Ocular Motor System

General Principles
1. 3 types of eye movement keep images in central vision (i.e. keep images on the fovea).
   a. Saccades
   b. Smooth pursuit
   c. Vergence
2. 2 types of eye movement stabilize the eye when the head moves:
   a. Optokinetic movements
   b. Vestibulo-ocular movements
3. We will consider each of these 5 eye movements in detail below.

Saccade
1. **Saccade**—a quick, voluntary eye movement that brings a *stationary* object of interest into central vision.
   a. For example, you make a saccade when you move your eyes from the TV screen to the clock.
2. Saccades are initiated by the *frontal and supplementary eye fields* of the frontal cortex, which project to cranial nerve nuclei III, IV, and VI in the brainstem to cause eye movement.
   a. Initiation of a saccade in the eye fields to the onset of eye movement requires about 200 msec.
3. Neuromuscularly, a saccade requires cranial nerve nuclei to be activated in a *pulse/step pattern* (see below).
   a. The “pulse” mediates the quick movement.
   b. The “step” allows the eye muscles to resist normal elastic restorative forces and remain in the desired position.
      i. A simple, perseverating feedback loop creates and maintains the “step” (see below right).

Smooth Pursuit
1. **Smooth pursuit** is the eye movements we make to hold a *moving* object in our central vision.
   a. For example, we’d use smooth pursuit to track a tennis ball being volleyed back & forth.
2. To see how smooth pursuit works, refer to the diagram below:
   a. When an object (dotted line) starts moving, there is a 150 msec delay before our eyes (solid line) start to move.
      i. This is because our brain takes this long to process object motion & initiate eye movement
   b. Once we start our pursuit movement, we need to **make a saccade to catch up** to the object, since we had a 150 msec delay in beginning our pursuit.
   c. Once we have caught up to the object with our saccade, we continue with smooth pursuit.
3. Smooth pursuit is limited in that **it cannot track objects that are moving very fast**.
   a. In this case, we have to rely on sequential saccades to keep up with the object.
Vergence

1. **Vergence** is the simultaneous movement of both eyes to focus on an object and achieve binocular fusion
   a. Failure to do this causes diplopia (“double vision”).
   b. To look at an object closer by, the eyes rotate towards each other (“convergence”).
   c. To look at an object far away, the eyes rotate away from each other (“divergence”).
2. Side note: the term “vergence” implies that the eyes move in opposite directions while saccades and smooth pursuit involve eye movement in the same direction (“conjugate movements”).
   a. However, note that in some cases, the eyes may move more or less independently of each other to attain vergence (see diagram below).

Optokinetic Eye Movements

1. The optokinetic system allows us to **maintain steady gaze during slow, sustained head rotation.**
   a. For example, this system operates when we look out the window of a car (since the world moving by us is analogous to slow, sustained head rotation).
2. To understand how optokinetic eye movements work, we must remember what nystagmus is: **nystagmus** is a general term for repetitive slow-fast oscillations in eye movement.
   a. **It turns out that there are multiple types of nystagmus.**
      i. One type, **optokinetic nystagmus (OKN),** involves optokinetic eye movements.
      b. Imagine being spun to your left in a chair with your eyes open, gazing out at the world.
         i. Your brain detects the visual world moving across the retina (“**retinal slip**”).
            1. It doesn’t like this “slip,” and it will cause your eyes to move right so as to maintain constant gaze on something...**anything** in the visual world.
a. Even though it may seem like you’re not gazing at anything in particular, you brain is indeed picking something & tracking it *(freaky!)*

2. However, your eyes can only move so far to the right…they will eventually need to be reset by quickly jumping back to the left.
   a. This process repeats itself over and over again such that you get alternating periods of slow, eye movements followed by quick, resetting eye movements. This is optokinetic nystagmus.
      i. To review, **we refer to nystagmus by indicating the direction of the fast phase (i.e. the direction of the “beating”)**
         1. Thus the above example demonstrates left-beating nystagmus.

c. One question you might be asking is, “What, if anything, is the difference between the slow phase of OKN and smooth pursuit? In both cases the eyes are tracking a moving object.”
   i. There are 2 main distinctions:
      1. Smooth pursuit operates when a single object is moving; the slow phase of OKN operates when there is movement of the entire visual field.
      2. Smooth pursuit is voluntary; the slow phase of OKN is “less” voluntary in the sense that it involves your brain automatically seeking to reduce retinal slip.

**Vestibulo-ocular Eye Movements**

1. The vestibulo-ocular system allows us to **maintain steady gaze during brief, rapid head rotation (or in other words, rotations that will stimulate hair cells of the semicircular canals).**
   a. Remember, brief, fast rotations will allow the hair cell stereocilia to move relative to the endolymph since the endolymph will lag behind due to its inertia.
      i. On the other hand, slow, sustained rotations allow the endolymph to move along with the hair cells, and no activation will occur.

2. The vestibulo-ocular system is **fast.**
   a. It takes about 10 msec after head rotation for eye movements to be made.
      i. Compare this to saccades & smooth pursuit which have latencies of 200 & 150 msec.

3. As we said, **nystagmus** is a general term for repetitive slow-fast oscillations of eye movement.
   a. **It turns out that there are multiple types of nystagmus.**
      i. One type, **vestibular nystagmus**, involves vestibulo-ocular eye movements.
   b. Imagine being spun to your left in a chair **with your eyes closed (so no OKN occurs) and then suddenly stopping (and concurrently opening your eyes)**, so as to **induce an inertial flow of endolymph past the hair cells in the semicircular canals.**
      i. Firstly, it will seem to you that the world is spinning to the right.
      ii. Secondly, the activated hair cells will cause your eyes to move left via the vestibulo-ocular reflex (VOR) circuitry (afferents from hair cells→vestibular nuclei→cranial nerve nuclei of the eye muscles (III, IV, VI)).
         1. However, your eyes can only move so far to the left…they will eventually need to be reset by quickly jumping back to the right.
            a. This process repeats itself over and over again such that you get alternating periods of slow, eye movements followed by quick, resetting eye movements. This is vestibular nystagmus.
               i. To review, **we refer to nystagmus by indicating the direction of the fast phase (i.e. the direction of the “beating”)**
Thus the above example demonstrates right-beating nystagmus.

c. Note that vestibular nystagmus (not OKN) is the type of nystagmus induced by pouring cold or warm water in the ear.

Miscellaneous Topics

1. Brain regions involved in generating eye movements:
   a. Saccades = frontal and supplementary eye fields.
   b. Vergence = V1, medial superior temporal area (MST), middle temporal area (MT).
   c. OKN = V1, medial superior temporal area (MST), middle temporal area (MT).
   d. VOR = afferents from hair cells → vestibular nuclei → cranial nerve nuclei of the eye muscles (III, IV, VI).

2. **The VOR and smooth pursuit are complementary:**
   a. The VOR is good at stabilizing images when the head moves at high frequencies.
   b. Smooth pursuit is good at stabilizing images when the head moves at low frequencies.

3. The downside of the VOR being fast is that it has to do what it does **without getting feedback**.
   a. In other words, it has no knowledge of whether it is making errors or not.

4. The OKN is the exact opposite: it is slow, but has the benefit of receiving feedback information on its performance so that it can correct itself and be highly accurate.

5. In certain situations, the OKN circuitry in visual cortex (together with the cerebellum) can analyze errors made by the VOR and feedback into VOR circuitry to **calibrate** it, keeping it working properly.
   a. Specifically, retinal slip caused by overactivity or underactivity of the VOR can be detected and corrected.
   b. **Such calibration takes hours to days.**
   c. As an example, astronauts must undergo this calibration when returning to earth because their vestibular sense is out of whack and needs recalibrating.

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**Lab (Vestibulo-ocular Reflex)**

**Demo 1**

1. Hold your coursebook at arm’s length, stare at a word, and rotate your head back and forth about 3 times per second.
   a. You can maintain focus on the word because the VOR moves your eyes to counteract the motion of your head.

2. Hold your coursebook at arm’s length, and **while keeping your head still**, move it back and forth about 3 times per second, all the while trying to focus on one of the words with your eyes.
   a. You can’t do it. We cannot use smooth pursuit to view things that are moving too fast.

3. **Question 1:** Could you read the print during coursebook jiggling or did it blur?
   a. Blur

4. **Question 2:** Which condition produced the clearest image?
   a. Head jiggling.

5. **Question 3:** What does this tell you about the frequency range in which the two systems work best?
   a. Smooth pursuit works better at low frequencies; VOR works better at high frequencies.

6. **Question 4:** Why do you need both systems?
   a. To allow us to stabilize images that are moving at both low and high frequencies.

**Demo 2**

4. Have a partner stare at a rotating optokinetic drum (see below) and observe their eye movements.
5. **Question 1: What do you see?**
   a. The rotating drum mimics slow, sustained rotation of the head, producing OKN in the subject.

6. **Question 2: Draw a representative tracing of OKN you observe.**
   a. See diagram below.

![Diagram of OKN](image)

7. **Question 3: What function do the slow phases serve?**
   a. Your brain tries to minimize “retinal slip” by causing your eyes to maintain constant gaze on something...anything in the visual world.

8. **Question 5: What function do the quick phases serve?**
   a. As your eyes are moving to maintain constant gaze, they eventually reach the limit of their range of motion in the eye socket and must be reset to the midline.

**Demo 3**

1. Have a partner spin you in a chair **with your eyes closed (so no OKN occurs)** and then have them abruptly stop you so as to induce an inertial flow of endolymph past the hair cells in the semicircular canals. Open your eyes so your partner can see the vestibular nystagmus that has been induced.

2. **Question 1: What happened to the initially strong sensation of self-rotation as you continued rotating?**
   a. It went away because the endolymph overcame its initial inertial drag, and began to move along with the hair cells. The hair cell stereocilia were not deflected, and the hair cells were not activated.

3. **Question 2: What did you feel when you were stopped?**
   a. The room seemed to be spinning in the opposite direction.

4. **Question 3: What was happening to the endolymph and the hair cells embedded in the gelatinous cupula of each horizontal semicircular canal?**
   a. Endolymph was moving past the hair cells due to inertial flow. This produced the vestibular nystagmus visible to your partner upon opening your eyes.

5. **Question 4: How many action potentials are being conveyed over the vestibular nerve 1 second into rotation, 30 seconds into rotation, and 1 second after rotation?**
   a. One second into rotation
i. If you spin left, left nerve will have high firing; right nerve will have low firing (remember, the semicircular canals work as antagonistic pairs).

b. 30 seconds into rotation
   i. Left nerve and right nerve will have an equal, intermediate rate of firing.

c. One second after rotation
   i. If you initially spun left, the inertial flow of endolymph on stopping will now cause the right nerve to have high firing and the left nerve to have low firing.

Demo 4
1. Look at a spot on the wall and move your head in all three axes: Twist your neck left and right to move in the horizontal plane (yaw); tilt your head forward and backward to move in the vertical plane (pitch); touch your head to your left and right shoulder to move in the torsional plane (roll).

2. **Question 1: Which semicircular canals were turned on during these movements?**
   a. Semicircular canals are activated in antagonistic pairs such that when one is excited, its partner in the other ear will be inhibited. For horizontal motion, the canal in direction of motion is turned on (i.e. rotating left activates the horizontal canal in the left ear). Dr. Tychsen doesn’t expect you to know the nitty-gritty details of which ones get turned on and off for pitch and roll head movements…it is quite complicated, involving various combinations of anterior and posterior semicircular canal activation.

3. **Question 2: Which extraocular muscle pairs are turned on during rotation?**
   a. Rotation left:
      i. Right lateral rectus + left medial rectus.
   b. Rotation right:
      i. Left lateral rectus + right medial rectus.
   c. Rotation up:
      i. Both inferior recti.
   d. Rotation down:
      i. Both superior recti.
   e. Rotation torsionally to the left:
      i. Left superior oblique + right inferior oblique.
         1. You don’t need to know this…just know that the oblique muscles are involved in torsional movements.
   f. Rotation torsionally to the right:
      i. Right superior oblique + left inferior oblique.
         1. You don’t need to know this…just know that the oblique muscles are involved in torsional movements.

4. **Question 3: In one sentence understandable to a 12-year-old, explain the grand purpose of the VOR.**
   a. The VOR keeps images still by compensating for movement.