

The orientation bandwidth of cyclopean channels

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Abstract

Orientation bandwidths of cyclopean channels were estimated using a notched noise technique. Observers were presented with random dot stereograms depicting a horizontal or vertical target sinusoidal depth modulation and a mask consisting of sinusoidal depth modulations whose orientations flanked that of the target. Masking reduced as the orientation difference between signal and mask increased. The orientation bandwidth of the masking effect was similar to that found for stimuli defined by luminance contrast, and showed no systematic difference for horizontal and vertical targets. These results suggest that the elongated summation found by Tyler, C. W., and Kontsevich, L. L. (2001). Stereoprocessing of cyclopean depth images: Horizontally elongated summation fields. *Vision Research*, 41, 2235–2243, for horizontal stimuli occurs after a processing non-linearity.

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1. Introduction

Spatial variation in binocular disparity provides the visual system with important information about the three-dimensional shape of surfaces such as their slant and curvature. Tyler (1975) proposed that this information is spatially pooled by cyclopean depth channels, which process depth information beyond the basic encoding of disparity. Such channels were proposed by direct analogy to channels for the processing of spatial contrast information (Campbell & Robson, 1968).

Similar to their analogues for spatial contrast, these channels are tuned for the spatial frequency and orientation of disparity variation. This has been demonstrated by the existence of tilt and size aftereffects in the cyclopean domain (Tyler, 1975). Prolonged inspection of a sinusoidal modulation of disparity of a particular orientation causes subsequently presented modulations of gratings of different orientations to appear shifted in orientation away from the adapting grating. Similarly, pro-

longed inspection of a sinusoidal depth modulation of a particular size will cause subsequently viewed modulations to appear shifted in size.

These experiments demonstrate that the processing of disparity information may be usefully described in terms of the action of a number of channels, differing in their tuning for the spatial scale and orientation of depth variation. The properties of these channels have been further quantified by measuring their spatial frequency bandwidths. Measures that have been obtained using a notched-noise paradigm to prevent off-frequency viewing have estimated the bandwidth to be around ± 1.6 octaves (Cobo-Lewis & Yeh, 1994). The current study used a similar notched-noise paradigm to estimate the orientation tuning bandwidth of these channels.

There has been much recent interest in the nature of spatial pooling in visual processing, for both luminance contrast (Hess & Field, 1999; Polat & Tyler, 1999) and binocular disparity (Tyler & Kontsevich, 2001). This is of direct relevance to the issue of orientation and spatial frequency tuning. Broadly speaking, elongation of the receptive field of an orientation- and spatial frequency-tuned mechanism in a direction parallel to its preferred

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orientation will increase the orientation-specificity of the mechanism, while elongation in the orthogonal direction will increase its spatial frequency specificity. This is relevant to the current study since Tyler and Kontsevich (2001) showed that disparity is pooled across a horizontally elongated spatial region in the detection of horizontal cyclopean stimuli. In contrast, the detection of vertically oriented cyclopean stimuli relies on pooling in a relatively compact, isotropic region. This might be expected to lead to much narrower orientation-tuning for the detection of horizontal than for vertical stimuli. However, the effects of spatial pooling on orientation-specificity depend critically on the nature of the pooling.

Moulden (1994) proposed that spatial pooling might be performed by second-stage ‘‘collator units’’, summing the outputs of earlier, first-stage mechanisms. If the summation of the first stage mechanisms across their receptive fields, and the summation by the collator units were both linear, the response of an elongated collator unit would resemble that of a single, elongated receptive field. The response at this stage would therefore be expected to be narrowly-tuned for orientation.

Alternatively, there may be some non-linearity occurring prior to summation by the collator units. This has been proposed to account for conditions under which summation is not phase- or polarity sensitive (e.g. Chen & Tyler, 1999; Levi & Waugh, 1996). In this case, the response of the collator unit would not be equivalent to that of one single, elongated mechanism. Specifically, the orientation tuning of a collator unit performing non-linear summation would preserve the (relatively broad) tuning of the first-stage mechanisms. An elongated region of spatial summation, as observed for the detection of luminance or disparity defined stimuli (Polat & Tyler, 1999; Tyler & Kontsevich, 2001), is consistent with either linear or non-linear summation. The orientation tuning of cyclopean mechanisms, when considered in conjunction with the anisotropy found by Tyler and Kontsevich (2001), provides important constraints on the nature of spatial pooling. Orientation tuning for horizontal and vertical cyclopean mechanisms was therefore estimated on the basis of two notched-noise masking experiments.

2. Experiment one

2.1. Method

2.1.1. Apparatus

The stimuli were presented on a single 19” Sony Trinitron monitor. The resolution of the monitor was set to 800 × 600 pixels and the refresh rate was 100 Hz. Stimuli were viewed through four first-surface mirrors, arranged in a modified Wheatstone stereoscope configuration. The left and right images were presented side-by-side

on the monitor, and the observer’s field of view was carefully masked so that only the appropriate stimulus was visible to each eye. The viewing distance was 937 mm, at which each pixel subtended 1.28 arc min of visual angle. The orientations of the mirrors were carefully adjusted so that vergence was appropriate for the viewing distance. All experiments were carried out in a dark room.

2.1.2. Stimuli

Stimuli consisted of random dot stereograms. In all cases, these contained 800 dots, presented randomly in a circular region with a diameter of 5.4°. Each dot had a Gaussian luminance profile, with a standard deviation of 1.96 arc min. The maximum luminance of each dot was 103.7 cd m⁻² and the background luminance was 0.3 cd m⁻². Dots were positioned with subpixel accuracy.

The sequence of events for each trial was as follows. Firstly, the observer was presented with a nonius fixation marker. When this was fixated, the trial was initiated by the observer pressing one of the two response keys. Two stereogram stimuli were then presented, in random order. Each was presented for 500 ms, with a 500 ms interval between the two stimuli. The nonius fixation was presented between and after the two stimuli. On each trial, one signal plus noise stimulus and one noise only stimulus were presented (these are described below). The observer’s task was to indicate which of the two contained the signal. This was done by pressing one of two response keys, which initiated the next experimental trial.

2.1.3. Signal plus noise stimulus

The disparity of each point in the image was determined by a two-dimensional depth profile formed from the sum of a number of component sinusoidal depth modulations. These components consisted of the signal plus a number of noise components. The spatial frequency of the signal component was 0.73 cycles/degree, and its orientation was horizontal or vertical, depending on the block of trials.

The spatial frequency of all the noise components was also 0.73 cycles/degree. Their orientations fell into two regions, symmetrically arranged around the orientation of the target. For each block of trials, a notch region of orientations, symmetrically placed around the target, was defined. The orientation of the noise components did not fall into this region. Noise components filled a 10° range of orientations abutting the notch region on either side. Thus, for a horizontal target with a notch size of ±10°, the orientations of the noise components fell in the ranges 11° to 20° and -11° to -20°. Within each region, 10 noise components were summed, sampling the range in 1° intervals. The phases of both the signal and noise components were set at random for

each trial. The root mean square magnitude of the noise stimulus was 0.48 arc min.

2.1.4. Noise only stimulus

The noise only stimulus was identical to the signal plus noise stimulus except that the signal component was absent.

For each block of experimental trials, the orientation of the signal was either horizontal or vertical, and the notch width was set at one of 6 values (0° , $\pm 10^\circ$, $\pm 20^\circ$, $\pm 45^\circ$, $\pm 67^\circ$, $\pm 80^\circ$). Between trials, the magnitude of the signal was varied. Seven different levels were each presented 40 times (20 times each in two blocks of 140 trials). Probit analysis was used to estimate 75% correct discrimination thresholds for signal orientation and notch width, using the bootstrap procedure described by Foster and Bischof (1991).

3. Results

75% correct detection thresholds are plotted as a function of notch width for each observer in Fig. 1. For both horizontal and vertical gratings, detection thresholds decreased as the notch became wider, i.e., as the orientation of the mask became progressively less similar to the orientation of the signal. These results are similar to those reported in notched noise experiments in which the spatial frequency of the mask was varied (Cobo-Lewis & Yeh, 1994), and confirm that the cyclopean channels supporting the detection of depth corrugations are tuned for the orientation as well as the spatial frequency of depth corrugations (Tyler, 1975).

The aim of the current study was to estimate orientation tuning functions for cyclopean channels. To do this, it is necessary to know the function relating the magnitude of the noise mask to its strength of masking (Hoger-
vorst, Bradshaw, & Eagle, 2000). The results of the first experiment demonstrate that the degree of masking observed varied with the relative orientation between the

signal and mask. This result suggests that the effective strength of the mask for the channel(s) detecting the signal is attenuated by the difference in orientation. By measuring the function relating the degree of masking to the magnitude of the mask, as its orientation is held constant but its magnitude varied, it is possible to infer the effective strength of the mask from the degree of masking it produces. This was measured in experiment two.

4. Experiment two

4.1. Method

The apparatus and observers were the same as in experiment one. The procedure and stimuli were also the same, except that the notch size was fixed at 0° and, between blocks of trials, the magnitude of the noise mask was varied. Magnitudes of between 0 and 0.48 arc min RMS were used. In each case, seven levels of signal were presented, as before, and used to estimate 75% detection thresholds. Again, thresholds were measured for both horizontal and vertical gratings.

4.2. Results

75% detection thresholds are plotted in Fig. 2 as a function of the mask magnitude. Thresholds increased with increasing mask magnitude. These data were used to deduce orientation tuning functions from the results of experiment one as follows. Firstly, linear regression was performed on the data in Fig. 2, to describe the relationship between mask magnitude (M) and detection threshold (T),

$$T = aM + b. \quad (1)$$

It was then assumed that the variation in thresholds with increasing gap found in experiment one is due to the attenuation of the mask in the orientation filtering stage. Eq. (1) was then used to determine an effective mask magnitude, M_θ , for each notch width,

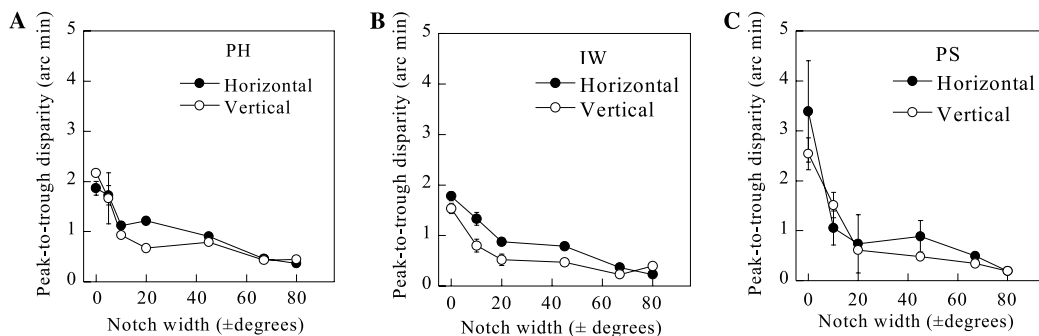


Fig. 1. Peak-to-trough disparity detection thresholds for each observer as a function of the notch width. In all cases, thresholds decreased with increasing notch width (decreasing similarity between signal and noise orientation). Error bars in these and all other graphs show ± 1 standard deviation of the threshold estimate.

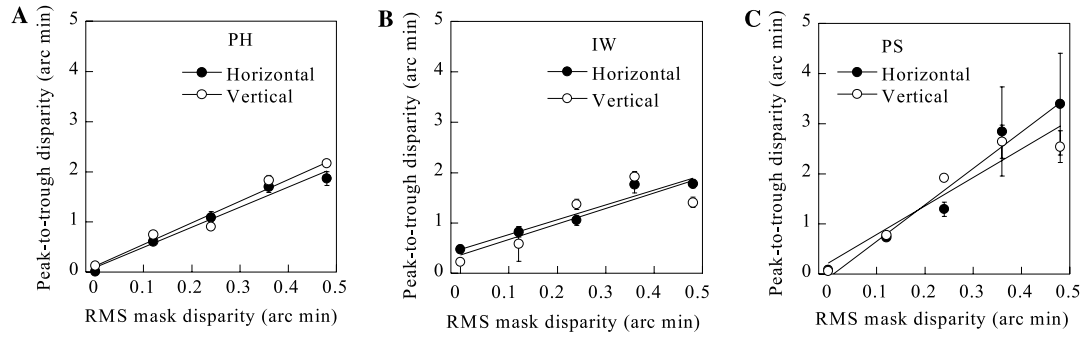


Fig. 2. Peak-to-trough disparity detection thresholds for each observer as a function of the noise amplitude (for a fixed notch size of $\pm 20^\circ$). Thresholds increased with increasing noise amplitude.

$$M_\theta = \frac{T - b}{a}, \tag{2}$$

M_θ represents the magnitude of mask with a notch width of zero that would be expected to produce the same threshold as the current notch width and magnitude. M_θ therefore represents the effectiveness of a given mask relative to the zero-width mask, and thus the degree of attenuation of that mask due to its difference in orientation to the signal. Filter tuning functions derived in this way are shown in Fig. 3.

In all cases, these functions are characterised by a rapid initial decline in the response with gap width for small gaps, followed by a much more gradual decline for larger gap sizes. To determine whether this pattern of results can be explained by a simple model of channel responses, it is assumed that the orientation tuning of cyclopean channels is a Gaussian function of orientation, $F(\theta)$, given by:

$$F(\theta) = \frac{1}{2\pi\sigma} \exp\left(-\frac{(\theta - \theta_0)^2}{2\sigma^2}\right). \tag{3}$$

The response of a single channel to the noise only stimulus was calculated as a function of the gap size, and the orientation tuning width of the channel, σ . The response of a channel tuned to the orientation at the centre of the gap was calculated, since this is the channel that will produce the best signal-to-noise ratio (Cobo-Lewis & Yeh, 1994). The results are shown in Fig. 3D, and show a rapid decline in response for small gap widths, similar to the data in Figs. 3A–C. Even for infinitely narrow bandwidths ($\sigma = 0$) there is some response to the mask for gap sizes greater than zero, resulting from the bandwidth of the mask, although this response drops off rapidly. The best fitting model to the psychophysical data was calculated, and is shown by the smooth curves in Figs. 3A–C. This model had two free parameters, the standard deviation of the Gaussian tuning function, and a vertical offset. With one exception, this model gave a good fit to the data. This exception was the data for horizontal gratings for observer PBH. The best-fitting curve, which was given by a channel with a half-width at half-height of 56° , fails to model the sharp increase in the response of the channel to the noise as the gap width approaches zero. Also shown in Fig. 3A (the dotted line) is a curve fit with the orientation bandwidth of the filter fixed at 5° (the same as that for vertical stimuli for this observer). Although this gives an overall poorer fit to data ($r_2 = 0.7187$) it does provide a better fit for small gap widths. In all other cases, the best fit was given by a model with relatively narrow orientation tuning. Half-widths at half-height of the channel tuning are given in Table 1. These results are similar

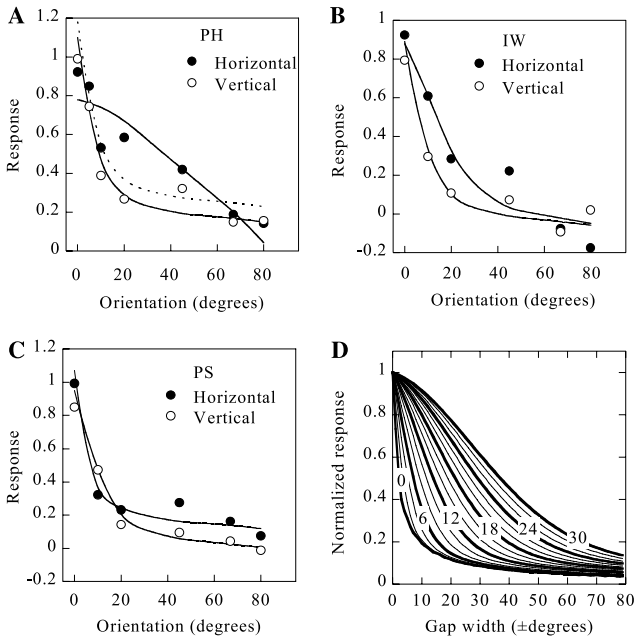


Fig. 3. (A)–(C) Estimated orientation tuning functions. Symbols represent the (normalised) orientation tuning of the channel based on the data from the two experiments. Smooth curves represent the best fitting model of the data (see text for details). (D) Results of a simple model of cyclopean processing in which the response a single channel to a masking stimulus is determined by the orientation tuning function of the channel, and the orientation profile of the mask in the Fourier domain. Results are shown as a function of the orientation tuning of the channels, σ , (shown by the labels on the graph), and the gap width in the mask stimulus.

Table 1
Best fitting parameters of the model assuming a simple Gaussian orientation tuning function

	PBH		ICW		PS	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Orientation bandwidth (°)	56	5	16	7	1	9
Vertical offset	−0.22	0.1	−0.12	−0.11	0.07	−0.05
r^2	0.7343	0.9467	0.9305	0.9491	0.9605	0.9767

in magnitude to estimates obtained for luminance channels (around 12° (Campbell & Kulikowski, 1966)). Although there is variability across observers, there is no clear trend for the horizontal channels to be more narrowly tuned than the vertical channels.

5. Discussion

The current results demonstrate that the cyclopean mechanisms processing horizontal and vertical depth structure have a similar orientation tuning to the channels processing luminance information. There was no clear evidence of any difference in orientation tuning between channels tuned to horizontal and vertical orientations. Tyler and Kontsevich (2001) demonstrated the existence of horizontally elongated summation fields for the detection of horizontal depth structure. The lack of a consistent difference between bandwidths for horizontal and vertical channels reported here suggest that this summation does not take the form of elongated linear summation fields for horizontal depth structure. An elongated linear receptive field would have a much reduced orientation bandwidth in comparison to an isotropic receptive field. What form then might the elongated summation shown by Tyler and Kontsevich (2001) take?

Tyler and Kontsevich themselves ruled out the possibility of (i) a local attentional tracking system, (ii) an adaptive channel system (iii) a single channel system of generic summation and (iv) a multiple channel system. Rather, they argued that cyclopean stimuli are processed by a specialised channel system. It was then argued that the horizontal and vertical channels exhibit different summation areas.

Here, it is proposed that such physiological summation occurs after some non-linear form of processing. Simple, linear physiological summation would result in receptive fields with very different orientation bandwidths. However, if such summation occurred after some other form of processing, then the orientation bandwidth would be conserved.

This idea is consistent with previously published literature on the summation of luminance contrast information. Moulden (1994) found that the degree of integration by second-order collator units was not affected by either contrast polarity or colour. Levi

and Waugh (1996) also provide evidence from position acuity experiments for non-linear second stage collector units. Polat and Tyler (1999) found spatial summation that is consistent with either elongated, linear receptive fields, or interactions between laterally displaced filters.

The current results are also consistent with the suggestion by Tyler and Kontsevich (2001) that anisotropic summation serves to compensate for the difficulty of detecting horizontal cyclopean edges in the natural environment. The detection of horizontal edges defined by horizontal disparity will be dependent on disparities in surface texture, rather than the disparities in the coincident luminance edges which can supply horizontal disparity information for vertical and other orientations. Non-linear second order summation would allow for an increased spatial summation area without resulting in a potentially overly restrictive narrowing of the orientation bandwidth.

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