCs during the VOR: (i) The primary change in synaptic efficacy may occur in the brain stem vestibular inputs to FTNs. The resulting change in the VOR would then cause changes in PC firing through the eye movement feedback. (ii) The primary change in synaptic efficacy may occur in the vestibular inputs to the flocculus. The monosynaptic inhibitory connection from PCs to FTNs would then cause changes in FTN firing. (iii) The primary change in synaptic efficacy may be at any locus within the eye movement feedback pathway. We now introduce additional evidence that helps to discriminate among these alternatives.

First, we compare the latency of neuronal responses to natural vestibular stimulation with out inferences about the latencies of the unmodified (14 ms) and modified (19 ms) VOR pathways. To make the comparison, we assume that changes in the firing of VOR interneurons and FTNs affect eye movement after a delay of 7 ms and that changes in PC firing affect eye movement after 9 ms (*29*). This means that FTNs and VOR interneurons must respond to

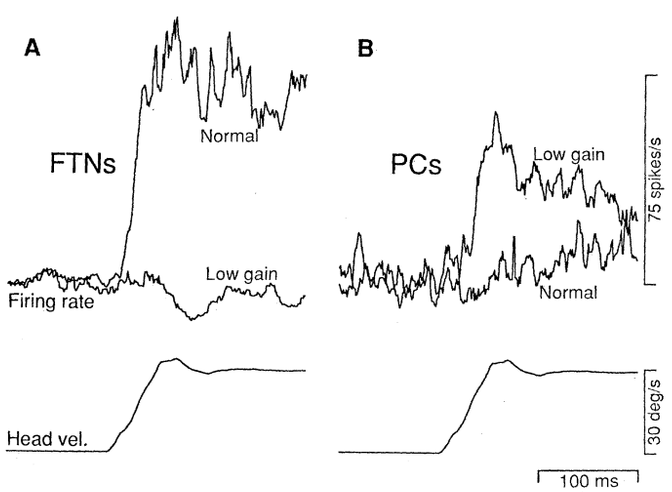


Fig. 4. Effect of motor learning on the firing of FTNs and PCs during the VOR. (**A**) Comparison of firing rate of two typical FTNs recorded before motor learning and after the gain of the VOR had been reduced with miniaturizing spectacles. (**B**) The same comparison for two PCs recorded in the flocculus. In both panels the vestibular stimulus was a rightward rapid change in head velocity that was imposed in darkness. Each record of firing rate was obtained by averaging the responses to at least 50 individual vestibular stimuli.

vestibular stimuli at latencies of 12 ms if they are within modified pathways. PCs must respond at latencies of 10 ms. Figure 5 illustrates the responses of one VOR interneuron, one FTN and one PC with latencies that are close to their respective population means of 8.2, 14.9, and 21.3 ms (*25*). VOR interneurons respond to vestibular stimuli too early to be within the modified pathways but at the correct time to be in the unmodified pathways. As a population, PCs have latencies that are too long either to cause the earliest part of the modified VOR or to cause the changes in the firing of FTNs. Of the neurons we have studied, only FTNs have a latency that is appropriate for interneurons in the modified pathways.

If based on population means, the latency data argue that motor learning results from changes in noncerebellar, brain stem inputs to FTNs. However, the distribution of response latencies within each population raises a possible problem. For example, a few of the FTNs responded early enough to be part of the unmodified pathways. Similarly, among the 34 PCs we recorded, a few responded early enough to cause the earliest change in the VOR (*25*). We cannot exclude the possibility that a small subgroup of PCs cause motor learning while others follow. It seems more appropriate, however, to consider the PCs as one homogeneous group, because they had the same qualitative response properties during horizontal eye movements (*30*). Further experiments with electrical stimulation of the vestibular apparatus may resolve this issue by providing more precise measurements of latency.

Miles and his co-workers have provided direct evidence against mechanism (ii), that motor learning is caused by changes in synaptic efficacy in the vestibular input to the flocculus (*31*). They recorded from PCs while monkeys tracked a target that moved exactly with them during sinusoidal head rotation. To track the target, the monkeys held their eyes stationary in the orbit. This inactivated the eye movement feedback pathway through the flocculus and allowed PC firing rate to be used as a direct estimate of the efficacy of vestibular inputs to PCs before and after motor learning. Miles *et al.* found that PCs show changes in their sensitivity to vestibular inputs in association with motor learning, but that changes are in the wrong direction to cause the altered VOR. We will return to these changes later.

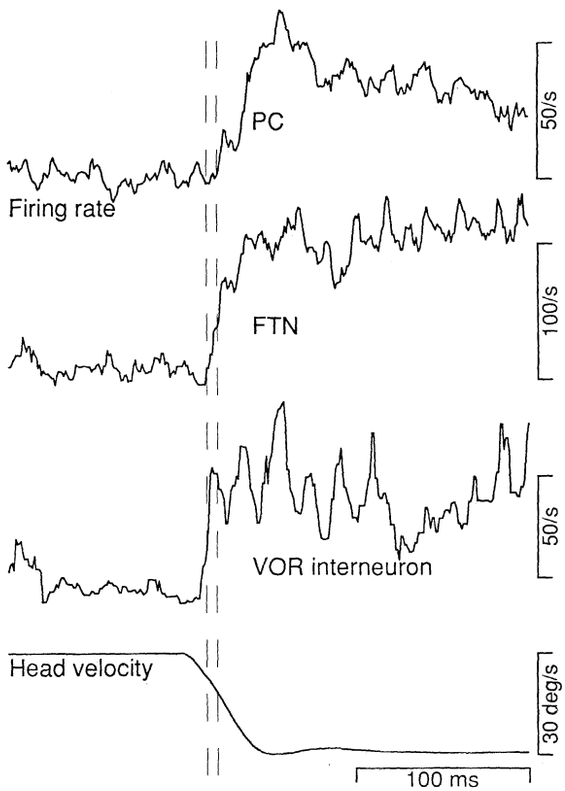


Fig. 5. Latency of responses to vestibular stimuli in VOR interneurons, FTNs, and PCs that were selected to represent the population means. Each record of firing rate was obtained by averaging the responses to at least 50 individual rapid changes in head velocity. The vertical dashed lines are drawn at 13 and 20 ms after the onset of the vestibular stimulus. The response of the PC was obtained when the gain of the VOR was low. The responses of the FTN and the VOR interneuron were obtained before motor learning.

Several lines of evidence argue against mechanism (iii), that there are changes in synaptic efficacy within the eye movement feedback pathway. First, recordings from PCs after motor learning did not reveal appropriate changes in their responses during smooth eye movement with the head stationary (*31*). Second, the eye movement feedback pathway is important for the smooth pursuit eye movements that are made to track a small, smoothly moving target when the head is stationary (*8*). If the site of modification were within the feedback loop, motor learning in the VOR should cause changes in the performance of pursuit eye movements. But, motor learning in the VOR does not cause changes in pursuit (*32*).

Third, the experiment summarized in Fig. 6 implies that efficacy is not changed in the synapses from PCs to FTNs. Figure 6A illustrates the eye movement that is evoked by applying a train of ten pulses to the flocculus of an awake monkey. If motor learning in the VOR were associated with a change in synaptic efficacy anywhere in the pathway from the flocculus to the motoneurons, the magnitude of the evoked eye movement should change along with the gain of the VOR. Figure 6B shows for two monkeys that this does not occur (*33*). The ordinate plots the peak horizontal eye velocity evoked by stimulating the flocculus, and the abscissa plots the gain of the VOR. Points were obtained on successive days before, at various stages during, and after motor learning. This experimental strategy has been validated by preliminary experiments in which we have studied the eye movements produced by electrical stimulation of the vestibular apparatus. Single shocks evoke an eye velocity twitch that has two peaks, and the amplitude of the second peak varies in parallel with the gain of the VOR (*34*).

Two sites of learning with different functions? The data presented above suggest that motor learning is mediated by changes in synaptic efficacy in the brain stem, in pathways that provide vestibular inputs to FTNs. In an earlier study (that did not analyze FTNs or other neurons that discharge in relation to eye movement), we failed to find changes in the firing of other neurons in the vestibular nucleus (*27*). Therefore, we think that the modified synapses are directly on FTNs. We refer to these synapses as the site of learning because their modification causes the change in the VOR. In this section we will propose a second site of synaptic modification that subserves another function.

Our conclusions contradict an hypothesis proposed by Ito almost 20 years ago to explain motor learning in the VOR (*35*). On largely theoretical grounds, he suggested that the site of motor learning is in the flocculus and that the mechanism of learning is changes in the efficacy of vestibular mossy fiber inputs, guided by visually driven climbing fiber inputs. His proposal is a specific example of Marr's and Albus' more general hypotheses of cerebellar learning (*36*). Ito's hypothesis is supported by the facts that (i) lesions of the flocculus prevent motor learning (*20*) and (ii) the output from the flocculus, if measured during the VOR, changes in an appropriate direction after motor learning (*37*).

We have concluded that the site of learning is in the brain stem because of additional results that were either not available to Ito or not considered by him in his interpretation of the data (*10*). Thus,

neither our data nor those of Miles *et al.* disagree with the data that support Ito's hypothesis (*38*). Furthermore, the differences between our conclusions and Ito's cannot be attributed to differences in the site of plasticity between the rabbits used in his work and the monkeys used in ours, because the experiments cited in support of Ito's hypothesis yielded the same results in both species (*20, 37*).

In the next paragraphs, we will incorporate our conclusion about the site of motor learning into a more general hypothesis for the neural basis for motor learning. This includes a discussion of (i) the pathways that function as the "teacher," to guide the learning process and (ii) secondary effects on the responses of neurons other than FTNs as the changes that cause learning are propagated through the VOR pathways. The discussion will show how our conclusions about the neural basis for motor learning can explain the data that have been cited in support of Ito's hypothesis.

If the site of motor learning is outside the flocculus, why is the flocculus required for learning to occur? We suggest that the flocculus provides signals that guide the learning process. The VOR undergoes motor learning only when image motion and head turns occur at the same time. Therefore the site of motor learning should receive convergent visual and vestibular inputs. The flocculus is a good candidate to provide the visual component of these convergent inputs. PCs have a visually driven simple spike response to retinal image motion (*23*) and project to the site we have proposed as the locus of motor learning. If the flocculus provides visual signals that guide learning, then ablation of the flocculus would prevent learning by interrupting the pathway that transmits information about retinal image motion to the site of learning.

We can construct a truth table for a simple learning rule that incorporates the flocculus in guiding motor learning (Fig. 7). The rule compares of the amount of neuronal activity in the vestibular and floccular axons that provide inputs to the proposed site of motor learning. Because all the neurons in the circuit are spontaneously active at rates of nearly 100 spikes per second, comparison of absolute amounts of neuronal activity will not work. Instead, we suggest that learning is guided by first determining if firing rate is above or below resting rate in each input, and then comparing the situations in the vestibular and floccular inputs to FTNs.

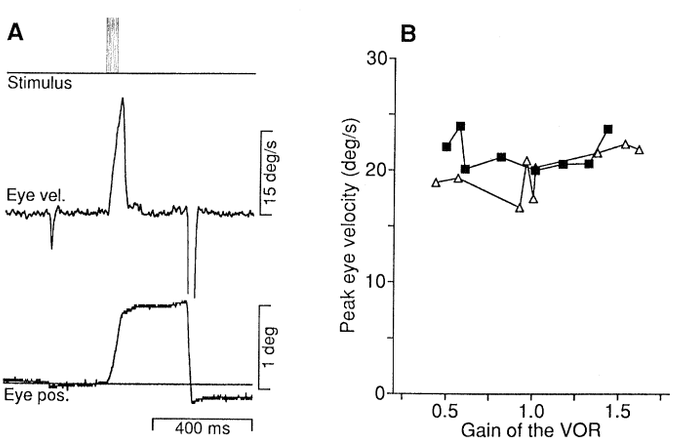
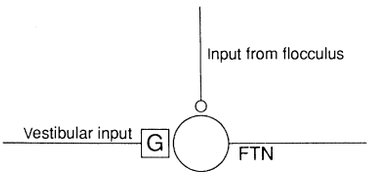


Fig. 6. Motor learning in the VOR does not modify the eye movements evoked by stimulation of the flocculus. (**A**) The eye movement evoked by applying a train of ten shocks through electrodes implanted in the right flocculus. The horizontal line in the lower trace shows the position of a fixation target. The target was extinguished from 100 ms before until the end of the stimulus. Upward deflections represent rightward eye movements. Thus, the rightward deflection of eye velocity is the response to stimulation of the flocculus, and the leftward deflection that has been truncated is associated with a saccade. (**B**) Each point represents data for 1 day and shows the average peak eye velocity in response to trains of ten stimuli applied to the flocculus. Different symbols represent different monkeys. Note the absence of any change in the evoked eye movement with changes in the gain of the VOR.



Vestibular input	Floccular input	Effect on G
Above resting	Above resting	Decrease
Above resting	Below resting	Increase
Below resting	Above resting	Increase
Below resting	Below resting	Decrease

Fig. 7. Learning rule for changes in synaptic efficacy at the proposed site of learning. The cartoon illustrates one FTN receiving convergent inputs from the flocculus and from brain stem vestibular neurons. G represents the efficacy of synaptic transmission in the synapse we have proposed as the site of motor learning. The fact that G is in the presynaptic terminal is not intended to imply that the actual site of modification is necessarily presynaptic. The learning rule is described by the truth table in the lower half of the figure. Note that the column labeled floccular input refers to the firing rate in the axons from the PCs.

The details of the truth table were deduced by considering a specific example. If the VOR is too large, a rightward head turn will cause the eyes to move too far to the left, so that the visual scene will move to the right with respect to the eyes. Single unit recordings have shown that rightward head motion causes an increase in the firing of vestibular afferents from the right horizontal canal (*39*), and that rightward motion of the visual scene causes an increase in the simple-spike firing of PCs in the right flocculus (*23*). Thus, a rightward head turn when the VOR is too large will cause firing to be above resting rate in both the vestibular and floccular axons that provide inputs to FTNs in the right vestibular nucleus. Conversely, firing will be below resting rate in both inputs to the companion FTNs in the left vestibular nucleus. Knowing the firing rates of the floccular and vestibular inputs to FTNs during a VOR that is too large allows us to infer the correct learning rule: the efficacy of the modifiable synapses (called G in Fig. 7) should decrease if the floccular and vestibular inputs to FTNs either both increase or both decrease at the same time. Similar logic argues that synaptic efficacy should increase when firing rate is above resting in either the floccular or vestibular input to FTNs and below resting rate in the other input.

If the site of motor learning is not in the cerebellar cortex, why does motor learning cause changes in PC firing during the VOR? We think that the changes in PC firing result from changes in inputs transmitted over the eye movement feedback pathway. Normally, the modulation of firing in the eye movement input is proportional to the magnitude of eye velocity (*40*). A change in compensatory eye velocity, such as that induced when the gain of the VOR changes, brings about a comparable change in the modulation of firing in the eye movement input pathway. Thus, measurements of PC firing during the VOR will reveal changes after motor learning, but the changes can be secondary to the change in the VOR. This logic is the reason we do not accept the data in two studies from Ito's laboratory (*37*) as evidence that the site of motor learning is in the flocculus.

What is the function of the changes in vestibular sensitivity in the flocculus, which are in the wrong direction to cause motor learning? We think these changes reflect a second site of modifications in synaptic efficacy, with a different function. Normally, the flocculus combines several input signals so that the simple-spike firing rate of PCs provide an accurate internal representation of eye motion with respect to the world (*40*). Because the VOR keeps the eyes stable with respect to the world, PC firing rate is normally unmodulated during the VOR.

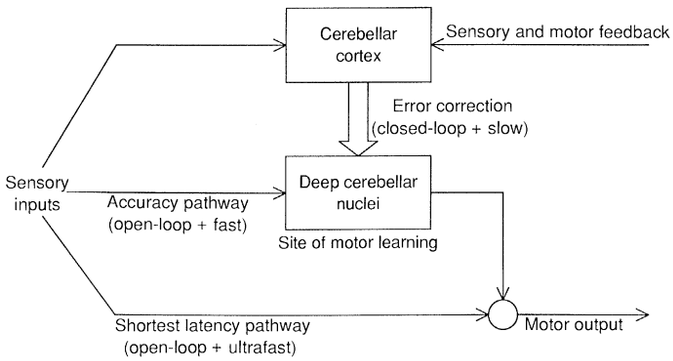


Fig. 8. A general model for learning of simple motor skills. The signals that drive motor output travel along the solid lines, in the directions indicated by the arrows. The circle labeled motor output computes the algebraic sum of its inputs.

As we described above, the eye movement feedback pathway is configured so that motor learning automatically causes PC firing to become modulated during the VOR. The changes in the modulation of firing in the eye movement input would be partially counteracted by the changes observed by Miles *et al.* (*31*) in the strength of the vestibular inputs to the flocculus. These data suggest that flocculus actively regulates the strength of its vestibular inputs in an effort to minimize the modulation of PC firing rate during the VOR and thereby prevent inappropriate changes in the VOR. We suspect that this second site of modification is in the flocculus and that its function is to adjust the signal processing of the flocculus in a way that compensates for the motor learning that has occurred in other VOR pathways.

Does the climbing fiber input to the flocculus play a role in motor learning? Several experimental observations suggest that it may, but the exact role remains obscure. First, recent work in slice preparations has shown that climbing fiber inputs can cause changes in synaptic efficacy in the mossy fiber inputs to the cerebellum (*41*). Second, in the case of the VOR, climbing fiber firing is modulated under conditions that cause motor learning (*42*). Third, motor learning does cause changes in vestibular sensitivity in the flocculus, even though the changes are in the wrong direction to cause learning. Further experiments are needed to determine if the climbing fibers are involved in learning and whether they play a specific role in guiding learning or a nonspecific, permissive role. We also do not know whether the climbing fibers affect the learning process through their massive synapses in the cerebellar cortex or through collaterals to the vestibular nucleus, presumably to FTNs (*43*).

Conclusions: Parallel Pathways Subserving Different Computations

Investigation of the VOR has allowed us to identify several parallel VOR pathways and to assign specific functions to each pathway. The classical three-neuron arc appears to be specialized for operating at short latencies. It is not under the control of inputs from the flocculus and acts as a simple relay that initiates the VOR at the earliest possible moment. The brain stem pathway containing FTNs appears to be specialized for providing an accurate VOR. It transmits vestibular inputs to the eye muscles with slightly longer latencies, it receives inputs from the flocculus, and we think it is subject to modification by motor learning. The cerebellar pathway through the flocculus provides outputs that are suitable for detecting and correcting errors in the VOR.

Studies of motor learning in eye movement (*44*), arm movement (*45*), and eyelid movement (*46*) and of classical conditioning (*47*) have revealed several similarities to our data for the VOR. In general, learning does not occur in the pathways with the shortest latencies, cerebellar lesions prevent learning, and the output from the cerebellar cortex is modified in association with motor learning. The generality of our findings on the VOR suggests that we can think of simple motor systems in terms of three sets of parallel input pathways (Fig. 8). One set of pathways is specialized for initiating a response at short latencies, one for providing accurate movement, and one for detecting and correcting errors in motor performance.

Our work on the VOR has suggested some anatomical correlates for the pathways in Fig. 8. In particular, we have argued that the site of motor learning in the VOR is in vestibular inputs to FTNs. Although located in the vestibular nucleus in the brain stem, FTNs form a portion of the deep cerebellar nucleus for the flocculus, since they receive monosynaptic inhibition from Purkinje cells. This raises the possibility that the deep cerebellar nuclei are the site of learning in many motor systems.

One general role of the cerebellar cortex may be to assemble an output that guides motor learning (Fig. 8). The flocculus, however, provides more than just visual guidance for motor learning in the VOR. Through its inhibitory synapses on FTNs, the flocculus provides signals that are used for immediate visual guidance of smooth eye movement (*40*). Visual feedback affects smooth eye movement with a latency of 100 ms and is the first backup mechanism that can be invoked if the VOR becomes inaccurate. Ablation of the flocculus, in addition to preventing motor learning, causes severe deficits in immediate visual correction of an inaccurate VOR (*48*).

Thus, the output from the cerebellar cortex of the flocculus appears to be essential for immediate guidance of eye movement as well as for its long-term calibration. These two error-correcting functions may be linked. The fact that the flocculus is used to provide immediate correction of retinal image motion during head turns renders its output automatically appropriate for guiding motor learning. If immediate visual feedback is used to correct retinal image motion during a head turn, then the image motion must have resulted from an inaccuracy in the VOR that should ultimately be prevented through motor learning. This dual effect of the output from the cerebellar cortex may be the neural basis for the saying that practice makes perfect.

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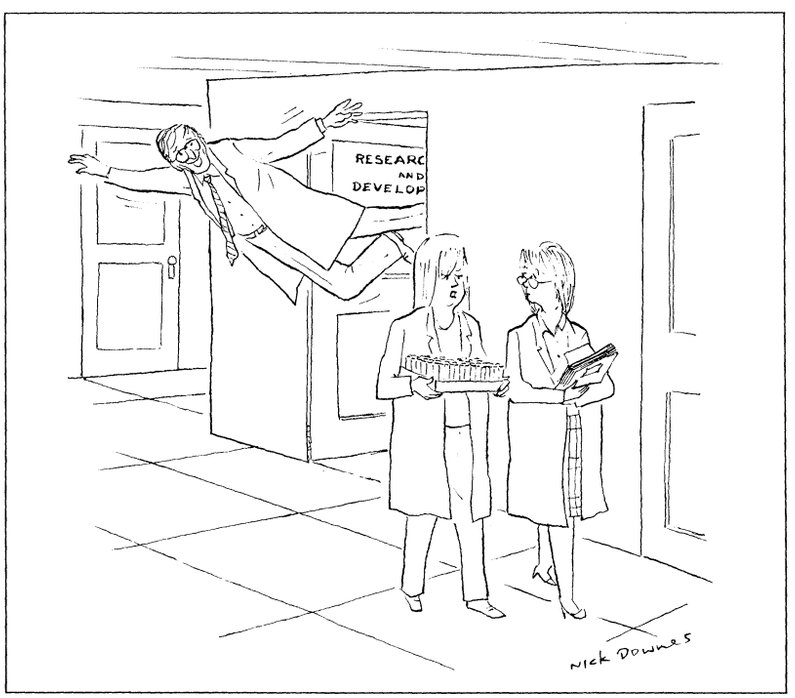
49. I thank T. A. Pavelko for her contributions to this research, and D. Belknap, C. Kenyon, F. Miles, and M. Stryker for helpful comments on the manuscript. Research from my laboratory was supported by EY03878 from the National Eye Institute (NIH), BNS 8444605 from the National Science Foundation, a Scholars Award from the McKnight Foundation, and a Development Award from the McKnight Neuroscience Endowment Fund.



"Ignore him."