Spatial Characteristics of Static and Dynamic Stereoacuity in Strabismus

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The spatial and temporal organization of stereoscopic depth perception were compared in normal and strabismic observers. The minimum and maximum disparities for stimulating static and dynamic stereopsis in strabismus were examined as a function of spatial separation of disparate stimuli. Disparities and their spacing were produced by spatial modulation of two vertical lines viewed haploscopically. Most strabismics had normal upper disparity limits but elevated static and dynamic stereothresholds. Moderate stereothreshold elevations (100 arc sec) were constant for spatial separations greater than 15 arc min.

Two new types of spatial crowding effects upon stereopsis were observed. The first type resulted from the constant elevation of the disparity threshold. The second type consisted of a reduced maximum disparity limit for stereopsis. In both cases, the constriction of the range of perceivable depth produced a reduction in the spatial and temporal frequency limits for depth perception.

Clinical tests of stereoacuity that crowd stimuli closer than 0.25 degree underestimated the strabismic patients' potential stereoacuities by a factor of 2 to 4. Similarly, tests of dynamic stereopsis that use temporal frequencies greater than 1 Hz will underestimate optimal dynamic stereoacuity. Invest Ophthalmol Vis Sci 24:1572-1579, 1983

Both static1 and dynamic stereoacuity2,3 can be reduced in the central visual field of patients with strabismus and other anomalies of binocular vision. Recent psychophysical4-8 and electrophysiologic studies4 indicate that separate mechanisms underlie static and dynamic stereopsis. Furthermore, static disparities are believed to be processed optimally by spatial channels whose receptive field sizes are proportional to disparity magnitude.10 This model is supported by a correlation between stimulus size and amplitude of static stereoscopic threshold.11-13 Disturbances of stereopsis associated with binocular disorders may involve some or all of these mechanisms that support binocular depth perception.

Spatial properties of clinical tests for both static and dynamic stereoacuity vary markedly. Some tests use small figures (Keystone visual skills series),14 whereas others use large objects that subtend a constant disparity (Wirt test and Verhoeff Stereopter).15,16 Tyler11,12 observed for normal subjects that the abrupt changes in disparity that occur with small targets and the uniformly constant disparities subtended by large targets, yield stereoacuity inversely proportional to target size. In this study, we have measured both the upper disparity limit and lower disparity threshold for static stereopsis in strabismic observers with spatially varying targets. We observed a constant elevation of the stereothreshold over a range of coarse target sizes and an increase in the minimum target size for any depth perception, although the spatial limit for fusion, as shown previously, remained normal.17

Dynamic stereoacuity usually is measured with vertical straight lines oscillating in depth.18-21 The straight lines subtend a constant disparity and yield dynamic stereothresholds that decrease slightly as temporal frequency increases up to 1 Hz and then remains constant up to 5 Hz.18,19,21 We have examined dynamic stereoacuity in observers with normal and abnormal binocular vision using simultaneous spatial and temporal modulation of disparity. The purpose of this study was to define in greater detail the types of stereoscopic loss that can occur with complex disparity modulation similar to that found in a normal environment.

Materials and Methods

We measured static stereopsis for a full range of stimulus patterns of the form introduced by Tyler.11,12 Spatial variations of disparity were produced on two CRTs with dichoptic vertical sinusoidal lines, one before each eye, (8° long and 1.5 min thick) having a luminance of 15 cd/m² and a binocular spatial phase...
difference of 180° (Fig. 1, inset). When these vertical sinusoidal lines (one on each CRT) were fused haploscopically, observers perceived a single line curved sinusoidally in depth, with the plane of curvature passing through the midline between the eye (Fig. 1, inset).

The spatial frequency of the vertical sinusoidal lines determined the proximity or spatial crowding of sinusoidal peaks in depth (spatial disparity modulation) and it also provided a means of defining the gradient or rate of change of horizontal disparity variations along the vertical meridian. Varying the spatial frequency of the disparity modulation allowed examination of both upper disparity limits and lower disparity thresholds across a full range of disparity patterns.

Horizontal and vertical vergence errors were controlled by adjusting the mirrors of a haploscope to the observer's angle of strabismus or to an angle where the targets could be fused easily. The boundaries of the 8 × 13 degree rectangular test field and a small central fixation spot served as sensory fusion locks. Horizontal nonius lines were placed to the left and right of the vertical sinusoidal line and the small fixation spot (1.5 arc min). The observer could detect vertical vergence errors by observing a misalignment of the horizontal nonius lines. The targets were viewed at a distance of 57 cm on a background screen with a luminance of 50 cd/m².

Thresholds were obtained by method of adjustment. During tests of static stereopsis the observer was instructed to fixate the small spot in the center of the space between the two horizontal nonius lines and adjust a ten turn pot that controlled the amplitude of sinusoidal disparity modulation, until the sinusoidal line appeared to be just non-uniform in depth, and then until it appeared to be uniform in depth. Since depth judgments involved simultaneous comparison of crossed and uncrossed disparities, amplitude of disparity equalled the difference between unioocular peak-to-peak amplitude of sinusoidal modulation. The mean of six settings constituted a threshold measurement. Stereoscopic thresholds were obtained in the same manner for square wave variations in disparity as an additional condition to more closely approximate the disparity profile of standard tests of stereopsis.

The maximum sinusoidal disparity that could elicit a static depth modulation (upper disparity limit) also was determined by the method of adjustment. Depth usually was perceived beyond Panum's fusional limit, i.e., where diplopia was present. Subjects were instructed to maintain the criterion of absence of depth difference, although diplopia was clearly present in the display. Both strabismic and normal observers reported that depth was clearly present for a limited range of disparities beyond the diplopia threshold and that beyond the upper depth limit they perceived two sinusoidal lines lying flat in the fixation plane. Subjects verified their depth perception by correctly identifying portions of the sine curve that appeared proximal and distal from the fixation point. Comparison of the upper and lower thresholds for stereopsis provided a measure of the range of disparities as a function of spatial dis-
parity modulation that could be perceived as depth differences. The points for maximum spatial frequency were obtained by adjusting the frequency for a fixed amplitude rather than the reverse.

Dynamic stereopsis was investigated by modulating the amplitude of sine images seen by each eye with an AM function generator (using methods described previously\(^1\)). This counterphase stimulus provided a sinusoidal disparity modulation in both time and space. Observers fixated the stationary spot and perceived a vertical line curved sinusoidally in depth. The peaks of the curved line appeared near and the troughs far away. The peaks and troughs continuously reversed in depth with sinusoidal amplitude modulation. As in the investigation of static stereopsis, the observers adjusted the amplitude of disparity by turning a ten turn pot until the dynamic depth variations just appeared and then disappeared. Dynamic stereothresholds were obtained for combinations of spatial and temporal frequencies ranging from 0.05 to 3 cycles/degree, and from 0.1 to 3 Hz, respectively.

Observers

Three normal and seven strabismic observers participated in the study. All were experienced in psychophysical observations. During childhood, six of the clinical observers had had congenital nonaccommodative esotropia and the seventh had congenital exotropia (Table 1). The angle of strabismus during childhood was cosmetically noticeable for all cases, exceeding 10 degrees, and was reduced surgically or by orthoptic exercises and optical prescription such that three of the observers became intermittent exotropes, one a constant exotrope, and three became intermittent esotropes. Age of onset of strabismus for all observers was before the age of 3 years. No observer had amblyopia, and all but two post-surgical exotropes had normal binocular correspondence. The angle of anomaly was small (0.5–1.0 degrees) in the two patients with anomalous correspondence and did not prevent these observers from making reliable judgements of stereoscopic depth. All acuities were at least 20/20 in each eye with refractive corrections in place as assessed by a multiple E chart which controls for crowding effects.\(^1\) Static stereoeaucty was assessed using the clinical Wirt test,\(^1\) which consists of a series of rings which subtend disparities ranging from 40 to 800 arc sec at a 40-cm viewing distance. Stereocuaties of the seven clinical observers ranged from 100 to 600 arc sec, whereas the three normal observers had stereocuaties of 15, 18, and 20 arc sec. In the cases of constant strabismus, stereoeaucty was assessed with the angle of strabismus corrected by a prism.

Results

Static Stereopsis

Graphs are shown for four of the seven strabismic observers. The limits of static stereoscopic resolution are plotted on log-log coordinates in Figure 1 for two of the normal observers. The results of three observers with intermittent exotropia who had raised stereothresholds (100 to 600 arc sec clinical stereoeaucty) are plotted in Figure 2. A reduced upper disparity limit is evident in one exotropic observer (Fig. 3). Circles and squares represent thresholds for sine and square wave stimuli, respectively. The standard errors of the mean were less than 5%, usually falling within the width of the plotted symbols.

Normal observers: In Figure 1, the “camel’s nose” region of stereoscopic sensitivity labeled “DEPTH” replicates that reported by Tyler.\(^1\) There is an approximately inverse linear relationship between the upper disparity limit and the spatial modulation frequency of disparity over a large range. This represents a disparity scaling effect since the ratio of the upper disparity limit to the period of the sinusoidal disparity stimulus remains constant. Thus, the magnitude of the upper depth limit increases with the spacing between depth contours.

The lower stereothreshold does not show a scaling effect except at the lowest spatial frequencies tested.
Stereosensitivity is greatest at approximately 1 cycle/degree, and it is reduced at higher spatial frequencies probably as a result of a crowding effect which is an elevation of the stereothreshold resulting from surrounding contours within about 10 arc min of the test target. Some observers also showed reduced sensitivity at lower spatial frequencies, perhaps as a result of a disparity gradient limit at threshold. Similar disparity gradient limits have been shown for binocular fusion. Since the disparity gradient in square wave stimuli is independent of spatial frequency, the reduction of a stereosensitivity at low fundamental spatial frequencies is not found with the square wave stimulus.

Strabismic observers: New observations of the spatial limits and the disparity range of static stereopsis for strabismics with raised clinical stereothresholds are shown in Figure 2. The upper disparity limits of these three observers are indistinguishable from those of the normal observers shown in Figure 1. The difference from the normal function is in the elevation of the disparity threshold at all spatial frequencies. At higher spatial frequencies these cases exhibited a lower threshold for static stereopsis that was elevated above the normal upper disparity limit for depth. As a consequence, strabismic observers were unable to perceive depth with higher spatial frequencies and their spatial frequency limit for perceived depth was reduced from a mean of 3 cycles/degree for normal observers to a mean of 1.5 cycles/degree. The higher sensitivity to square wave over sine wave disparity modulation at low spatial frequencies indicates that, as with normal observers, strabismic observers also have a disparity gradient limit for maximum stereoscopic depth.

Figure 3 shows a second type of stereoscopic loss in a constant exotrope with a clinical stereoacuity of 400 arc sec. Unlike the other strabisms shown in Figure 2, D.M.'s upper disparity limit was reduced to one-third of the normal maximum depth limit. The reduction is uniform across spatial frequency of disparity modulation such that disparity scaling with spatial frequency is still obtained. This observer also had a slight elevation of his stereothreshold relative to the normal observers, but no greater than a factor of two (in the range of spatial frequencies where it is measurable). The combined effect of the reduction of the upper disparity limit and the small increase in stereothreshold was to produce a dramatic reduction (by a factor of five) in the spatial frequency limit for stereopsis.

Dynamic Stereopsis

Normal observers: Dynamic stereothresholds for the three normal observers are plotted in Figure 4 as a two-dimensional function of temporal and spatial disparity modulation frequency. The influence of spatial crowding upon dynamic stereopsis is revealed by comparing temporal frequency responses at low and at high spatial frequencies. The upper left edge of the graphs (A-B) is comparable to the temporal frequency response of dynamic stereothreshold measured without spatial crowding by Tyler and by Regan and Beverley. Dynamic stereothreshold remained fairly constant as a function of temporal frequency when tested with a low spatial frequency of disparity modulation. In contrast, thresholds for dynamic stereopsis measured with a higher spatial frequency (0.5 cycles/degree) increase by an order of magnitude as temporal frequency increases from 0.1 to 3 Hz. The increase in threshold was even more dramatic at higher spatial frequencies as shown along the lower right edge of the graphs (C-D). Thus, as with static stereopsis, spatial crowding also reduced dynamic stereoacuity.

Temporal factors influencing dynamic stereopsis are revealed by comparing the spatial frequency responses at low and at high temporal frequencies. At low temporal frequencies (lower left edge, A-D) stereothreshold was elevated at low spatial frequencies (<0.5 cycle/degree) just as it was for static stereothresholds (Fig. 1). At high temporal frequencies (upper right edge, B-C) the low spatial frequency elevation in threshold is very small and occurred gradually, whereas there was a
Fig. 4. Dynamic stereoscopic thresholds are plotted for three normal observers on a spatio-temporal surface. The lower left-hand edge resembles the variations in static stereothresholds of Figure 1. The lower right-hand edge reveals the steep rise in dynamic stereoscopic thresholds as temporal frequency is increased from 0.1 to 3 Hz. Optimal dynamic stereoaucuity occurs at combinations of low temporal (0.3 Hz) and high spatial (0.5–1 cycles/degree) frequencies.

Fig. 5. Dynamic stereothresholds for three strabismic observers are plotted on a spatio-temporal surface. The spatial frequency range is limited for all three observers by their elevated dynamic stereoscopic thresholds which are above the normal dynamic disparity range at high spatial frequencies.

marked and abrupt elevation of threshold at high spatial frequencies (>1.5 cycle/degree). Comparison of these two spatial frequency responses reveals that the main effects of temporal frequency upon stereoaucuity occurred with crowded (high spatial frequency) targets.
Table 1. Description of strabismic observers

<table>
<thead>
<tr>
<th>Observer number</th>
<th>Angle of deviation</th>
<th>Binocular correspondence</th>
<th>Stereoacuity (arc sec)</th>
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<td></td>
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<td>Current</td>
<td>Wirt</td>
</tr>
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<td>Intermittent</td>
<td>Normal</td>
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<td>Normal</td>
</tr>
<tr>
<td>3</td>
<td>Esotrope</td>
<td>Intermittent</td>
<td>Anomalous A = 0.5 degree</td>
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<tr>
<td>4</td>
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<td>Constant</td>
<td>Anomalous A = 1.0 degree</td>
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<td>7</td>
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Seven strabismic observers are described in terms of their distance angle of ocular deviation during childhood and in adulthood, the constancy of the deviation, the state of binocular correspondence, stereoacuity measured with the clinical Wirt test, and with the static and dynamic sinusoidal disparities utilized in the current investigation. Dynamic stereoacuity was consistently higher than static sine stereoacuity and both of these measures were higher than static stereoacuity measured with the Wirt test.

Increasing temporal frequency reduced stereoacuity whereas decreasing temporal frequency enhanced stereoacuity.

The two main effects (spatial and temporal) upon dynamic stereopsis and their interaction are seen most clearly in Figure 4, top. The tilt of the response plane towards the lower left (C–D) shows the main effect of temporal disparity modulation, where higher temporal frequency yields higher stereothresholds, while the tilt of the plane to the lower right (A–D) reflects the main effect of spatial disparity; higher spatial disparity modulation yields lower thresholds. The counterclockwise twist of the plane shows the interaction of these effects, where temporal modulation of disparity has a greater effect on stereothresholds at high spatial frequencies and spatial modulation of disparity has a greater effect on stereothresholds at lower temporal frequencies. Thus, a combination of high spatial and low temporal frequencies yielded the optimal stimulus for dynamic stereopsis.

Strabismic observers: Figure 5 illustrates dynamic stereothresholds for three of the four strabismic observers (B.B., L.H., D.M.) whose static functions were plotted in Figures 2 and 3. Although they were abnormally elevated, dynamic stereothresholds were consistently lower than static stereothresholds (Table 1). The dynamic stereothreshold function for B.B. resembles a uniformly elevated version of the normal functions in Figure 4. Dynamic stereothreshold functions for L.H. and D.M. were also elevated and they both had reduced spatial frequency limits that corresponded with the spatial frequency limit for their static
stereoacuities. D.M. also had a reduced temporal frequency limit of 1.0 Hz for all spatial frequencies. L.H. had a similar reduction of her temporal frequency limit for 0.5 cycle/degree, but retained normal temporal frequency limits at lower spatial frequencies.

The reduced temporal frequency limit for dynamic stereopsis resulted from an elevation of the lower disparity threshold for dynamic stereopsis above the normal upper disparity limit at high spatial frequencies. Figure 6 compares the dynamic depth range limits of a normal observer with those of a strabismic observer (D.M.). D.M.'s lowest threshold at 1 Hz coincides with the upper depth limit for the normal observer at 2 Hz. As a consequence, D.M. was unable to perceive dynamic depth at higher temporal frequencies where the entire normal depth range was below his elevated threshold.

**Discussion**

Two types of stereoscopic loss are evident in the strabismic observers. In one type of loss, both static and dynamic stereocuities were abnormally elevated. In the second type of loss, the upper disparity limit was markedly depressed, although stereoacuity was affected only slightly. Both losses appear to be fairly uniform across spatial frequency. The uniform reduction of stereoscopic vision across spatial frequency could result from reduced sensitivity of a single mechanism or disparity pool. However, this observation does not exclude the possibility of a uniform reduction of sensitivity of multiple spatial channels tuned to disparity.

The mechanisms involved in the reduced stereoscopic resolution are separate from those underlying the binocular sensory fusion process. Schor and Tyler observed normal temporal frequency limitations of Panum's fusional area in a stereoblind observer. This observation was extended to spatial variations of Panum's area in observer L.H. Although she had no stereopsis at spatial frequencies above 0.5 cycles/degree, she had normal Panum's horizontal fusion limits of 3 and 1.5 arc min at spatial disparity modulation frequencies of 1 and 2 cycles/degree, respectively. These observations support the suggestion that stereopsis and fusion result from independent spatial and temporal processes.

The elevated thresholds for static and for dynamic stereopsis in strabismus impose spatial and temporal frequency limitations on stereoacuity. In severe stereoscopic loss these spatial and temporal limits have implications for the design of clinical tests of stereopsis. The spacing between disparate figures must be great enough so that crowding will not elevate the stereothreshold above the disparity subtended by the test target. It is also important for tests of normal stereopsis that small disparities be spaced at the 1 cycle/degree optimum for highest stereoacuity. Similarly, tests of dynamic stereopsis should be limited to a temporal frequency of less than 1 Hz in order to obtain optimal acuities.

For the observers with clinical stereoacuities raised by factors of about 5, 7, 10, 15, 20, and 30 the static sinusoidal stereothresholds were raised by factors of only about 1, 2, 2.5, 3, 3, and 8, respectively, compared with normal sine stereoacuity (Table 1). Thus, data from this small sample of patients suggest that the Wirt test seriously underestimates the stereoscopic capabilities of stereoanomalous observers. This may be a result of the crowding effects of having a number of disparate stimuli presented in close proximity (less than 15 arc min). Redesign of target size and spacing in clinical stereotests could provide a more accurate estimate of stereopsis in people undergoing treatment for strabismus. Stereocuity should be tested at several low spatial and temporal frequencies, because it is clear that spatial crowding effects with the close spacing used in the current clinical tests will not reveal maximum stereoacuity in patients with elevated thresholds. One simple improvement would be to use large spots instead of annuli and to vary spot size and separation in proportion to the amplitude of the test disparity.

**Key words:** static and dynamic stereopsis, strabismus, disparity modulation, Panum's area, spatial and temporal frequency, upper depth limit, spatial crowding

**References**