8-1-1998

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Recommended Citation
Nield, Chris and Fromm, Kevin, "The relationship of monocular vernier biases and fixation disparity" (1998). College of Optometry. 82.
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Degree Type
Thesis

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THE RELATIONSHIP OF MONOCULAR VERNIER BIASES AND FIXATION DISPARITY

By

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KEVIN FROMM

A thesis submitted to the faculty of the
College of Optometry
Pacific University
Forest Grove, Oregon
for the degree of
Doctor of Optometry
August, 1998

Advisor: Scott Cooper, O.D., M.Ed., FAAO
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Abstract

Hyperacuities are visual alignment discrimination judgments which yield lower thresholds than expected, given the photoreceptor density of the retina. Vernier bias is the perceptual alignment error (or subjective alignment position relative to true physical alignment) that is manifest during vernier hyperacuity testing. Few studies have been performed on vernier bias, leaving its purpose and etiology unknown. Since monocular vernier biases and the monocular components of fixation disparity are similar in magnitude and distribution, it is hypothesized in this study that non-stressed fixation disparity equals the sum of the monocular vernier biases. Twenty-six subjects were tested both with the Mentor BVAT II and with a software program developed at the Pacific University College of Optometry in order to measure fixation disparity and monocular vernier biases respectively. A two-tailed T-test and linear regression performed on the data show that under these testing conditions a significant correlation between monocular vernier biases and fixation disparity does not exist (mean difference = 23.7 arc sec, P-value < 0.1176; R-value = 0.0122, R-squared value = 0.015).

Key Words: hyperacuity, vernier hyperacuity, vernier hyperacuity bias, monocular alignment error, fixation disparity
Introduction

Hyperacuity

Resolution Acuity vs. Hyperacuity. Resolution acuity is the ability to distinguish two objects in space as separate and depends on two main factors. First, the luminance difference between "peak and trough" of the combined light distribution on the retina created by two separate objects in space must exceed the eye's threshold level. Second, the distance between the two retinal images must be large enough to result in the stimulation of different receptive fields -- this, in turn, is a function of photoreceptor density.

The minimum angle of resolution, however, is not the smallest judgment the visual system is capable of making. Even finer judgments can be made during localization tasks. These judgments are termed "hyperacuities," a name chosen because they yield lower than expected thresholds, given the photoreceptor density of the retina.

One type of hyperacuity, often termed alignment hyperacuity or vernier hyperacuity, involves monocularly detecting the alignment of two points in space and is usually between 8 and 13 arc seconds of visual angle. Because alignment hyperacuities are in the 8 to 13 arc second range, but the foveal intercone spacing is of the 25 to 30 arc second magnitude, hyperacuities are assumed to be the results of cortical (rather than retinal) processing.

Hyperacuity Bias. Vernier hyperacuity is determined from the distribution of several subjective responses during a monocular alignment task. The more tightly grouped the responses are within the distribution, the lower the calculated threshold will be (i.e., the
sensitivity to misalignment is greater). The term "bias" in hyperacuity testing refers to the mean of the leftward and rightward responses (assuming a task based on horizontally aligning vertically displaced targets). Thus, bias can be thought of as a person's constant or mean response error and represents a subjective "skew" of the true, physical alignment of two objects in space (i.e., a person's perception of "straight up and down" may not actually be "straight up and down"). The actual hyperacuity is represented by the distribution of responses around this habitual "skew" point.

In short, vernier bias indicates the position of subjective alignment relative to true, physical alignment, while vernier hyperacuity represents a measure of variation around this position. Vernier bias can be expressed arithmetically (i.e., rightward bias = +) or in absolute terms without regard to direction.

Factors Affecting Hyperacuity Tasks. Monocular alignment tasks are affected by several variables. O'Shea et al. and Levi et al. report that alignment discrimination is much better for same than opposite-contrast stimuli; they also report that as the contrast decreases, the threshold increases.9

Furthermore, under high contrast conditions, hyperacuity threshold is not affected by variations in spatial lengths of stimuli. Instead, the gap length between the stimuli has a more significant effect.10 In general, as the gap size increases, the targets move further from the fovea, causing the threshold to increase. More specifically, optimal hyperacuity is found with 1 to 5 arc minutes of separation between objects, such that the objects can be easily distinguished as two, with no vertical overlap of retinal images when
performing a horizontal alignment task.\textsuperscript{11} Contrast and gap length aside, the visual system is very resistant to noise produced by spatial jitter when performing a separation discrimination task such as alignment hyperacuity,\textsuperscript{2} but the alignment hyperacuity task is made easier by the presence of nearby stationary references.\textsuperscript{12}

While several studies have investigated hyperacuity in general, research focused specifically on vernier bias is relatively meager and ambivalent. Variables which affect vernier bias include retinal diseases and age, though different studies report completely opposite findings in relation to the effect of age on vernier bias.\textsuperscript{11,15,16}

**Fixation Disparity**

**Fixation Disparity Explained.** Ogle coined the term fixation disparity (FD) in 1949 and defined it as “a misalignment of the visual axes under binocular conditions.”\textsuperscript{17} Despite the misaligned images not falling on exactly corresponding retinal points, sensory fusion still occurs because of the visual integration of a single retinal point of one eye and a corresponding group of points, termed Panum’s fusional area, in the other eye.\textsuperscript{18}

While the exact cause of fixation disparity is unknown, two main theories attempt to explain it. One theory holds that fixation disparity is merely the result of -- or rather a reaction to -- stress placed upon the binocular system during fusion, as evidenced by the widely acknowledged fixation disparity curves.\textsuperscript{19,20,21} A second theory acknowledges the effect of vergence upon fixation disparity but maintains that fixation disparity is not merely a result of stress;
rather, it is a purposeful perceptual error which provides feedback that is essential to maintaining sensory fusion.

Variables affecting Fixation Disparity. Research shows that fixation disparity is affected by luminance, target blur, and target distance. The work by Jaschinsksi and Kruza indicates that either decreasing luminance or increasing target blur results in a shift toward the tonic vergence level and a related exo shift in FD.22 Jenkins et al. find that patients without associated phorias show a greater increase in binocular visual acuity than those with associated phorias.23 Jaschinki and Kruza also observe that fixation disparity measured at different distances remains unchanged over time.24

Are Hyperacuity Bias and Fixation Disparity Related?

Initially, as expressed in Ogle's original definition, it was believed that fixation disparity was simply a measure of the anatomical misalignment of the visual axes under fused conditions. Several studies performed since that time suggest that fixation disparity results not from an anatomical misalignment but instead is fundamentally the result of a perceptual mechanism.25,26,27,28 In fact it has been shown that FD is present even when the foveal centers of the two eyes are in exact alignment.29 In order to describe the angular difference between the fixation misalignment and fixation disparity, recent studies have used the term "projection change" because it is believed that the difference is due to a change in perceived visual direction during fusion.30

These recent findings regarding fixation disparity raise the
following question: With fixation disparity resulting from a perceptual misalignment during fused conditions, is it possible that vernier bias results from the same perceptual mechanism, only under monocular conditions? If so, it seems plausible then that the monocular perceptual alignment error (i.e., vernier bias) is related to the binocular perceptual alignment error (i.e., fixation disparity). The purpose of this study is to explore if the sum of the monocular vernier biases equals the fixation disparity.

No study has tested this exact hypothesis, but others show the possibility of this relationship. Hebbard proposes that the total fixation disparity is the algebraic sum of uniocular components, and numerous experiments characterize the distribution of the monocular components of fixation disparity to ascertain whether or not the fixation disparity is equally divided between the two eyes or has an unequal distribution. Ogle, in his experiments, concludes that the monocular components of fixation disparity are dependent upon the ocular dominance of the subject, with the nondominant eye taking up most or all of the total fixation disparity. Irving and Robertson similarly conclude that approximately one-third of the population with otherwise normal binocularity has unequal distribution of the monocular components of fixation disparity. Carter also agrees that the monocular components of fixation disparity are unequal, but only in those with sensory fusion defects.

Similarly, in a study regarding hyperacuity, all subjects showed monocular biases on the order of tens of arc seconds (and therefore similar in magnitude to the uniocular components of fixation disparity), with a large difference between the two eyes commonly
Thus, with monocular vernier biases being unequal between the two eyes and having the same magnitude as the monocular components of fixation disparity, these studies suggest that the proposed correlation between vernier bias and fixation disparity has merit.

Methods

Protocol

This project was performed concurrently with another project that was seeking to find a relationship between hyperacuity and stereopsis. Since the protocol for each project was similar, the same subjects were used for each project, and a combined protocol for collecting all of the necessary data was implemented. This protocol was designed with the aforementioned factors which affect hyperacuity and fixation disparity taken into consideration.

Subjects. The subjects for this experiment were twenty-six students from the Pacific University College of Optometry. Subjects for the study were obtained on a volunteer basis. Criteria which qualified a subject to participate in the study were the following: a comprehensive vision and ocular health examination within the past year, visual acuity of at least 20/20 through habitual prescription (OD, OS, OU), no previous history of amblyopia or strabismus, no vertical heterophoria greater than 1/2 pd, no large lateral heterophoria (5 pd esophoric or 10 pd exophoric), and no ocular or systemic disease.

Pretesting. Prior to testing, each subject was screened for the
above criteria in a brief pretesting session. A brief patient history was followed by visual acuity measurement using a projected Snellen chart at 6 meters and a reduced Snellen near acuity card at 40 centimeters. Next, a distance Maddox Rod test was performed to screen for vertical heterophoria. Finally, unilateral and alternating cover tests were performed with prism neutralization to screen for heterophoria and strabismus.

Hyperacuity testing. The testing distance for measuring hyperacuity, hyperacuity bias, and fixation disparity was determined by first assessing threshold stereopsis (which was being measured for purposes of the other project) with the Mentor BVAT II Visual Acuity Tester under normal room illumination. The stereopsis mode on the BVAT was set for 15 arc seconds at a testing distance of 6 meters, and the distance at which the subject could consistently demonstrate stereopsis was determined. This exact distance was then used as the testing distance for measuring hyperacuity, hyperacuity bias, and fixation disparity.

Once the testing distance was determined, alignment hyperacuity was then tested using software developed at the Pacific University College of Optometry. The stimuli were presented on a 15" Macintosh color high resolution RGB monitor that was aligned side by side with the Mentor BVAT. The hyperacuity testing was conducted under the same testing conditions as the threshold stereopsis testing. The subject was instructed to sit in a chair in front of the Macintosh monitor at the same distance that threshold stereopsis was detected. Once seated, one of the subject's eyes was patched and a computer mouse was placed on the table in front of
him/her. During the testing procedure, the screen displayed two
dots five arc minutes in size, one above the other, separated by one
arc minute. The bottom dot was held at a constant spot, and the top
dot was randomly displaced by the computer to the left or to the
right of the bottom dot. With each trial the subject was instructed to
move the mouse accordingly to line up the top dot directly above the
lower. Each subject was encouraged to be as accurate as possible in
determining alignment of the dots. When the subject believed the
dots to be aligned, he/she clicked the mouse, causing the value of
any lateral offset to be registered within the software and the
computer to subsequently displace the top dot again. The subject
aligned the dots a total of 150 times for each eye to allow an accurate
assessment of his/her monocular vernier hyperacuity. Data
collection was broken down into 6 sets of 25 trials with a 10 to 15
second break between sets. The subject was kept monocular during
the entire testing procedure. The same procedure was followed for
testing monocular alignment hyperacuity for the subject's other eye.

**Fixation disparity testing.** Immediately following alignment
hyperacuity, fixation disparity was measured using the Mentor BVAT
II, under the same testing conditions and at the same testing
distance as the alignment hyperacuity testing. Each subject
remained patched until fixation disparity was measured in order to
maximally reduce the impact of binocular pre-tasks on fixation
disparity results. The fixation disparity mode on the BVAT was
calibrated for a testing distance of 6 meters. Ten measurements
were taken, in which a common central target was seen by both eyes
and top and bottom targets seen by opposite eyes. During each
measurement, the top target was displaced either to the right or left of the bottom target; the subject would then tell the controller which direction to move the top target, who would in turn move the target in 1 arc minute steps (at 6 meter calibration) as directed by the subject until the subject reported perfect alignment.

The average of the ten measurements was then converted to the mean fixation disparity by using the following formula:

\[
FD = (6.0/D)(\text{average})
\]

Key:
- FD = actual fixation disparity (arc min)
- 6.0 = calibrated testing distance of the BVAT (meters)
- D = actual testing distance (meters)
- average = average of the ten FD measurements (arc min)

Data handling. All data obtained were entered in tabular format into an Excel 4.0 spreadsheet. Alignment hyperacuity data were grouped and organized into a descending column of alignment points for each eye respectively. Outliers in these columns were determined on the basis that if the greater value of two sequential values was more than 50% greater than the immediately lesser value, the greater value was not used in further calculations. This method typically resulted in 2 or 3 alignment points on each end of the scale treated as outliers and not used in further calculations. In addition, one subject’s data were eliminated entirely because the subject failed to follow instructions during the fixation disparity
measurements.

The hyperacuity data analyzed provided a very narrow distribution. The peak of data distribution was estimated based upon greatest frequency for a given hyperacuity measurement. It was necessary to extrapolate the peak value from the most common central 2 or 3 values of the subject's hyperacuity data. This extrapolated value was considered to be the subject's own point of perfect alignment—the vernier hyperacuity bias. A temporalward bias was assigned a negative (-) value, while a nasalward bias was assigned a positive (+) value. The algebraic sum of the two eyes’ biases was then compared to the subject’s actual fixation disparity, where an exophoric fixation disparity was assigned a negative (-) value and an esophoric fixation disparity assigned a positive (+) value.

Results

In order to compare predicted fixation disparity (i.e., the sum of the monocular hyperacuity biases) and actual fixation disparity, a two-tailed T-test for a within subjects design was performed. This yielded a mean difference of 23.7 arc seconds (P-value < 0.1176). Figure 1 illustrates the data distribution for predicted and actual fixation disparities and the difference between them.

Linear regression was also performed on the data and revealed an R-value 0.122 and an R-squared value of 0.015, as illustrated in Figure 2.
Figure 1 -- Histograms showing the distributions of the predicted and actual fixation disparities.
**Discussion**

Because the subjects in general showed fixation disparities on the order of 60 arc seconds, a mean difference of 23.7 arc seconds between predicted and actual fixation disparities as found with the T-test indicates that the sum of the monocular vernier biases is not an accurate predictor of fixation disparity given these testing conditions. Linear regression confirms the lack of correlation between the two, at least for this particular study.

While the predicted relationship between vernier bias and fixation disparity was not supported, there are other possibilities for a relationship between the two. For a truly non-stressed (vergence-free) measure of fixation disparity, it would be best to neutralize with prism the vergence demand that is present during the FD
testing. Under the protocol of the present experiment, even though the subjects were monocular for approximately 30 minutes prior to testing fixation disparity, there still was a vergence demand during the FD measurements corresponding to the testing distance, which of course was different for each subject. Additionally, most subjects would be actively fusing compared to their tonic vergence posture resulting from the prolonged occlusion. Thus, while we measured relatively non-stressed fixation disparities, we did not measure totally non-stressed fixation disparities. This leaves open the possibility that the sum of the monocular vernier biases is related to fixation disparity, but only with respect to vergence-free fixation disparity measurements.

Another possible source of error in our study was that our clinically-adaptable protocol was not sensitive enough to accurately detect each subject's true fixation disparity. This was due to the fact that when measuring fixation disparity, the top target on the BVAT could only be adjusted in one arc minute increments as directed by the subject. With the magnitude of vernier bias being much smaller than one arc minute, fixation disparity would need to be measurable in arc second increments to permit greater sensitivity and precision. In this study, ten fixation disparity measurements were averaged to give a value on the order of arc seconds rather than on arc minutes, but this does not eliminate the possibility of insensitivity.

A study by Carter regarding fixation disparity raises another possibility. Carter found that about 75% of his subjects showed a "constant error" during binocular vernier alignment tasks (which differs from FD testing in that while both are tested under fused
conditions, the binocular alignment task allows both eyes to see top and bottom targets). "Constant error" was Carter's term to describe the physical misalignment of targets that was present when the subject reported alignment during the binocular alignment task. Carter found that when the uniocular components of FD were measured relative to the "perceptual zero" -- or subjective alignment -- rather than to the "physical zero" -- or objective alignment -- that the uniocular components were much closer in magnitude to each other. Carter's finding of "constant error" under binocular conditions raises the possibility that it is equal to the sum of the monocular "constant errors" (i.e., monocular vernier biases). If such is the case, then obviously the relationship tested in our study between FD and vernier bias could be discounted completely.

Furthermore, Carter's study raises the interesting possibility of a different type of relationship between monocular vernier biases and fixation disparity. Perhaps it is the "constant error" (or "perceptual zero") that accounts for the perceptual mechanism underlying the "projection change" (which, as discussed previously, is the angular difference between fixation misalignment and fixation disparity). If this is the case, and if it could be shown that binocular "constant error" is directly related to (if not equal to) the sum of the monocular vernier biases, then there would obviously be a relationship between monocular vernier biases and fixation disparity, albeit not the one we tested.

Of course, the possibility exists that hyperacuity bias does not even represent a perceptual mechanism, as we assumed. It is possible that hyperacuity bias (at least as it was measured in this
study, with circles rather than lines) results simply from the cyclotorsion that occurs under monocular conditions. In other words, it could simply represent the physical rotation, or skew, of the eye that occurs during cyclotorsion, in which case it would more appropriately be called vernier skew rather than bias or error, and in which case there could be no presumed relationship between FD and monocular vernier biases. A mathematical prediction of vernier biases that would result from common amounts of cyclotorsion under monocular conditions (typically one to six degrees) yields values on the order of six to thirty-eight arc seconds, which are comparable to the actual vernier biases found in this study (see Appendix). However, the effects of cyclotorsion were likely minimized to some degree by the peripheral vertical references of the testing area (such as computer screen, walls, doorways, etc.) Thus, while the cyclotorsional effect is probably minimal, it was unaccounted for, and thus represents a potentially significant confounding factor.

In any case it is clear that much research is still needed regarding hyperacuity bias. Only a minimal amount has been performed, and what results have been found are equivocal, with our present study being no exception. Perhaps a more revealing study would be the following: a project that seeks concurrently to find a relationship between monocular vernier biases and fixation disparity (with and without prism to neutralize any vergence demand) or between monocular vernier biases and binocular vernier bias; the testing could be performed at 3 or 4 pre-determined distances, and the number of trials during the alignment task could be significantly reduced compared to this study -- such a study would be much more
efficient and revealing. A software program could be designed that allows for measurements of fixation disparity and monocular vernier biases concurrently and allows arc second precision in measuring both.

Additional studies that may be warranted include one that compares the amount of cyclotorsion under monocular conditions to the vernier bias, another that compares fixation disparity to fixation misalignment with respect to the binocular vernier bias, and a third that compares the uniocular components of fixation disparity to the monocular vernier biases with and without respect to the binocular vernier bias.
## Appendix

<table>
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<tr>
<th>Patient</th>
<th>Hyperacuity Bias OD (arcsec)</th>
<th>Hyperacuity Bias OS (arcsec)</th>
<th>Predicted F.D.</th>
<th>Actual Mean F.D.</th>
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