Stimulus Features that Determine the Visual Location of a Bright Bar

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A modification to the standard vernier target that has a detrimental effect on acuity is described. The addition of an extra bar alongside one of the test bars and directly underneath the other increases thresholds by an amount that is a monotonic function of its luminance. This allows for the hypothesis that the location of a bright bar is a function of some widespread description of the light distribution arising from such a bar on the retina, rather than some local feature of such a distribution. In particular, the data are not consistent with any simple notion of boundary extraction and support the conjecture that position of a bar is assigned to the mean or centroid of its light distribution.1 Invest Ophthalmology Vis Sci 24:66-71, 1983

Vernier acuity thresholds of less than 5 sec arc are usually taken as indicators that the visual system can compare the position of two features with a very fine precision. Careful study of such results should lead to an understanding of the processes behind the assignment of relative location of features and therefore of shape perception. The first important question to tackle is this: what particular feature of the vernier target is being located by the visual system? A bright bar has a number of features that may be used for positional judgments. It has local features such as boundaries, and it has features that may be used to characterize location, but that are determined by the entire light distribution, such as the center or mean of the light distribution.

Berry, Riggs, and Richards2 demonstrated that the width of a dark vernier target on a light background had no effect on performance for widths up to 7 min arc. They concluded that in all cases one or both target edges provide response information. On the other hand, Westheimer and McKee1 have demonstrated that spatial offset hyperacuity thresholds may be obtained in the absence of edge information. They presented subjects with bands of light 2.7 min arc wide and required an alignment decision from subjects as in the ordinary vernier task. The cue for response was of two possible types. Either the edges of the ribbon had a real spatial misalignment, or the light distribution within the ribbon alone provided a pseudo-position cue. The cues were interleaved randomly, and threshold displacements for both were obtained. Subjects were not able to discriminate the two types of cue. Threshold displacement of the centroid of the light distribution was the same for the two cues. Westheimer and McKee conjecture that position is assigned to the first moment of the light distribution in such cases.

The conclusion so far might be that the position of a bar is determined by its edges, if available, and by some total measure of centrality in the retinal light distribution if no edges are available. However, the following finding argues against such a conclusion, at least for moving objects.

Morgan3 has demonstrated that stereo-disparity is determined by the centers of bright moving bars, even when edges are available. If two moving bars of different widths are presented dichoptically to the two eyes, they may be fused and a single bar is perceived. The width of this bar is that of the wider element, and unexpectedly, it is not slanted in depth. Its relative depth is that arising from the disparity of the centers of the two elements, rather than at either edge.

Is this a special case, or are there static examples of the preferential use of centers for bar location? We shall now describe an experiment that provides such an example. Consider a standard vernier target: two bright vertical bars, one above the other and separated by a small gap (see Fig. 1A). On each presentation to the subject, the lower bar may be slightly to the left or right of the axis of the upper bar, and the...
subject is required to decide which. Now add an extra bar, directly below the upper bar and alongside the lower bar (see Fig. 1B). If the vernier offset cue is less than about 40 sec arc, the two lower bars are unresolved in the visual system, and their joint light distribution on the retina will be unimodal. Figure 1D illustrates this in the case where the two lower bars are of equal luminance, and the vernier offset cue is 20 sec. arc.

There is still a boundary misalignment cue of magnitude 20 sec arc, i.e., there is a difference in the positions of the first non-zero points of 20 sec arc on the right tails of the two distributions, but the center (mean) of the light distribution is now only providing a cue of magnitude 10 sec arc. Further, the magnitude of the boundary cue is not a function of the luminance of the extra bar, but the magnitude of the center cue is inversely related to the luminance of the added bar. The question is whether the visual system can perform the vernier task using the edge cue in preference to the center cue. If it can, then threshold vernier offset should be independent of the luminance of the added bar. If, on the contrary, threshold is determined by the distance between centers, it will rise as the luminance of the added bar is increased. To decide between these possibilities, we first measured threshold where the luminance of the added bar was zero (the classical vernier case) and then compared it to the case where the added bar and offset bar were of equal luminance. We also measured threshold in a number of intermediate cases where the ratio of the luminance of the added bar to that of the target bar was 0.25, 0.5, and 0.75.

Materials and Methods

Subjects

The observers were the authors, all of whom have normal uncorrected vision.

Apparatus

Targets were generated on a display oscilloscope with a spot size of less than 0.3 mm (Hewlett-Packard 1333a) and a fast decay P15 phosphor. Each of the target lines was 12 min arc in length when seen from the viewing distance of 114 cm, and was composed of 20 spots that were not visually resolved. Distance between the nearer ends of the bars was 6 min arc; thus, the vertical dimension of the whole target was 30 min arc. The display was controlled by digital to analogue convertors (DACs) from a CAI LSI 2/20G minicomputer and refresh rate was 333 Hz. Luminance of the bars was controlled by an additional DAC connected to the Z modulation input of the oscilloscope. Luminances were measured by a microphotometer (United Detector Technology), and the basic luminance of a bar was 30 ft Lamberts, or some specific fraction thereof. Observers lay supine and observed the display through a 45° mirror placed above their head. Ordinary room lighting (fluorescent tubes) was used, ensuring that all observations were carried out at photopic levels.

Procedure

The observer's task on each trial was to report, by pressing the appropriate one of two digital switches, whether the top line was shifted to the right or left of the lower line. Over a series of 80 trials, preceded by 20 practice trials, the offset in position was varied randomly from side to side and selected from a number of preset magnitudes, in order to obtain a psychometric function. An adaptive version of the Method of Constant Stimuli (APE) was used, and Probit Analysis5 was used to determine the standard deviation of the psychometric function (83% correct point), defined as the threshold. Four independent thresholds were determined for each condition, and the final datum point represents the RMS of these estimates, with the standard deviation of their distribution serving as a measure of dispersion, defined as

![Fig. 1. Stimuli used in Experiment 1. The upper diagrams illustrate the appearance of the stimuli on the oscilloscope with a test offset of 45 sec arc. The lower diagrams show the retinal distributions of light arising from the corresponding stimuli in the upper diagrams. The actual functions employed are the convolution product of a diffraction pattern for a circular aperture of diameter 2 mm and light of wavelength 550 nm which is a good approximation to the point spread function of the human eye, and the Gaussian distribution of light generated by a spot on the oscilloscope screen. Note that in the case where two bars are combined (d), the peak in the joint light distribution is shifted by 50% towards the origin.](image-url)
the standard error and typically less than 15% of the standard deviation.

**Experiment 1**

Threshold spatial offset or displacement was measured as a function of the luminance of a third bar present in the display (see Fig. 1), directly beneath the upper standard bar. Thresholds were obtained for luminances ranging from 0% to 100% of the luminance of the standard bars.

Figure 2 presents the individual data for each of the three observers, with threshold on the ordinate, (note the logarithmic scale) and relative luminance of the third bar on the abscissa. When the third bar has a relative luminance of zero, the display is that used for standard vernier acuity measurements, and the thresholds we have obtained correspond well for the experienced observers (RJW and MJM) with results previously obtained for the display dimensions we have used.

As the relative luminance of the third bar is raised, threshold was systematically increased, being slightly more than doubled in the case where the relative luminance of the third bar was 100%. On most trials the two bars comprising the lower element of the display were far too close to be visually resolved, and thus appeared as a single bar of greater luminance than the single bar above.

In order to control for the effects of this luminance difference itself, we carried out additional threshold measurements. In the first of these, the additional bar was plotted in exactly the same position as the lower of the two standard bars, thus increasing its luminance without affecting its position. In the second, a further additional bar was plotted exactly in the

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**Fig. 2.** Thresholds for vernier offset for the three observers, as a function of the luminance of the added bar. Note that a logarithmic scale is used. Error bars represent +/- one sd.

**Fig. 3.** Thresholds for vernier offset are presented as a function of the various luminance conditions employed as controls in experiments 1 and 3 (see text for details).
same place as the upper bar, making four bars comprising two pairs. The upper pair were superimposed, and the lower pair were separated, with one directly below the upper pair and one to the left or right, as before. In both cases all individual bars had the same luminance. Results are shown in Figure 3: conditions A and C are from the main experiment with relative luminance of the added bar of 0.0 and 1.0 respectively; condition B is the first control procedure; condition D is the second control procedure. The first procedure increases threshold from the standard vernier case by a small proportion, and it is worth noting that threshold in condition C is almost exactly twice that in condition B. The second procedure produces a threshold that is not significantly different from that in the main experiment. Thus, we conclude that the effects of the main experiment are due to an interaction of spatial and luminance parameters, not the luminance parameter alone.

It was also the case that at threshold the bars were sufficiently close together for their light distributions to overlap on the CRO screen. In order to establish whether discrete distal stimuli might have a different effect, we repeated this experiment at a viewing distance of 8 m so that even at vernier threshold the bars were physically resolved on the screen. The results obtained were similar to those of Figure 2, and we conclude that, as expected, the resolution of the distal stimulus is not important.

Experiment 2

It is possible that the additional third bar in experiment 1 is influencing the apparent width of the lower element of the target, rather than just its position. This in turn might affect the size of an boundary misalignment cue and depress performance. No subject consistently observed this, but to rule out the possibility a separate experiment was performed to measure the effect of real separation between two close bars and the perceived width of the resultant unresolved line. We determined threshold for increase in apparent width in the following manner. The subject was presented with a display comprising two bars one directly above the other, and a third bar added to either the upper or the lower bar at one of a number of preset separations. The subject was required to report whether the additional bar was in the upper or lower half of the display, ie, to judge which bar was double. We thus measured thresholds for apparent width increase, expressed as threshold separations. Note that this is not the same as a resolution task, where perceptual separation is the criterion, not perceived width. To avoid luminance cues, the luminance of the unpaired bar was doubled, by plotting it at twice the refresh rate of the other bars. To avoid vernier type of positional cues, the side (left or right) on which the additional bar was presented was randomized and was thus uninformative to the subject.

Thresholds for apparent width as a function of display luminance are shown in Figure 4. Thresholds are plotted as a function of relative luminance level. This is luminance relative to a standard of 30 ft Lambert for the pair of bars. It is apparent that for luminance levels corresponding to those in Experiment 1, threshold separation is much higher than threshold displacement. The vernier location task, therefore, is not a boundary alignment task. We conclude that an unresolved pair of bars that are less than about 0.5 min arc apart have a minimum perceptual width, and therefore an unique perceptual location. Le Grand and Geblewicz found that point sources less than 1.5 min arc could not be distinguished by their apparent diameter, and attributed this to the effects of diffraction, comparing these thresholds with the diameter of Airy's disc (approximately 1.25 min arc). This is not a sound argument, since for any bounded object it may be demonstrated that band-pass operations such as diffraction do not remove any information that cannot be restored by extrapolation in the spatial frequency domain. This so-called super-resolution allows the physical possibility of width discrimina-
tions with much greater precision than the diameter of Airey's disc.

**Experiment 3**

It is established that unresolved bar pairs have an unique location that is a function of their total distribution of light on the retina. The question of a mechanism remains. There are two broad possibilities. First, it might be the case that the extra bar has some interaction with the standard bars that results in lower performance. This has been reported for extra bars that are as remote as 2 to 5 min arc distant from a vernier target. Secondly, it might be the case that the extra bar and its companion standard bar are integrated, and considered as a single bar by the visual system. These alternatives may be distinguished by adding a second extra bar of the same luminance as the first extra bar to the lower element, so that the lower standard bar now has a bar on each side, and at equal distances (Fig. 3E). If the presence of the additional bar disturbs performance because of some local interactions, then vernier acuity with this new compound stimulus should be poor. If the visual system is integrating energy, on the other hand, and assigning position to some central measure of the light distribution, then performance should be independent of the relative level of the luminance of the extra bars and the standard bars, and should be like that obtained in the standard task (Fig. 3A).

Our finding is that the luminance of the extra bars have no effect on performance, which is essentially constant at 6 sec arc. We conclude that the data from Experiment 1 show the mechanism of location assignment at work. The threshold for one luminance level is to be found in Figure 3E.

**Discussion**

We initially posed the question whether the position cue in a vernier target is some central point on the light distribution, or the luminance boundaries. Our data show that location is assigned to some widespread property of a retinal light distribution rather than a local feature. This does not rule out the possibility that a subject uses perceived edges or boundaries as the position cue. We have demonstrated that the perceived location of such an edge cue is a function of the whole light distribution. The continuous and progressive rise in threshold as the luminance of the extra bar is increased shows that even when two bars of different luminance lie close together and their joint diffraction pattern or light spread function is asymmetrical, the stimulus is processed as if it were a single, narrow, bright line.

This relationship between retinal light distribution and perceived position suggests that the visual system has a fixed manner of assigning relative location to retinal light distributions of width less than about 2 min arc, irrespective of their form. This is, of course, very informative because in a sense it demonstrates a breakdown in the performance of vernier acuity: the results expose a limitation in the system.

Any stimulus gives rise to a distributed pattern of light on the retina, and it is from such a distribution that the visual system must determine the nature of the stimulus. By sampling this pattern at each receptor, the visual system is able in principle to reconstruct that distribution to an accuracy constrained only by the modulation transfer function of the optical elements of the eye and by the spatial frequency of sampling. In practice it is only the optics that limit such performance, leading to the conclusion that the retinal sampling is adequate. Once the light spread pattern has been reconstructed, the visual system is required to identify the source stimulus for the received sensation and assign a visual location to such a source.

Our experiments have demonstrated that the visual system makes errors of identification, confusing a doublet of bars with a single bar, eg, in a manner that is consistent with the physical constraints imposed by the optical properties of the eyes, and the mathematical properties of sampling theory. However, it also makes arbitrary judgments when assigning location to such a feature, that are not constrained by such physical considerations.

We conclude, therefore, the following points. First, the visual system assigns location for a compound light spread pattern to a centroid-type parameter, as suggested by Westheimer and McKee, rather than a luminance boundary. This applies for both symmetric and asymmetric distributions of light on the retina. Secondly, we suggest that this is due to a misidentification of the real source of such a distribution and not to inadequate sampling. Thirdly, we conclude that the mechanism responsible for very precise vernier judgments achieves such precision at the expense of other light distribution information.

There are important questions remaining. Our data leave open the question whether the feature used to localize a light spread distribution is the centroid, as conjectured by Westheimer and McKee, or some other feature such as the peak. We have used a deliberately crude model of the edge or boundary of a light distribution. An alternative, which would agree with our data is the zero-crossing model of Marr.

It is possible to distinguish between these by using
suitably designed stimuli in the vernier task, and we shall report the result in a future communication.¹³

Key words: Vernier acuity, diffraction theory, retinal light distributions, centroid location, boundary extraction, luminance effects

References