BINOCULAR SUMMATION

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DEGREES OF FUSION

Binocular fusion requires both motor fusion and sensory fusion. Motor fusion is a prerequisite for sensory fusion, but complete sensory fusion does not always follow motor fusion. Sensory fusion may be broken down into successively more sophisticated qualitative levels. Quoting from Saladin in Borish (p. 766): "*Early in the twentieth century, Worth (1903) developed a classification scheme for binocularity that has withstood the test of time in clinical practice. In this scheme, which is described in Chapter 5 in conjunction with the Worth 4-Dot Test, there are three degrees of fusion: The first degree is simultaneous perception […] the second degree is flat fusion, and the third degree is stereopsis*."

Even early in the twentieth century, practitioners realized the importance of stereopsis to oculomotor diagnostics, considering its manifestation as the pinnacle of sensory fusion ability.

The lower degrees of fusion are fundamental levels that must be in place before a person can achieve higher levels. The grades of fusion may be useful in analyzing a patient who is having binocular difficulties. By diagnosing his or her current level of fusion, you can design a vision therapy regime to promote higher levels.

Dr. Maples includes a level of fusion between Worth's first and second degree fusion, so he teaches four levels. Table 23.1 compares the traditional degrees of fusion of Worth with those of Dr. Maples.

Table 23.1 Degrees of binocular fusion.

Worth Degree	Maples Degree	Sensory Fusion	Description
0	0	None	Supression/ Monocular vision
1	1	Simultaneous	Diplopia/Confusion
2	2	Superimposition	No diplopia or confusion
	3	Flat Fusion	Motor fusion holds flat fusion with BI or BO
3	4	Stereopsis	Ultimate sensory fusion

BINOCULAR SUMMATION AT THRESHOLD

The most significant benefit of binocular vision is stereopsis, which is the pinnacle of binocular fusion. We will study stereopsis in greater detail later, but before that, we'll study another, more subtle benefit of binocular vision:**binocular summation**. This is the process by which vision with two eyes is enhanced over what would be expected with just one eye.

We previously discussed how the binocular visual field is larger than either monocular field. The study of binocular summation is usually concerned more with other visual functions, such as thresholds, and how they improve with two eyes.

Two eyes are better than one, but how much better? Do you see twice as well with two eyes? For example, we do not expect binocular visual acuity to be twice as good as monocular acuity. If a person loses one eye, does he/she lose half of his/her sense of vision? Again, this is obviously not the case. Monocular patients have some decrement in visual performance compared to binocular patients, but apart from stereopsis and the visual field, most visual functions are nearly the same for a monocular patient as for a binocular patient.

Experiments have shown that for the absolute detection of a dim light, the binocular threshold is approximately 0.7 times that (1.4 times better) of monocular viewing. This is approximately a 0.15 log unit improvement in sensitivity, which is small, but in certain situations, such as night driving or flying, it could be important.

What accounts for the greater sensitivity with two eyes? It could be due to some physiological process that enhances the input from the two eyes, or it could simply be a matter of statistics. When you have two sensors, you have a greater probability of detection than if you had just one. If each eye alone had a 0.6 probability of detecting a stimulus, the statistical probability of detecting the stimulus using two sensors (two eyes) would be:

$$\mathbf{Pb = Pr + Pl - (Pr \times Pl) = 0.6 + 0.6 - (0.6 \times 0.6) = 0.84 \qquad (1)}$$

The improvement from 0.6 to 0.84 represents a 1.4 fold improvement; or the binocular threshold should be 0.7 times the monocular threshold. Pirenne (1943) did experiments to test the monocular and binocular probabilities of detection, and he found that, for detection of a dim light, the binocular threshold was about 1.4 times better or 0.7 times that of the monocular threshold. He concluded that this kind of binocular summation could be explained simply due to the greater probability of detection. This is known as **probability summation**. Steinman refers to this as the **independent theory** of binocular summation. That is, you can account for the improvement simply due to the fact that two independent detectors have a greater probability of detecting a faint light than one. This, however, does not prove that binocular summation is simply due to statistics; it simply suggests that it may be due to the increased probability of detection. It is possible that binocular summation might be due to both probability summation and some physiological mechanism that further enhances binocular vision.

Experiments by Matin in the 1960's showed that under certain conditions, the increase in binocular sensitivity was greater than that which could be explained by probability alone. Optimal summation occurred when:

1. Corresponding points on the two retinas were stimulated with like targets, and
2. When the stimuli were presented to the two eyes simultaneously, or at least within ~100 msec of each other.

These are basic requirements for **neural summation**, which refers to a neural mechanism that combines the input from the two eyes. Steinman has a nice summary of Matin's experiment on p. 160-161. Campbell and Green provided another explanation of why binocular summation should decrease visual threshold by a factor of 1.4. They said that by combining the input from two eyes, neural signals would be added while background neural noise (assumed to be random and uncorrelated) should partially cancel. They predicted that this process alone would cause binocular thresholds to improve by a factor of √2 or 1.4 (see p. 162 of Steinman, where there is a printing error, √2 is written as 2). Therefore, a 1.4-fold improvement in visual function could be explained by either probability, an increase in signal-to-noise ratio or neural summation, but an improvement by more than this would strongly indicate that neural summation or some other form of physiological summation is involved.

SUPRATHRESHOLD BINOCULAR SUMMATION

Examples in which binocular summation enhances visual function over monocular vision include:

- Visual acuity
- Contrast sensitivity
- Flicker detection
- Brightness perception
- Detection of a dim light

Visual Acuity

Both visual acuity and contrast sensitivity are slightly better with binocular viewing, probably due to both statistical and physiological summation. Generally, you would expect binocular visual acuity to be about one line better than monocular acuity in clinical testing.

Contrast Sensitivity

Binocular contrast sensitivity is better than monocular contrast sensitivity by a factor of 1.4 across the entire range, if both eyes are well corrected. (See **Steinman Fig. 6-4**). The degree of binocular summation changes, however, when one eye is blurred. With monocular blur, which can be created by over-plussing the eye, the binocular contrast sensitivity declines with increasing blur.

With enough monocular blur, it is possible to reduce the binocular contrast sensitivity below that expected for monocular viewing. That is, a severely blurred image in one eye seems to degrade binocular vision to be worse than the image provided by the good eye.

The effect is more pronounced at higher spatial frequencies. For higher spatial frequencies, monocular blur greater than about 1.50-2.00 diopters seems to degrade binocular contrast below the monocular level. This varies with individuals and could explain why some patients fitted with monovision cannot accept more than a 1.50-2.00 diopters difference in focus between the two eyes.

Flicker

In-phase flickering lights presented to each eye appear to flicker more brightly than if seen monocularly. If presented out of phase, however, the flicker nearly disappears. (**Steinman Fig. 6-2**) Also, the highest critical flicker frequency that can be detected (CFF) is greater for binocular than monocular viewing if the lights are presented to the eyes in phase.
If they are out of phase, the binocular CFF is actually smaller than the monocular CFF (see Table 23.2).
This also indicates a summation or interaction of input from the two eyes. (**See Steinman Fig. 6-3**.)

Table 23.2 CFF under monocular and binocular conditions.

Condition	Typical Photopic CFF
Binocular – OD, OS flicker in phase	45
Binocular – OD, OS flicker out of phase	30
Monocular	40

When plotting the temporal modulation transfer function (Steinman calls it the temporal contrast sensitivity function in his Fig. 6-3), we see that temporal sensitivity is better under binocular conditions for in-phase flicker, but is worse for counter-phase flicker. The difference is more pronounced for low temporal frequencies.

Brightness Perception and Fechner's Paradox

The binocular perception of brightness shows that binocular summation is more complex than just the sum of two inputs. When both right and left eyes have a similar retinal illuminance, the binocularly perceived brightness may be only slightly brighter than that seen by either.

In some conditions, the brightness of a light seen binocularly is actually lower than if seen monocularly. If a neutral density (ND) filter is placed over one eye, while the other eye views a bright light directly, the binocular perception of

brightness is less than the brightness seen by the unfiltered eye alone. This is called **Fechner's paradox**, and it suggests that the visual system averages the brightness between the two eyes. (See **Fig. 6-6 in Steinman**).
This can be demonstrated experimentally using an apparatus illustrated in Figure 23.1-left.

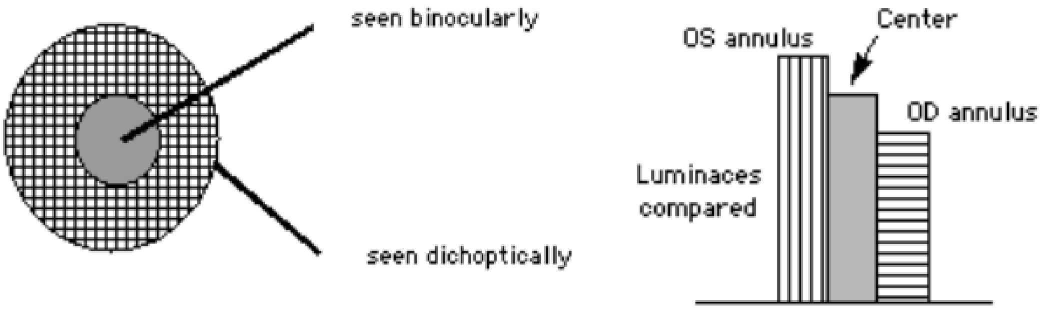

Figure 23.1 *Stimulus for brightness matching experiment.*

The center spot is designed so that the same brightness is presented to both eyes and it is fused binocularly. The annulus is designed so that it is also fused, but each eye sees a different brightness. When different stimuli are presented to the two eyes, they are said to be seen dichoptically. This can be accomplished using a haploscope (such as the Synoptophore) or with polarizers. The center is set to a standard brightness and is flashed alternately with the annulus. The brightness of the annulus presented to OS is preset, and the subject must adjust the brightness of the OD annulus to make the annulus appear to be the same brightness at the center. When the OS annulus is set brighter than the center, the OD brightness must be set lower to match. This is shown in Figure 23.1-right.

Brightness averaging explains **Fechner's paradox**. Below is an example question on this topic from the Optometry exam review book (p. 153, 187).

***"450**. With respect to apparent brightness, Fechner's paradox suggests that binocular sensory integration is based upon*

A. *Right-eye, left-eye sensory independence*
B. *Averaging*
C. *Linear summation*
D. *Potentiation*
E. *Facilitation*

*Answer: **B***

Fechner's paradox refers to the observation that a bright stimulus viewed monocularly appears brighter than when it is viewed binocularly with an ND filter in front of one eye. The paradox is simple: by opening the filtered eye, more light enters the visual system, but the light appears darker. It appears as though the perceived brightness is determined by some averaging of the brightness of the two eyes."

Instead of using an ND filter, what happens if you simply occlude one eye? Based on simple averaging, the light should appear much darker when viewed binocularly than monocularly. In this case, however, they look nearly the same. This suggests that the binocular perception of brightness also requires contour information from both eyes if the interaction is to occur. Removing contours from the image seems to negate the averaging mechanism that causes Fechner's paradox.

This can be tested by repeating the experiment for Fechner's paradox, but in addition to placing an ND filter before one eye, defocus the image with a plus lens. This blurs the previously visible contours. When this is done, the monocular and binocular brightness are similar and Fechner's paradox is not observed.

Interocular Transfer
Motion after-effects can be transferred to the fellow eye even if it had been covered during stimulus presentation. This indicates that input from the two eyes are combined and processed together by the brain. Tilt after-effects (**Steinman Fig. 6-7**) are also transferred to the other eye. Interocular transfer is stronger when the dominant eye is stimulated.

When binocular summation is a disadvantage
In some persons, flashing lights can trigger an epileptic attack, but closing one eye can mitigate this effect. In this case, the greater binocular sensitivity is a disadvantage. Disability glare that interferes with vision or causes discomfort also seems to be more noticeable when viewed binocularly than monocularly. This is also a case in which the greater sensitivity gained by binocular vision is a disadvantage.

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