Oculomotor System

Prerequisite: Spinal Cord and Reticular Formation

The muscles of the eye are like other muscles in that they take on a precise position dependent on the nervous signal sent to them. However, they don't need neuromuscular spindles or other muscular systems to determine position and stress. Since the eyes experience no external forces on them, there are no unpredictable stresses and those that do exist are small, and further, the position of the eye is that which the brain gives it since the eye travels exceedingly fast from one position to another.

In order to position the eye on an object of interest you need to know how far the object is from the position the eye is currently in, i.e. the number of degrees right, left, up or down, and you need the eye's current position, i.e. number of degrees from looking straight ahead. The brain sees the eye's current position as the muscle position signal the motor cortex is sending to the eyes. The object of interest's position is seen as the location on the person's visual cortex that they're focused on. The image the person sees is mapped out on this cortex and if something appears on this cortex that is exciting (bright, strongly colored, contrasted, or is associatively exciting, i.e. desirable, fearful, ect.) then that excitement makes that something the individual's focus. The memory cells observe the motor neurons that are active and the part of the visual cortex that is excited, and from past experience remember the motor neurons that were active after an eye movement and the new position of the excitatory stimulus after such a movement. When the individual desires to put the focus at the center of their visual cortex for better viewing, this desire appears in the cortex as an excitement at the center of the visual cortex. The memory cells read the current position of the eyes in the motor cortex and the current focus, in the visual cortex, plus the desired focus, and from past experience remembers, and then, consequentially, activates the correct motor neurons necessary to center the eyes on that focus. Because this method relies on RNA memories it is slow and unreliable, but it does allow for successful positioning of the eyes until the cortical reflexes are developed, which is important the learning of these reflexes.

The cortical reflexes involve a different type of memory cell, one that learns by trial and error. As the individual becomes accustomed to focusing their eyes on objects, the cortical fibers produce a large number of connections between locations of potential stimulus on the visual cortex and potential, resultant muscular positions of the eyes in the motor cortex. Every muscle position that ever produced centering of an interesting image in the cortex has cortical connections to that imaging part of the cortex, so when an image is seen in the future this image activates many different muscle positions at the same time. For instance, an individual may have had two instances in which an interesting image appeared 20° left of center in their cortex. One instance involved their eyes being straight ahead so successful centering of the image on the cortex involved the eyes moving to 20° left. Another instance involved their eyes being 20° to the right, so successful centering involved looking straight ahead. In the future, when an image appears at 20° to the left on their cortex, fibers in their cortex will activate both a 20° left and a straight ahead eye position. Because these reflexes involve large cortical fibers, with no unreliable, slow chemical memories, they can respond exceedingly rapidly, but they send to much information. This is where the second variety of memory cells comes into play. The way in which these memory cells work is that they take in the situation and indicators of success or failure, in the form of pain and stimulation, and output an inhibitory signal. If the cells receive a great deal of stimulus around the time they put out their response, they strengthen that output, but if little stimulus is experienced, or a need for stimulus is created by pain, then they weaken. In this way, they learn the precise cortical motor fibers to shut down in order to produce a desirable, and avoid an undesirable, situation. So, well before a stimulus (image) attracts your attention, the stimulus of the position of your eye is read by these trial and error cells which respond by deactivating every cortical pathway between the visual cortex and the motor cortex that would not lead to a correct positioning of the eyes. When a stimulus catches your eye, the part of the visual cortex this image appears in activates its cortical fibers to the motor cortex, but only the fibers that would produce the right positioning of the eyes are unblocked, so the eyes move to that position. Because the memory cells are used in preparation for a reflex, not the reflex itself, they don't decrease the reflexes speed.

A second form of eye motion is tracking, where the eye smoothly follows the object of interest. There are two forms of tracking. One is where you move your head and your eyes remain fixed on a stationary object. In the other, the head is stationary and the eyes move with a moving object.

The first type of tracking involves the semi-circular canals. When the head is rotated, the receptors in the canals put out a signal that increases in intensity (increased number of receptors being activated, less sensitive ones activate with fastest movements) with increased rate of rotation of the head. This information is sent to the motor nuclei of the eye where it excites the neurons that position the eyes. In this way, if the head is turned gently, the eyes try to reposition themselves as the object moves from the center of their vision, but since the excitatory stimulus they receive from the canals is small, they reposition themselves with little force and hence little speed, but the object is only moving across their vision slowly. If they move their head fast then the excitatory stimulus the muscles receive is large and the muscles reposition the eyes fast, which allows the eyes to keep up with the fast moving image.

For excitement of the muscles in the case of the stretch reflex calibration of the intensity of the reflex could be attained through the gamma loop. If the brain needed a stronger reaction, it could increase activity to the gamma fibers feeding the neuro-muscular spindles. In the case of the eye muscles calibration of the intensity of motion is vary important, without it the eyes would lag behind or move faster than the object they're tracking. However, I'm not aware of any direct connections between the cortex and this reflex pathway. There is every reason to believe that the cortex acquires information from the semi-circular canals (through the cerebellum) and this does allow for one type of calibration. Among the stimuli the memory cells can take in when determining the muscular positions of the eyes to produce is the degree of excitement of the canal receptors. If the eyes must be moved faster, the eyes can be displaced a shorter distance thereby increasing the force of their motion. If the eyes are moving to fast, the displacement can be lengthened. These changes in displacement won't cause the eyes to miss their target since, for moving a image, it's the rate of motion, not the position the eyes are going to that effects whether they maintain themselves on their focus. Only when the image stops does the position the eyes are going to matter. Another possibility is that the cortex receives information from the canals and, instead of directly effecting the intensity of the excitatory pathways between the canals and the oculomotor nuclei, the cortex instead, just adds on to this excitatory stimulus, sending excitatory as well as stimulatory fibers to the oculomotor nuclei.

Most objects in the world don't move or move vary little, so most of the images that move across our vision are the result of our own movements. So, the first type of tracking is the most important and the evolutionary development of the assistance of the semi-circular canals in understandable. For the second type of tracking another technique for following an image must be available since the canals provide no information about the movements of other objects.

In order to track an object purely by sight it is necessary for the brain to somehow measure the rate of travel across the eye (degrees per second) and then turn this information into a muscular excitement so that the eyes muscles can move at the correct rate. However, the memory cells do not possess any sense of time. Everything that occurs while the memory RNAs are forming is all clumped together with no reference to what came first or second. In order to detect the order of events memory cells use a sequence of inputs and outputs. The person sees a stimulus which causes them to remember something, but that memory acts as a stimulus causing them to remember something further. This sequence can be long and complex and is the fundamental basis of reasoning. This type of thought has no direct connection to time and so, can't be used to measure the rate of anything that occurs exceedingly rapidly. Depending on the number of steps and the time between individual memory RNAs activating, which may vary significantly, an act of reasoning will take a particular period of time to complete. This period of time is relatively long and unreliable and, as such, can only be used to estimate macroscopic periods of time. Memory cells can detect the time of a particular memory by using an external stimulus, such as a clock, and adding the observed time to the other stimuli in the memory, but this requires a particular stimulus that is unique to each moment of time and no such stimulus exists in the body. Further, this would require complex (from a memory cells point of view) calculations in order to work out the rate of something's movement from these memories. The one way a memory cell could figure out the rate of travel of something is by noting some change in the appearance of that thing as a result of its movement. A memory cell must be active for a period of time, long enough to form complex memories but short enough to get on to the next observation or reaction. As a result, when an object is traveling across a stationary eye, the memory cells will absorb the image along its course of travel. Consequentially, the image will appear elongated, smudged, but also transparent since the memory cells will see the object when it's over a location and when it's not at the same time. The degree of elongation, smudge and transparency will be unique to a given rate of travel across the eyes (degrees per second) for a given length of time that the memory cells are active. If the memory cells are active longer, these qualities will be greater since they'll absorb the image for a greater period of time, and visa versa. So, so long as this period is set, or the memory cells can detect the period of time they're active, which would likely be related to the level of excitement of the cells, something that is easy enough for them to deal with, then they can determine the rate of movement of an image.

When the eyes are moving with an object, the object doesn't appear to be moving across the eye. At this time, the memory cells will detect the level of excitement being sent to the eye muscles and will thereby know the rate of motion of the object and, as well, the correct excitement to send to the eye muscles (the same amount that was sensed).

The second form of tracking seems as though it might interfere with the semi-circular canal type, and further that this first type might be unnecessary in the face of the second type. The stimulus of the inner ear and that of seeing a moving object are from distinctly different sources and, as such, don't add together. If both sources are telling the eyes to move at the same rate, then the eyes will follow the orders of both sources and move at that rate, not twice that rate. However, this only relates to semi-circular canal signals that got to the cortex, not the ones that excite the oculomotor nuclei directly. As the head is rotated, the excitement of the eye muscles produced by the canals reduces the amount of excitement that needs to be produced by the memory cells observing the moving object. However, these cells can detect the signal from the canals (through the cerebellum) and, as a result, can respond by putting out less excitatory signal.

The reasons the canal type of tracking exist are firstly, that in the early evolution of the brain learning to track by sight took too long and was too complex for short lived, simple creatures. Secondly, most objects were stationary, so developing substantial brain power for something infrequently used may have been a waste. Thirdly, it may simply be much faster than the second type of tracking and hence too valuable to get rid of. Fourthly, it adds to the stimulus of the other type of tracking to make tracking more reliable under the circumstances it's most frequently used. And fifthly, for learning. It'd be difficult for a child to learn image recognition if every time they moved, images streaked across their vision. Canal based tracking allows the child to track most objects immediately, thereby allowing them to learn how they look. Once the child knows how objects should appear, then they can see how those objects change when they move and from this can develop a sight based tracking.

The final type of oculomotor functions are focusing and binocular vision. Each eye has eight muscles, six motor muscles around the eye, one muscle surrounding the lens which allows change in its shape and one iris muscle to moderate the amount of light entering the eye. Besides moderating light intensity the iris can increase the sharpness of an image by contracting. This can help overcome imperfection in the lens of the eye. There is little evidence that the iris is intentionally used in this fashion, although sight on a bright day is clearer than on a dark day. Of the six motor muscles, two deal with horizontal motion (left and right), the other four are more complicated. If you turn your right eye all the way to the right for instance, two of these muscles would move the eye up and down, the other two would turn it clockwise and counter-clockwise. Turning this same eye to the left, the second pair would move the eye up and down while the first pair would move it clockwise and counter-clockwise. When the eyes are centered, a combination of two of the four muscles working together can produce up, down, clockwise and counter-clockwise movements. To produce these movements the eyes have to remember different muscle positions for every left to right position of the eyes.

The eyes readily rotate to maintain the same position with respect to gravity; if you rotate (tilt) your head one way, your eyes rotate the other. In this way, when we see an object we see it in relation to the direction of gravity. Although our brains can identify an object that is rotated as the same object, this doesn't necessarily give us the ability to distinguish what angle an object is in. To distinguish the angle of rotation we need some reference point for the object to be tilted from. In the case of a person, we normally see people in the upright position, so, if an individual is leaning, the memory cells will recognize them as a person, but they will draw on memories of an upright person to do so which allows the memory cells to tell us how far from the norm the person is angled. If the eyes didn't keep a constant angle (tilt) with respect to gravity then the images of people (or other objects) would be seen in many different angles and so our ability to tell people's angle with respect to gravity would become vary inaccurate.

In the movement of the eyes, we always move our eyes together up and down but we are able to move them in opposed, sideways directions for binocular vision. The muscles that move both eyes up when the eyes are facing to one side are controlled by the same hemisphere of the brain, while the muscles that move both eyes down are controlled by the opposite hemisphere. Since the eyes are moved together up and down, always focusing on the same things, the brain equates a movement of one eye as the same as a movement of the other. In this way, when the memory cells set the position of one eye, the other takes on the equivalent position automatically, thereby making independent movement generally impossible. However, since the opposing muscles (down muscles for up muscles) are controlled by the opposite hemisphere, they do not necessarily take on a particular position with respect to each other. The separation of the hemispheres prevents equating a contraction of an upward muscle with the relaxation of a downward muscle. This is distinctly different from other muscles of the body where a muscle on one side of the body moves independently of muscles of the other side, while the opposed muscles (muscles where one must expand in-order for the other to contract) on one side of the body are controlled by one hemisphere, so that consequentially, the brain equates the contraction of one muscle with the relaxation of the other. Because of the way the eyes are set up, it's possible to command the eyes to go both up and down, rotate clockwise and counter-clockwise, by giving different commands with each hemisphere. This allows opposed muscles to be contracted or relaxed simultaneously, which acts to distort the eyeball and change its focus.

The lateral eye muscles are controlled through two different neural pathways; for a given eye, one pathway controls both of these muscles from one hemisphere while the other pathway controls each from opposite hemispheres. In this way, the brain can use these muscles both to distort the eyeball and to move the eyes independently in-order to converge them. In-order for this to work, however, these separate neural pathways must go to there own points on the lateral muscles with no overlapping muscle control between the two pathways. This is necessary so that the signals from both these pathways add together such that the muscles move to a position to produce the desired distortion and further, move to a position beyond this to produce the desired convergence as well.

The final issue is how/why the brain focuses on objects. When an object is out of focus, this is seen as blur in which a point on the image is seen at many points on the eye. Secondly, around the perimeter of the object a thin line is seen in which the object and the background are both seen. The brain can use this in a similar manner to that used to track an object but instead of exciting oculomotor muscles it sets the positions of the opposing oculomotor muscles and the retinal muscles so as to undo these optical effects. The convergence of the eyes in binocular vision is dealt with be the observation of there being no blur, but the image is transparent. This, combined with there being two near identical images laterally positioned with respect to each other, would be sufficient to identify that convergence of the eyes is necessary. As to the level of convergence, these stimuli would not be vary helpful. From everyday experience we know how large objects around us are, so likely we remember the position our eyes needed to be in in-order to see the object correctly for a particular, observed size. These memories would be a combination of trial and error, seeing an object in the past and remembering what position eventually brought the two images together, and association, in which you've seen one object together with another you know well. When you see the object again, the memory cells corresponding to the different size of the object are activated. This causes a recollection of the well known object, but with a different sized image of it than when the memory of the two objects together was formed. This memory contains the positioning of the eyes to produce proper convergence (and focus) for the first object. But none of this explains why the eyes develop focus, convergence and tracking; what about the brain makes these behaviors inevitable. The key to the reason focusing occurs is that unfocused images contain less information (stimulus) than focused images. Likewise, the blurred image of a object that is not being tracked is less stimulating than the sharp image of a tracked image. Nerve fibers that are used abundantly become strong and the connections they make are reinforced, nerve fibers that are used rarely will degenerate as cellular resources are transferred to reinforce the heavily used fibers. Only nerves that are in the excited state (in readiness for activation) are affected, so, only if your brain is trying to focus the eyes can the nerves involved in focusing be reinforced or degenerated. So, if the brain tries to activate a focusing muscle, but the brain is receiving relatively little stimulus as a result of poor focusing, the nerve fibers producing those muscle positions will degenerate, but if the brain produces a good focus, the nerve fibers will be reinforced and the focus will stay. This applies to all behavior, actions that produce stimulus are reinforced while actions that fail to produce stimulus degenerate and disappear. Conjugate movement of the eyes results since both sides of the brain focus on the same objects all or most of the time. If something attracts the attention of one side of the brain, then those same characteristics of attraction will almost certainly apply to the other side. Furthermore, the fibers that cross between the two hemispheres tell the opposite hemisphere that a given hemisphere sees something interesting, hence drawing the attention of the other hemisphere to that something.

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