Vision Science III - Binocular Vision Module

Lecture 5 - Combined Vergences; Sensory Fusion & the Horopter

(Borish Chapter 5, p. 162-175; Steinman Chapter 4, p. 81-83)

REVIEW MOTOR FUSION & VERGENCES

Six different categories of vergence eye movements

- Disparity / fusional vergence - stimulated by retinal disparity
- Accommodative vergence - stimulated by accommodation
- Tonic vergence - basal innervation of EOMs without any visual stimulus
- Vergence adaptation - stimulated by disparity vergence and accommodative vergence; takes over for them with time.
- Proximal vergence - stimulated by perception of object proximity
- Voluntary vergence - deliberate conscious vergence of the eyes

These mechanisms are controlled by discrete centers in the brain and work together to support **motor fusion**; that is, they aim the eyes so images fall on **corresponding points**.

INTERRELATIONS OF THE VERGENCES

Figure 5-16 in McCormack's chapter (Borish) summarizes the interrelation between the different vergence components.

Tonic vergence (TV) does the basic work of bringing the eye's from their anatomic position of rest (~17 prism diopters exo) to parallel or close to parallel.

If you are going to fixate a near object, proximal vergence (PX) stimulates a large convergent movement, which brings the eyes close enough for accommodative vergence (AC/A) and disparity vergence (DV) to work.

If near fixation is sustained, accommodative vergence innervation (avi) and disparity vergence innervation (dvi) stimulate vergence adaptation (VA), which takes over more and more of the convergence response (CR). As vergence adaptation increases, the need for disparity and accommodative vergence decrease. This is adjusted by the feedback loop.

Since the tonic posture of the eyes is normally slightly esophoric, a slight amount of negative disparity vergence and negative reflex accommodation is required to fixate a distant object. Voluntary vergence and accommodation are not shown in the figure.

MORE ON DISPARITY VERGENCE

Recall that **disparity vergence** (also called fusional convergence) is considered the primary mechanism used to *fine-tune* fixation on a new object. All the other vergences help with a more gross alignment of the eyes, but the final, precise motor fusion is provided by disparity vergence.

Disparity vergence is made up of two sub-components:

- positive disparity vergence (disparity convergence)
- negative disparity vergence (disparity divergence)

Separate brain-stem cellular groups called convergence cells and divergence cells innervate positive and negative disparity vergence, respectively. The number of divergence cells is significantly less than convergence cells, which may explain the lower amplitude and velocity of divergence movements. In

> *addition, both convergence and divergence exhibit behaviors suggesting that each is further subdivided into components analogous to coarse and fine sensory function. (McMormack, p. 165)*

Disparity vergence starts with **coarse disparity vergence**, which responds to large targets and large retinal disparities. Fine adjustments are then taken over by the **fine disparity vergence** mechanism.

The negative feedback system, shown in the diagrams in Borish, is what allows fine disparity vergence to precisely fixate the eyes and complete motor fusion. However, it usually does not do so perfectly. At the completion of fine disparity vergence, there is still usually a tiny residual misalignment of the visual axes. That is, there is still a small residual disparity, which continues to stimulate the fine disparity vergence mechanism. This is known as a **fixation disparity**. See Figure 1, below.

Fixation disparity is usually so small that the image can still be fused binocularly. Recall that disparity vergence is not solely responsible for motor fusion. It has help from the other vergence mechanisms (tonic, proximal, accommodative).

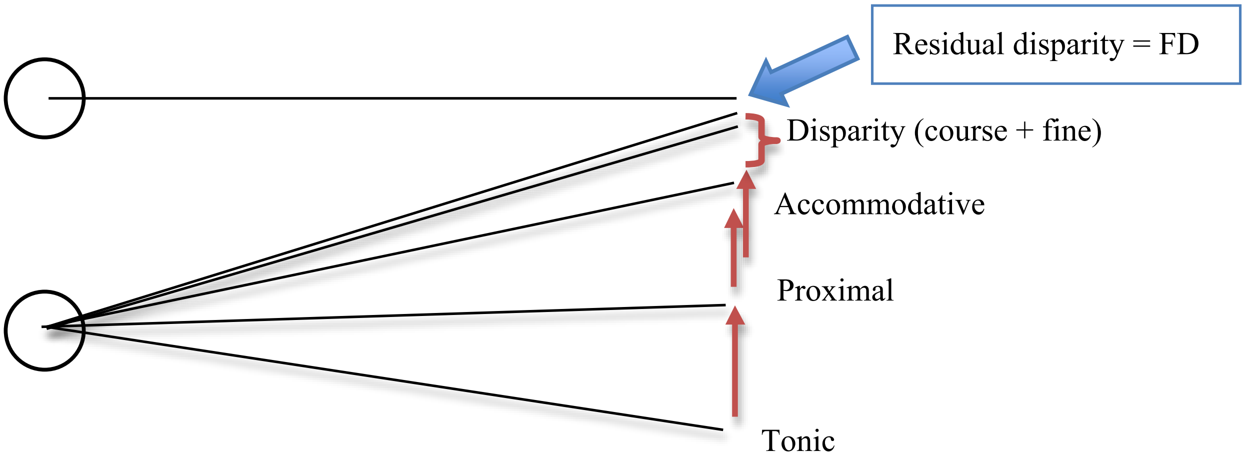

Figure 1. Vergence components at work when shifting fixation from far to near.

The amount of fixation disparity is determined by the disparity vergence demand (how close the object is) and the **gain** of the neurological signal. Gain describes how responsive the fine disparity vergence system is to retinal disparity. The relationship between the fixation disparity, disparity vergence demand (DVD) and the gain (G) are shown in the following equation (from McCormack, p. 166).

$$FD = DVD \times \left[1 - \left(\frac{G}{1+G}\right)\right] \tag{1}$$

Normal gain values are about 100, but with higher gain, fixation disparity is smaller for a given distance. For a fixed gain, fixation disparity will increase for nearer fixation distances.

As a simple illustration, consider a person whose tonic vergence makes the visual axes parallel, so the person is orthophoric at far. If he has a PD of 64 mm, the convergence demand to fixate at 40 cm is 15 prism diopters. If proximal and accommodative convergence together provide 10 prism diopters of vergence, the remaining disparity vergence demand is 5 prism diopters. Table 1 shows how fixation disparity will vary with different values for gain, according to Equation 1. We will study fixation disparity in greater detail later.

Table 1. Fixation disparity for different amounts of gain, when the disparity vergence demand is 5 prism diopters. All units are prism diopters.

Disparity vergence demand (DVD)	Gain (G)	Fixation disparity (FD)
5	100	0.05
5	125	0.04
5	150	0.03

Note that disparity vergence requires some disparity to continue working.

Q. What would happen if the mechanism perfectly aligned the visual axes on the fixation point?

A. The vergence demand would become zero and the stimulus to maintain the correct vergence would be lost. Without disparity vergence, the eyes would quickly swing back toward their position of rest. However, disparity would then increase and they would have to swing back toward fixation. This would be an inefficient and unstable way to maintain motor fusion.

Saladin (Chapter 20 in Borish, First Edition, p. 748-749) explains how fixation disparity helps to maintain a stable alignment.

> *One would think that, in a manner similar to that of the accommodative system, the disparity vergence control mechanism would direct the innervational pattern until the desired vergence level is reached and the controller no longer had an error signal. At first thought, this null situation would seem appropriate if the vergence level is at some rest position, but if this point were actually reached, the system would become unstable because it would have no input. It would fluctuate back and forth within a disparity deadspace (a few minutes of arc, depending on the stimulus configuration, and roughly equivalent to Panum's area) in which no error signal was generated. Instead of going to the null point (the center of the deadspace), however, the system goes to one side of the deadspace and thereby leaves a small directionally specific error. … The amount of disparity left to provide the necessary steady-state or maintenance innervation is known clinically as fixation disparity.*

SENSORY FUSION AND INTRODUCTION TO THE HOROPTER

Motor fusion is a prerequisite for **sensory fusion**, which is the process used by the visual system to combine the retinal images from the two eyes into one unified percept. We touched on some basic concepts of sensory fusion when we learned about corresponding visual directions between the two eyes. Motor fusion points the two eyes at the same object; now you should have similar images falling on corresponding locations in the two retinas. Early vision scientists tried to understand how sensory fusion occurs.

> *Father Franciscus Aguilonius (1613) appreciated that the images projected into the two eyes were slightly different, by virtue of the difference between each eye's viewing angle. He used this fact to develop an analysis of the positions in space that would fall on corresponding points in the two eyes. (from Tyler, The Horopter and Binocular Fusion, in Binocular Vision, edited by Regan. p. 19)*

From the laws of visual direction, we know that objects in different locations in space fall on different retinal locations, and each different retinal location has a different visual direction associated with it. In other words, each retinal point has its own oculocentric visual direction (local sign).

Recall from Hering's binocular law of visual direction, that for every visual line in one eye, there is a corresponding visual line in the other eye that has the same visual direction. It follows that, for every retinal point in one eye, there is a point in the other eye's retina that has the same visual direction. The pair of points in the two retinas that have the same oculocentric visual direction are known as **corresponding points**.

Figure 2 illustrates the concept of corresponding visual directions and corresponding points when the eyes are fixating an object at infinity. The image of the fixated object falls on both foveas, while another single point, located 42° to the left of fixation, stimulates a pair of corresponding points—on the left eye's nasal left retina and the right eye's temporal retina. Similarly, a single point in space, located 21° to the right of fixation, stimulates another pair of corresponding points. For every pair of corresponding points, you can locate a single point in space that stimulates them both.

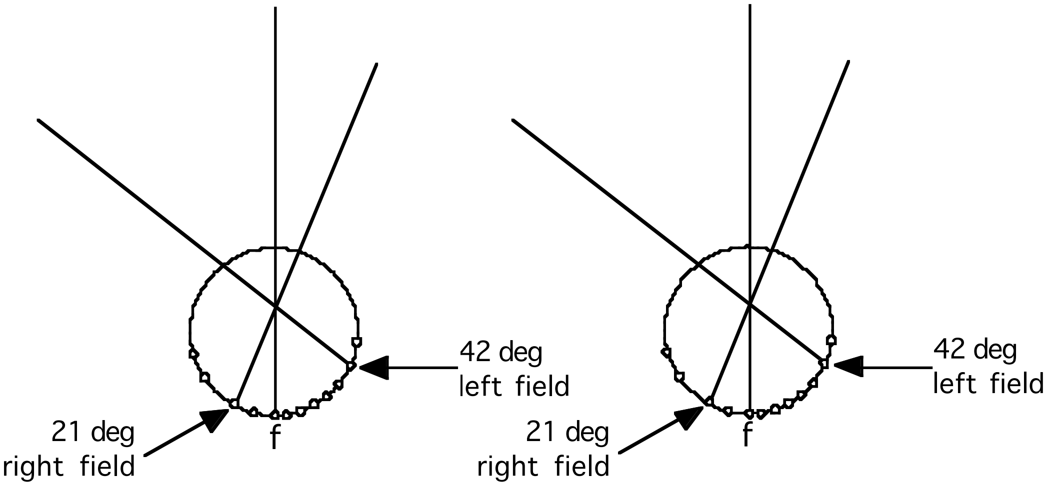

Figure 2. Corresponding points have the same oculocentric visual directions.

You can locate the points in space that stimulate corresponding points by finding the intersection of corresponding visual lines. This is easier to visualize and measure when the eyes are fixating a near object. If you connect a large number of corresponding visual lines from across the two retinas, you form an arc similar to that shown in Figure 3. This arc of points is known as the **horopter**. Aguilonius invented their term. It means the "horizon of vision."

CHARACTERISTICS OF THE THEORETICAL HOROPTER

Since, by definition, an object located on the horopter has the same visual direction in each eye, its image falls on corresponding retinal points. **Corresponding retinal points have zero disparity**, since they have the same oculocentric visual directions.

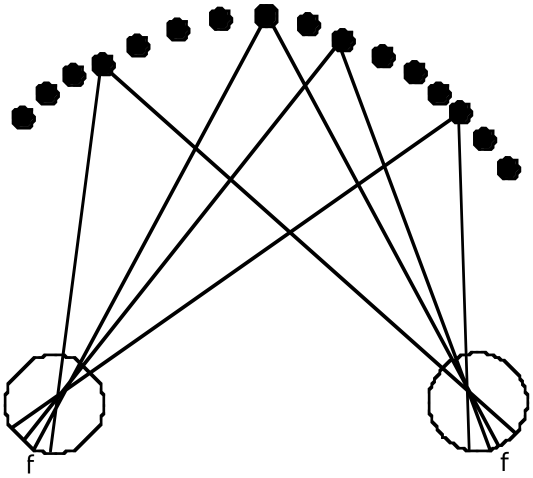

Figure 3. The horopter or “horizon of vision.”

*One definition of the horopter, therefore, is the locus of points in space that produce **zero retinal disparity**.*

Since disparity arises because of the horizontal displacement of the two eyes, the horopter is an arc in the horizontal plane. Aquilonius postulated that the horopter falls on a circle that includes the fixation point and the nodal points of the two eyes. When the eyes are fixating a distant object, the circle is large; when fixating a nearer object, the circle is smaller. Each fixation distance has a horopter associated with it. The shape of the horopter was studied by Vieth in 1818 and then Müller in 1840, and the theoretical circle with the geometry described above is known as the **Vieth-Müller horopter**, or **Vieth-Müller circle.**

Theoretically, for symmetric fixation in the midline, the horopter exists only in the horizontal plane and in a vertical line that passes through the fixation point. All other points in space will stimulate disparate retinal locations. With asymmetric fixation, the horopter becomes twisted into a complex curve (**Tyler's Fig. 2.5, 6**, in Christopher Tyler’s chapter, The Horopter and Binocular Fusion, in *Binocular Vision*, edited by Regan). The horopters shown in Tyler’s figures plot zero disparity points in three-dimensional space and are known as **point horopters**.

Our goal is to understand the basic principles of binocular fusion, and for this purpose, it is sufficient to limit consideration of the horopter to the horizontal plane. The horizontal horopter is usually measured by aligning vertical rods, such as those in the **Howard Dolman** apparatus, which we will use in Lab 2. Because it uses vertical rods to measure the horopter, the horizontal horopter is sometimes also called the **longitudinal horopter** (See **Steinman Fig. 4-3**)