Binocular Luminance Summation in Humans
With Defective Binocular Vision

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Subjects with no functional binocularity (no stereopsis and no peripheral fusion) show much less binocular summation of the pupillary response (about 12%) than normal subjects (29%). However, summation is occasionally quite high in clinically stereoblind subjects. The reasons could be the simultaneous use of nonoverlapping fields of the two eyes in large-angle exotropes, peripheral fusion (common in microstrabismus), a mosaic of inputs from the two eyes in different parts of the visual field (often seen in strabismic alternators), or the incomplete suppression of the deviated eye in subjects with double images. These results suggest that the binocular summation of the pupillary response can be used as a test for the simultaneous use of the two eyes, rather than as an index of functional binocularity and stereopsis.


In normal adult human observers, the pupils are smaller when both eyes are illuminated together than when one eye is illuminated and the other occluded. Birch and Held found that infants younger than 4 months did not show a significant difference in pupil diameter under monocular versus binocular viewing conditions (no binocular summation) and that, for individual infants, the age of onset of binocular luminance summation was positively correlated with the age of onset of stereopsis as assessed by preferential looking. They concluded that binocular luminance summation could be used to assess the integrity of binocular visual pathways. Birch and Held capitalized on a study of ten Doesschate and Alpern, who reported that in two strabismic observers, the pupil of the fixating eye was not influenced by light presented to the nonfixating eye.

We attempted to adapt this method in young kittens and adult strabismic cats. In two esotropic cats, we confirmed the absence of summation reported by ten Doesschate and Alpern for strabismic humans. However, in one extremely exotropic cat, we found that illumination of the deviated eye caused a clear constriction of the pupil of the dominant eye. Such cats show a complete breakdown of cortical binocularity. Thus, we had to assume that another mechanism, rather than functional binocularity, is responsible for the binocular luminance summation seen in exotropic cats. We proposed that binocular luminance summation is an index of the simultaneous use of the two eyes (or, in other words, of a lack of interocular suppression), rather than a test for functional binocularity. Subjects with an extreme exotropia are able to use both their eyes simultaneously because, unlike in esotropes, large parts of the visual fields of their two eyes do not overlap, but rather complete each other in a form of panoramic vision.

In view of these controversial findings and of the potential importance of binocular luminance summation as an objective index of binocular function in clinical and animal studies, I decided to probe this test in a large number of human subjects with known disorders of binocularity and known clinical histories. The present paper reports the results of this study. Part of the results reported here have appeared in abstract form.

Materials and Methods

The apparatus was a close replica of the apparatus used by Birch and Held. The subjects were asked to position their head on a chin-rest, at the entrance of a full-field, uniformly illuminated white dome 48 cm in diameter. The luminance of the dome was 55.2 cd/m², rather than the 1.92 cd/m² used by Birch and Held. This luminance was chosen to allow a direct comparison with young kittens and adult strabismic cats. The dome contained a 18-deg aperture through which a video camera monitored the subject’s eye. The camera was used on conjunction with a videotape recorder and a black and white display monitor. The distance between the camera and the subject’s eye was 25 cm.
Testing was usually begun in a binocular viewing condition. The subject was asked to fixate the center of the aperture. After 2–3 min adaptation to the background illumination, about a 2-min videotape of the right eye was recorded. The subject’s left eye was then covered (usually by the palm of his/her left hand). After another 2–3 min readaptation to the background level, 2 min of the monocular viewing condition was recorded. After a brief rest, the procedure was repeated for the left eye. For subjects with alternating fixation, the procedure was repeated with either eye fixating.

In the following session, the succession of viewing conditions was reversed (left monocular, right monocular, left binocular, right binocular). All subjects participated in at least two experimental sessions. When further sessions were necessary, the succession of the eyes was reversed.

Pupil- and iris-diameter were measured from single frames on the black and white monitor. Pupil diameter was converted to a percentage of iris diameter. Only frames that were clearly in focus were retained for analysis. One recorded session typically yielded 20–30 single frames for each viewing condition. Most of the pupil measurements were done by a naive observer.

The subjects were 18 young adults (age: 20–35 yr) with various deficits of binocular vision, and 3 normal controls. The refractive status of the subjects was assessed objectively with the aid of a refractometer and subjectively with trial lenses at a distance of 6 m. With the exception of the deep amblyopes Patient 14, Patient 13, and Patient 9, the data included in Table 1 are those obtained subjectively. Visual acuity was tested at 6 m, using Snellen optotypes (letters and figures). Fixation was tested with the aid of a visuscope. The angle of anomaly was assessed with several methods: the striated glasses of Bagolini, dark and light red filters in combination with the Maddox cross, and the test of simultaneous bifoveal stimulation (Clippers test).

The binocular status of the subjects was assessed with the TNO, Titmus, Randot, and Lang stereo tests. The subjects were also tested for residual peripheral stereopsis using a motion-in-depth test (described by Sireteanu, Fronius, and Singer). Twelve of the experimental subjects were unilateral amblyopes. Five had alternating fixation; of these, two had also a slight unilateral amblyopia. One subject with a deep bilateral myopia (Patient 1) had subnormal visual acuity in both eyes (bilateral amblyopia?). Patients 2 and 3 were twin sisters. The orthoptic status of the subjects is shown in Table 1.

Results

General Observations

Table 2 shows the results of the different tests for binocular vision. As an overall tendency, the TNO, Titmus, and Randot tests agreed roughly with each other (exception: Patient 6 was stereoblind according to the TNO test, but stereodeficient with the Randot and Titmus tests). With the Lang test the rate of failure was higher than with the other tests, especially in patients with microstrabismus (examples: 1, 6, 7).

The absence of motion-in-depth in the central visual field usually correlated with the absence of stereopsis in the Titmus test (including the fly). There were exceptions to this rule, however. Patient 3 was stereodeficient with the TNO, Randot, and Titmus tests and normal with the Lang test, but she could not see the motion-in-depth neither in the central nor in the peripheral visual field. Patient 7 was stereodeficient with the TNO, Randot, and Titmus tests and stereoblind with the Lang test; he was able to see motion-in-depth in the peripheral, but not in the central visual field.

In view of these inconsistencies, I grouped the subjects who failed on the TNO, Randot, and Titmus tests together (Patients 8–18 in Table 2); they were further subdivided as subjects with no stereopsis (stereoblind; \( n = 6 \)) and subjects with very low stereopsis (peripheral fusion and/or the fly in the Titmus test; \( n = 5 \)). The remaining subjects were considered stereodeficient (\( n = 7 \)).

Binocular Summation

Normal observers: The three normal observers included in this study were emmetropes with full visual acuity in both eyes (1.25–1.6). All had excellent stereopsis on all tests.

In these observers, binocular luminance summation (defined as the increase in pupil diameter from the binocular to the monocular viewing condition) ranged from 18% in one subject to 38% in another (Fig. 1, center and right panels, respectively) and averaged 29%. Summation tended to be similar in both eyes of the same observer.

To test the influence of refractive correction on binocular summation, the deeply myopic Patient 1 was tested wearing her full correction (contact lenses) and retested without correction. Since there was no difference between these two conditions, in all the following experiments the subjects were tested without correction.

Strabismic amblyopes: Strabismic amblyopes showed a variety of responses, from an absence of summation in the dominant eye (Patient 13, Fig. 2, top left panel),
<table>
<thead>
<tr>
<th>Patient</th>
<th>Eye</th>
<th>Refraction</th>
<th>Visus c.c.</th>
<th>Fixation</th>
<th>Strabismus</th>
<th>Correspondence</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RE</td>
<td>-7.75 -1.5/145°</td>
<td>0.6-0.8</td>
<td>foveolar, unsteady</td>
<td>far 0°*</td>
<td>normal</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>-6.75 -1.0/44°</td>
<td>0.8-1.0</td>
<td>foveolar, unsteady</td>
<td>near 0°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>RE</td>
<td>-1.5</td>
<td>1.25</td>
<td>foveolar</td>
<td>far 0°</td>
<td>normal</td>
<td>Family history</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>-1.5</td>
<td>0.8</td>
<td>foveolar</td>
<td>near 0°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>RE</td>
<td>-2.25</td>
<td>1.25</td>
<td>foveolar</td>
<td>far 0°</td>
<td>normal</td>
<td>Initially RE emmetropic, LE hyperopic (2D difference, Family history</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>plano</td>
<td>0.5-0.6</td>
<td>foveolar</td>
<td>near 0°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>RE</td>
<td>+2.75</td>
<td>0.8</td>
<td>foveolar</td>
<td>far 0°</td>
<td>normal</td>
<td>Occlusion therapy at 10 yr</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>+1.25</td>
<td>1.25-1.6</td>
<td>foveolar</td>
<td>near 0°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>RE</td>
<td>+0.75 -0.75/175°</td>
<td>1.25-1.6</td>
<td>foveolar</td>
<td>far 0°</td>
<td>normal</td>
<td>Family history</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+5.5 -1.5/17°</td>
<td>0.6</td>
<td>foveolar</td>
<td>near 0°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
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<td>foveolar</td>
<td>far +1°</td>
<td>angle of anomaly</td>
<td>1° (harmonious)</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+4.0 -2.5/35°</td>
<td>0.5-0.6</td>
<td>foveolar</td>
<td>near +1°</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>RE*</td>
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<td>0.8-1.0</td>
<td>1° nasal, 0.5° down, unsteady</td>
<td>far +1.5°</td>
<td>angle of anomaly</td>
<td>1.5° (harmonious)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>-0.25 -0.5/5°</td>
<td>1.25-1.6</td>
<td>foveolar</td>
<td>near +1-2°</td>
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<td></td>
</tr>
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<td>8</td>
<td>RE*</td>
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<td>foveolar</td>
<td>far +1°</td>
<td>angle of anomaly</td>
<td>1° (harmonious)</td>
</tr>
<tr>
<td></td>
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<td>near +1°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>RE</td>
<td>+0.25-0.75/150°</td>
<td>1.25</td>
<td>foveolar</td>
<td>far -2° -VD2°</td>
<td>angle of anomaly</td>
<td>5° (nonharmonious)</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+6.25-2.5/8°</td>
<td>0.08</td>
<td>5° nasal, unsteady</td>
<td>near +5° -VD3°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>RE</td>
<td>-0.75/150°</td>
<td>1.0</td>
<td>foveolar</td>
<td>far +17°</td>
<td>angle of anomaly</td>
<td>12° (nonharmonious)</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+0.5 -0.5/70°</td>
<td>0.6</td>
<td>foveolar</td>
<td>near +20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>RE</td>
<td>+0.75-0.75/15°</td>
<td>1.25</td>
<td>foveolar</td>
<td>far +4°</td>
<td>angle of anomaly</td>
<td>1-4° (nonharmonious)</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+1.75</td>
<td>0.12</td>
<td>3.5° nasal, 1.5° up, unsteady</td>
<td>near +10°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>RE</td>
<td>+4.5</td>
<td>1.0-1.25</td>
<td>foveolar</td>
<td>far 0°</td>
<td>angle of anomaly</td>
<td>0°-4° (variable)</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+3.5</td>
<td>0.6-0.8</td>
<td>foveolar</td>
<td>near 0°-+4°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>RE</td>
<td>+4.75</td>
<td>1.0-1.25</td>
<td>foveolar</td>
<td>far -10°</td>
<td>angle of anomaly</td>
<td>5-7° (esotropic) (nonharmonious)</td>
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<tr>
<td></td>
<td>LE*</td>
<td>+4.75</td>
<td>0.08</td>
<td>2.5° temporal, unsteady</td>
<td>near -4°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>RE</td>
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<td>1.0-1.25</td>
<td>foveolar</td>
<td>far -15°</td>
<td>angle of anomaly</td>
<td>4-5° (esotropic) (nonharmonious)</td>
</tr>
<tr>
<td></td>
<td>LE*</td>
<td>+4.25 -1.5/12°</td>
<td>0.08</td>
<td>0°-0.5° nasal, unsteady</td>
<td>near -20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>RE*</td>
<td>-4.75 -3.25/173°</td>
<td>0.8-1.0</td>
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<td>far +15° +VD2°</td>
<td>angle of anomaly</td>
<td>15° (harmonious)</td>
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<tr>
<td></td>
<td>LE</td>
<td>-1.0 -2.75/178°</td>
<td>1.25</td>
<td>foveolar</td>
<td>near +17°</td>
<td></td>
<td>Large-angle esotropia Operated at 17 yr</td>
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<tr>
<td>16</td>
<td>RE</td>
<td>+3.0</td>
<td>1.25</td>
<td>foveolar</td>
<td>far +8° +VD1°*</td>
<td>angle of anomaly</td>
<td>8° (harmonious)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>-1.75 -0.25/95°</td>
<td>1.25</td>
<td>foveolar</td>
<td>near +6° +VD1°*</td>
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<td>17</td>
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<td>1.0</td>
<td>foveolar</td>
<td>far +12° +VD3°*</td>
<td>angle of anomaly</td>
<td>12° (harmonious)</td>
</tr>
<tr>
<td></td>
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<td>1.0</td>
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<td>near +17° +VD4°*</td>
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<td>0</td>
</tr>
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<td>18</td>
<td>RE</td>
<td>-0.25</td>
<td>1.25</td>
<td>foveolar</td>
<td>far +20°</td>
<td>angle of anomaly</td>
<td>0°-20° (variable)</td>
</tr>
<tr>
<td></td>
<td>LE</td>
<td>-1.75</td>
<td>1.25</td>
<td>foveolar</td>
<td>near +25° +VD2°*</td>
<td></td>
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</tr>
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</table>

* The amblyopic eyes are indicated by asterisks. Patients 2-15 were unilateral amblyopes, patients 16-18 alternators. Patients 12 and 15 had a slight unilateral amblyopia, but could maintain fixation in both eyes.
Table 2. Binocular status (stereoacuity) of the tested subjects

<table>
<thead>
<tr>
<th>Patient</th>
<th>Stereodeficient</th>
<th>Very low stereopsis</th>
<th>Stereoblind</th>
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<tbody>
<tr>
<td>1</td>
<td>60°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>120°</td>
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<td>3</td>
<td>240°</td>
<td>&lt;20°</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>240°</td>
<td>70°</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>480°</td>
<td>70°</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td>12</td>
<td>-</td>
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</table>

Clinical stereopy

<table>
<thead>
<tr>
<th>Patient</th>
<th>Fly (400&quot;)</th>
<th>Lang</th>
<th>Motion-in-depth</th>
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<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
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<td>±</td>
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<td>+</td>
<td>+</td>
</tr>
<tr>
<td>6</td>
<td>±</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>±</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

* The arrows indicate the direction of the apparent motion in the motion-in-depth test (for details, see ref. 7).

through an asymmetric pattern in which the dominant eye showed less summation than the nondominant eye (Patient 14, Fig. 2, top right panel), to a normal (and symmetric) summation (Patients 10, Fig. 2, bottom left panel; 11, and 9, Fig. 2, bottom right panel). Patients 13 and 14 were stereoblind exotropes, Patients 10 and 11 were esotropes with no clinical stereopsis, but with peripheral fusion, and Patient 9 was an anisometrope with very low stereopsis (the fly in the Titmus test).

Strabismic alternators: In strabismic alternators, the pattern of results was again heterogeneous, from an absence of summation in the esotropic alternator (and mild amblyope) Patient 12 (Fig. 3, top panel) to the subnormal, but present summation in Patients 17 (Fig. 3, bottom panel), 16, 18, and 15. With the exception of Patient 12, these subjects were stereoblind, with no peripheral fusion (see Table 2).

Summary

Figure 4 shows the percentage of binocular luminance summation for all tested subjects. Since binocular summation is defined by the change in pupil size of the dominant eye when the deviated eye is illuminated, only the effect on the dominant eye was included in this figure (with the exception of the normal observers, for whom both eyes were represented).

Binocular luminance summation of the six stereoblind subjects without peripheral fusion was 12%, as compared to the 29% shown by the normal group. This difference was statistically significant at the 0.01 level on a two-tailed Student's t-test. The five subjects with very poor stereopsis showed an average summation of 0.00%.
STRABISMIC AMBLYOPES

ALTERNATORS

Fig. 2. Pupil diameter in four strabismic amblyopes. The amblyopic eye is indicated by asterisks (always the left eye).

Fig. 3. Pupil diameter in two strabismic alternators. Top panels, patient 12; bottom panels, patient 17.

19%, which was not statistically different from the normal population ($P < 0.20$). However, taking together the 11 subjects who would be considered stereoblind on the basis of the TNO, Randot, and Titmus tests (excluding the fly), their binocular summation (15%) was still significantly below the normal level ($P < 0.05$). The binocular summation of the seven stereodeficient subjects (24%) was not statistically different from that of the normal group ($P < 0.20$).

Discussion

Evaluation of the Results

In the present paper, I tested the validity of the binocular summation of the pupillary response as a measure of binocular function (as assessed by stereopsis). Subjects without stereopsis showed significantly less binocular summation than normal subjects. However, summation was occasionally very high in clinically stereoblind subjects. What could be the reasons for this finding?
Of the stereoblind subjects, the highest summation (22%) was shown by a large-angle exotrope (Patient 14). This could be due to the simultaneous activation of the nuclei responsible for pupil contraction by light coming from nonoverlapping regions in the two eyes. This possibility is reinforced by the fact that the small-angle exotrope (Patient 13) showed much less binocular summation (5%).

The four stereoblind strabismic alternators (Patients 15, 18, 16, and 17) showed varying amounts of summation. All these subjects were esotropes (see Table 1). The possible reason for summation found in these subjects is that alternators are able to use both eyes simultaneously, each eye being dominant in a different part of the visual field. Thus, as in large-angle exotropes, the pupils of alternators could be activated simultaneously from both eyes.

From the group of subjects with very low stereopsis, the highest percentage of binocular luminance summation was shown by the two esotropes, Patients $S$ (37%) and 10 (31%). Both subjects were clinically stereoblind, with peripheral fusion (see Table 2). It is conceivable that the simultaneous activation of both eyes in the peripheral visual field is the cause for the summation shown by these subjects. This argument obviously holds also for the stereodeficient subjects.

In summary, it seems that binocular luminance summation can be found whenever the two eyes are used simultaneously, either in the same or in different parts of the visual field, in other words, whenever the nonfixating eye is not eliminated from binocular function. It follows that this test cannot be used as a measure for functional binocularity (or even stereopsis), but rather as an index for the simultaneous use of the two eye (absence of interocular suppression).

Several other instances of simultaneous use of the two eyes without stereopsis can be imagined in addition to those found in the subjects included in this study—for instance anomalous correspondence, or the incomplete suppression of the deviated eye in subjects with double images. Unfortunately, it is difficult to test the relative role of these factors, since in most human subjects they are found in combination (see Table 1).

Relation to Other Studies

My results seem to be at variance with those reported by ten Doesschate and Alpern. These authors found that, in two subjects, one a deep amblyope without strabismus and the other an esotropic alternator with a mild amblyopia in the preferred eye, illumination of the nonfixating eye did not cause a constriction of the pupil of the fixating eye. This apparent discrepancy might be due to methodological differences between the two studies: ten Doesschate and Alpern did not use a Ganzfeld, but an illuminated central field of 12 deg. This would eliminate the contribution of the peripheral visual field to the pupil response; it is known, however, that the periphery often retains binocular function in stereoblind subjects.

Another potential source of discrepancy lies in the different orthoptical status of the subjects: The subjects most likely not to show binocular luminance summation are stereoblind esotropic amblyopes without peripheral fusion. None of my subjects met all these conditions (see Tables 1 and 2). Although ten Doesschate and Alpern do not give details on the binocular status of their subjects, it is conceivable that both their subjects might have qualified.

While this research was in progress, I became aware of another study on binocular luminance summation in stereoblind humans (Shea et al). These authors measured the pupil response to increment flashes presented on a $45^\circ \times 50^\circ$ field, and found that 11 subjects who failed to meet the 120° criterion on the TNO test showed a minimal, but statistically significant ($P < 0.05$) reduction of binocular luminance summation. Unfortunately, Shea et al do not give detailed descriptions of the orthoptic status and clinical history of their subjects. Nevertheless, their results agree closely with mine, if the same criterion for stereoblindness is applied: in the Shea et al study, mean binocular summation was 17% in stereoblind subjects, as compared to 28% in normal subjects. My recalculated data give a summation of 18% in "stereoblind" subjects ($n = 17$) and of 28% in "normal" subjects ($n = 4$). The difference is statistically significant at the 0.05 level. This agreement is remarkable, in view of the different methods used in the two studies.

In conclusion, the results reported here corroborate those obtained for strabismic cats, and indicate that binocular luminance summation cannot be used as a measure of binocular function, but rather as a crude index for the simultaneous use of the two eyes (or, in other words, for an absence of interocular suppression).

Does the absence of binocular luminance summation reported by Birch and Held in infants younger than 4 months of age indicate that these infants completely suppress one eye, or rather that, as in kittens, their pupillary reflex develops postnatally? Unfortunately, reports on pupillary motility in infants are controversial: according to Birch and Birch, young infants show a normal pupillary motility when tested under normal conditions of illumination; however, Shea et al found that young infants have a reduced pupillary motility to flashed increments of light; Shea et al also measured significant levels of binocular luminance summation in infants as young as 2 months of age. Obviously, further research is necessary in order to answer these questions.
Key words: humans, stereoblindness, pupil, binocular summation

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