Disparity increment thresholds for gratings

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Increment disparity thresholds typically rise steeply, usually exponentially, with disparity pedestal. Thus a threshold difference between small disparities is small, while a threshold difference between large disparities is large. We show here that the increment threshold function is subtly different for narrow-bandwidth stimuli. Thresholds vary only modestly over a ± quarter-cycle pedestal range, by about a factor of 2, and frequently show a dip, yielding best stereoacuity not at the fixation plane but at moderate disparities (20°-30° in phase) on either side of it. These features are consistent with predictions of certain models of disparity processing. Moreover, the relatively flat increment threshold function observed at any one scale is compatible with the steeply rising function observed for broad-bandwidth stimuli.

Keywords: stereo vision, depth perception, stereoacuity, binocular disparity, increment thresholds

Introduction

Having a fovea gives the retina a region of best acuity: All directions away from the fovea lead to regions with lower photopic spatial resolution. Having two foveas, one in each eye, adds another dimension to this resolution gradient, with resolution of stereoscopic depth decreasing with distance from the fixation plane (Ogle, 1953; Blakemore, 1970; Regan & Beverley, 1973; Krekling, 1974; Westheimer & McKee, 1978; Westheimer, 1979; Badeck & Schor, 1985; McKee, Bowne & Levi, 1990; Andrews, Glennerster & Parker, 2001). Thresholds for discriminating positions along the depth axis are usually described as increasing exponentially, or occasionally linearly, with off-horopter distance (Ogle, 1953; Blakemore, 1970; Schumer & Julesz, 1984; McKee, Bowne & Levi, 1990). The fall-off in spatial resolution away from the point of fixation has been reported to be at least as steep along the depth dimension as along the retinal eccentricity dimension (Schor & Badeck, 1985; see also McKee, Bowne & Levi, 1990). The coarseness in the spatial grain off the fixation plane, as measured by disparity increment thresholds, contrasts sharply with stereoacuity at the fixation plane, where under favorable conditions positional disparities as small as a few arcseconds are detectable.

Models of disparity increment thresholds have emphasized individual disparity tuning functions and how channel outputs are pooled. Yet only certain stimuli have been used to measure disparity increment thresholds and these haven’t necessarily been the ones most suited for testing these models. Here we use grating stimuli with narrow spatial-frequency bandwidths. These stimuli limit the range of disparities over which fusion and monotonic variation in perceived depth occur; their advantage is that they engage a correspondingly restricted range of mechanisms. Our results show that increment thresholds for these stimuli vary only modestly within this disparity range, generally around a factor of 2, and frequently show a dip, so that the best stereoacuity is not at the fixation plane but at moderate disparities on either side of it.

Increment thresholds and the size-disparity correlation: Increment thresholds have the potential for revealing channel disparity tuning, but this depends on the relative spatial-frequency bandwidth of the stimulus and the channel. If disparity-processing channels are few in number and broadly tuned—e.g., ‘near’ vs. ‘far’ (Richards, 1971)—a single channel could support discrimination across a substantial pedestal range (cf. Lehky & Sejnowski, 1990). In this case, tuning functions characterized by a slope that decreases with disparity (Poggio & Fischer, 1977) would yield highest-resolution discrimination near fixation. Discrimination between large disparities would be possible only if the difference is big enough to overcome the low responsivity gain. Thus increment thresholds would increase with pedestal disparity, following the inverse of the derivative of the tuning function.

A multi-resolution analysis of disparity would complicate this picture. This is so whether the analysis is
by multiple bandpass disparity channels for each of a few spatial scales, by a few broadband disparity channels for each of multiple spatial scales, or by multiple bandpass disparity channels for each of multiple spatial scales. For example, with multiple disparity detectors, each sensitive to a restricted range of disparities, processing will shuttle from one detector to another as the pedestal disparity increases in size. Threshold disparity would rise if the breadth of disparity tuning increased with the preferred disparity (Lehky & Sejnowski, 1990; Qian & Zhu, 1997; Tsai & Victor, 2003). As we’ll see below, the broad disparity tuning of detectors of large disparities may be connected to their preference for low spatial frequencies.

Multi-scale processing links disparity tuning and resolution largely through the size-disparity correlation (Felton, Richards & Smith, 1972; Marr & Poggio, 1979; Schor & Wood, 1983; Schor, Wood & Ogawa, 1984a; Smallman & MacLeod, 1994; Harris, McKee & Smallman, 1997). The size-disparity correlation implies that fine-scale channels limit discrimination thresholds at small disparity pedestals and coarse-scale channels do so at large disparity pedestals. Coupled with scale-dependent resolution, this provides for Weber-law discriminability, with low-frequency mechanisms covering low-resolution disparity discrimination over a broad range of disparities and high-frequency mechanisms covering higher-resolution disparity discrimination over a narrower, near-horopter range (Qian & Zhu, 1997; Smallman & MacLeod, 1997; Tsai & Victor, 2003). The size-disparity correlation is built into phase-offset coding of binocular disparity (Ohzawa, DeAngelis & Freeman, 1990; Fleet, Jepson & Jenkin, 1991; Fleet, Wagner & Heeger, 1996) and also arises from a parsimonious implementation of spatial-offset coding.

An implication of multi-resolution analyses of disparity is that a stimulus whose spatial-frequency bandwidth is broad relative to that of individual channels is unlikely to produce a disparity increment threshold function that depends on any one channel. Not only spatial-frequency bandwidth, but also orientation bandwidth and contrast must be taken into account in evaluating channel contributions to the increment threshold function—orientation, because a broader range of horizontal disparities can be read by an obliquely oriented receptive field than by a vertical one; and contrast, because a wider range of spatial-frequency and orientation components can contribute to disparity detection at high than at low contrast. Among the band-limited patterns previously used to measure increment thresholds, Rohaly and Wilson’s (1993) D6 patterns had a full-width, half-amplitude spatial-frequency bandwidth of one octave and a contrast of 50%, while Badcock and Schor’s (1985; Schor & Badcock, 1985) difference-of-gaussians had a spatial-frequency bandwidth of 1.75 octaves and a contrast of 100%. Difference-of-gaussians with the same bandwidth were also used by Siderov and Harwerth (1993a, 1993b), though generally at a lower contrast. McKee, Levi & Bowne (1990) used high-contrast lines as stimuli. All these patterns were oriented and their orientation bandwidths varied from one to another. Spatial-frequency bandwidths varied inversely with center frequency in Smallman & MacLeod’s (1997) filtered random-dot stereograms (RDSs), which had an r.m.s. contrast of 0.3, but these RDSs were isotropically filtered, so the stimulus horizontal spatial-frequency bandwidth was larger than the filter bandwidth. Schumer and Julesz (1984) used unfiltered RDSs and varied the frequency of the disparity modulation. Only in these studies using RDSs was disparity generated by offsetting the carrier only rather than both the carrier and the envelope; an envelope offset may introduce monocular cues (Smallman & MacLeod, 1997; McKee, Levi & Bowne, 1990). We measured thresholds for discriminating interocular carrier phase shifts of gratings patches with relatively narrow spatial-frequency and orientation bandwidths and relatively low contrasts in order to avoid multi-channel responses and interactions. We also measured thresholds for unfiltered RDSs. Initially the stimuli were presented in two-interval forced-choice trials, with the stimulus appearing at the pedestal disparity in one interval and at the pedestal-plus-increment disparity in the other. We also measured increment thresholds using several other versions of the task, each with two or three observers. This allowed us to gauge the generality of the results and to test for the influence potential artifacts specific to particular methods.

Methods

Stimuli: Gratings were sinusoidal luminance modulations limited spatially by either hard-edged or Gaussian circular envelopes. The gratings’ orientation was vertical (90°) and their contrast was 0.1 in most conditions; the other values investigated were 30° in orientation and 0.2 in contrast. Most data were collected at spatial frequencies of 0.5, 1.0 and 2.0 c/d; in other conditions spatial frequency ranged between 0.33 and 6.0 c/d. Stimuli were presented for durations of 150 ms and separated in time by 0.5 s in 2-interval methods.

The hard-edged envelope was 8° in horizontal and vertical extent for all spatial frequencies. The Gaussian envelope had a standard deviation = \( \sqrt{2}/F^\circ \) for spatial frequency \( F \) and was truncated at \( \pm 2\sqrt{2} \). The spatial-frequency bandwidth of the gabor patches, measured at half height and full width, was 0.38 octaves. RDSs were made of 2' square checks with a Gaussian luminance distribution with an r.m.s. contrast of 0.3; RDS displays were square, 2.8° on a side. The screen outside stimulus boundaries had a uniformly luminance of approximately 20 cd/m², matching the mean stimulus luminance.
Left and right half-stimuli were displayed on the two sides of a luminance-calibrated CRT. Viewing was through a mirror stereoscope. For viewing the gratings, the visible screen subtended approximately $21^\circ$ (horizontal) $16^\circ$ (vertical) in visual angle; viewing distance and screen resolution were both increased by a factor of two for viewing RDSs. The stimulus envelope was centered on black fixation squares, either $6'$ or $3'$ of visual angle on a side, which were continuously visible throughout the run of trials. Thus the envelope had a disparity of zero. The only non-zero disparities were interocular carrier phase shifts.

Two computer programs were used. One was written in C and controlled the three guns of the monitor operating with a frame rate of 120 Hz. Alternate frames presented the stimulus to left and right eyes. Each half-stereogram was drawn separately using separate color lookup tables to achieve sub-pixel resolution. The other program was written in MATLAB using the Psychophysical Toolbox extensions (Brainard, 1997; Pelli, 1997) and employed an attenuator (Pelli & Zhang, 1991) to combine the video outputs to drive the monitor’s green gun with a luminance resolution of about 12-bits; the frame rate was 75 Hz, with each frame presenting the stimulus to both eyes. Disparity in the first program was produced by shifting the phase of the grating presented to one eye and in the second program by shifting the phase of both gratings by equal and opposite amounts. Pixel-unit ($0.5'$) shifts to either one or both half-stereograms were used for RDSs. No systematic difference appeared between data collected by the two programs.

**Procedure:** In the 2-interval methods the stimuli were identical across the two intervals except for the disparity and absolute phase of the gratings. In one interval the grating had the pedestal disparity; in the other, it had the pedestal disparity plus an increment. In separate conditions this increment was always positive and required a 2-interval forced-choice detection response (Fig. 1a), or either positive or negative and required a ‘Near’/’Far’ forced-choice discrimination response (Fig. 1b) (Farell, 1998). The absolute phases of the gratings were randomized in every interval identically for the two eyes, translating the grating unpredictably between intervals, eliminating possible positional cues without affecting disparity.

Two single-interval methods were used. In one, the stimulus was a bipartite gabor patch—two half-gabor patches separated by a hard-edged horizontal band 18’ high—in the first of these methods (Fig. 1c). The lower patch was presented at the pedestal disparity. The upper patch was presented either at the pedestal-plus-increment disparity or at the pedestal-plus-decrement disparity, where increments and decrements were equal in absolute value. The observer judged the upper patch as ‘Near’ or ‘Far’ relative to the lower patch.

The second single-interval task was a form of absolute identification using the method of single stimuli (Fig. 1d). Here one grating was presented on each trial at one of four alternative disparities. None of these disparities was the pedestal; the pedestal was never explicitly shown. The gratings appeared with disparities that resulted from combining two pedestals, one positive and one negative (gray disks in Fig. 1d), and two increments, one positive and one negative. The absolute magnitudes of the two pedestals were the same, as were the absolute magnitudes of the two increments. The observer’s task was to classify the grating with respect to its distance from the fixation point, two of the grating positions being ‘Near’ the fixation point and two ‘Far’. At a pedestal of zero there were only two distinct distances, one on the ‘Near’ side of the observer and the other on the ‘Far’ side. Performance in this task, unlike the others, depends on memory across trials; indeed, the first trial of a run contains no information on which to base a response. Thus, for this method only, feedback about the correctness of responses was provided, as were 20 practice trials within each run before data-collection trials began.

Except for the absolute-identification task, trial-to-trial disparities were under the control of the QUEST algorithm (Watson & Pelli, 1983; King-Smith et al., 1994) with a threshold criterion of 82% correct. A constant-stimulus method was used for the absolute-identification task, where psychometric functions were fit with a Weibull function and the disparity yielding 67% correct responses was taken as threshold (the task was difficult and two of the observers did not reach even this level of performance.

Responses were made by clicking labeled buttons that appeared on-screen 0.5 s after the end of the final stimulus interval of a trial. A subsequent click initiated the following trial.

In principle, the periodic stimuli used here have a useful phase disparity range spanning $\pm 180^\circ$. In practice, this range encompasses several qualitatively distinct percepts (Ogle, 1952; Tyler, 1991), making the measurement of thresholds on large pedestals problematic (see Badcock & Schor, 1985; Siderov & Harwerth, 1993b). Gratings with phase disparities much more than $90^\circ$ often appear as diplopic, as also found by others (e.g., Schor, Wood & Ogawa, 1984b) or with ambiguous or reversed depth at disparities well below $180^\circ$. These variations in the percept could change the observer’s task, in some cases making performance problematic without response feedback. For example, a disparity difference that is discriminated by a quantitative change in depth at a small pedestal might be discriminated by a qualitative change (fusion vs. diplopia, or appropriate depth polarity vs reversed depth polarity) at a large pedestal. Near the transition point a modest increase in the pedestal can lead to a decrease in threshold, especially at high carrier...
Figure 1 Four methods of measuring disparity increment thresholds. Left side shows stimulus configurations presented with a pedestal disparity of zero; right side shows configurations with non-zero pedestal. (a) Two-interval detection. Observer chooses the interval in which the grating appears with pedestal-plus-increment disparity. (b) Two-interval discrimination. Observer judges the depth of the grating (‘near’ vs. ‘far’) shown in the second interval relative to that of the pedestal-disparity grating shown in the first interval. (c) Single-interval discrimination. Observer judges the depth of the upper grating relative to the pedestal-disparity lower grating. (d) Absolute identification, method of single stimuli. Observer judges the grating’s disparity magnitude relative to the fixation marker. In this method the four alternative positions in depth arrayed around non-zero pedestals (right) reduce to two when the pedestal is zero (left). In (d) the pedestals are marked by disks. For all cases, light bars are at the pedestal disparity, dark bars are at the pedestal plus or minus a disparity increment, and curly bracket shows the disparity increment. A fixation point was present throughout the run of trials in all conditions. For two of the observers nonius lines were presented above and below the fixation point; these disappeared 125 ms before stimulus onset and returned after the observer responded. The importance of maintaining fixation throughout stimulus presentations was stressed.

frequencies. Thresholds increase again with still larger pedestals, presumably because the two disparities to be discriminated give rise to qualitatively similar percepts, e.g., both diplopic. Our interest here was in increment thresholds mediated by changes in perceived depth, so pedestals were limited in phase to 90° or 120°, keeping the disparity (pedestal plus increment) below the diplopia, depth-ambiguity and depth-reversal thresholds.

**Observers:** Four observers, three of them (including one of the authors) highly experienced in stereo experiments, were run in the experiments; not all observers ran in all four of the methods. A fifth observer, another of the authors, ran in a single method. Two of the observers were naive about the purposes of the experiments. All had normal or corrected-to-normal acuity and normal stereo vision.

**Results**

The disparity increment thresholds shown in Figures 2a and 2b were collected using the 2-interval methods, and those shown in Figures 2c and 2d are from the 1-interval methods. For two of the three observers tested with both pedestal polarities, thresholds were approximately symmetrical about the fixation plane, showing essentially equivalent results for positive and
negative pedestals. One observer showed higher thresholds for negative pedestals, by nearly a factor of two. Where applicable, data for increments and decrements were combined and thresholds examined as a function of the pedestal’s absolute value.

Grating thresholds were generally rather flat between pedestals phase disparities of 0° and 60°, then rose at 90°, as seen in Figure 2. Across a pedestal phase disparity range of 0° to 90°, increment thresholds typically show a 2- to 3-fold range of values overall. The fine structure shows a dip for most observers, with the lowest thresholds occurring at a pedestal of approximately 30°. There was little systematic effect of spatial frequency on threshold phase disparity over the 0.33–6.0 c/d range tested, though two observers showed uniformly elevated thresholds for frequencies greater than 3 c/d. Also, no systematic difference in phase disparity thresholds appeared between gratings with different orientations (30° and 90°) (Farell, 2003). Likewise, there was also no systematic effect of grating envelope type, hard-edged or Gaussian.

A typical data set is shown in Figure 2a, where

![Figure 2](image_url)

**Figure 2** Disparity increment thresholds for gratings. Pedestal disparities (abscissa) and threshold disparities (ordinate) are given as degrees of phase (bottom and left scales) and as minutes of visual angle (top and right). (a) Thresholds as a function of disparity pedestal for a vertical 1c/d grating with contrast of 0.1 appearing in a hard-edged envelope 8° in diameter. Two observers data are shown. Method was two-interval detection (Fig. 1a). (b) Thresholds as a function of disparity pedestal for same stimulus as in (a), using the two-interval discrimination method (Fig. 1b). Data for near and far increments, and their means, are plotted. (c) Thresholds as a function of disparity pedestal for a 1c/d bipartite gabor patch with contrast of 0.1, using the single-interval discrimination method (Fig. 1c). (d) Thresholds as a function of disparity pedestal for the same stimulus as in (a), using the absolute-identification method (Fig. 1d). Note that the ordinate is scaled differently in (a) than in the other graphs. Error bars are ±1 s.e.m.
threshold and pedestal disparities for 1 c/d gratings are expressed as phase offsets (in degrees) and as spatial displacements (in minutes of visual angle) for two observers. The data come from the 2-interval increment detection method (Fig. 1a). The noticeable dip and the 2:1 range of thresholds across the 0°-90° range of pedestal values was also found using the 2-interval increment discrimination method (Fig. 1b) and the single-interval bipartite-stimulus method (Fig. 1c), as seen in Figures 2b and 2c, respectively. Thresholds for the absolute-identification method (Fig. 2d) were unmeasurable for two observers tested and required a reduced criterion for threshold (67% correct) for those who could perform the task. Even with the low criterion, threshold could not be measured on any observer at the largest pedestals (90°). The psychometric functions on which thresholds were based were shallow, noisy, and asymptoted at low values. Yet thresholds were low, indicating that observer's sensitivity in this task was limited by the overall range of disparity values that had to be monitored, a range that was smaller for small increments as well as small pedestals. Absolute performance levels aside, the threshold function did resemble those of other methods in that it displayed a dip at a pedestal of 30°, which was followed at larger pedestal sizes by a sharp rise in threshold.

The scaling of increment thresholds with spatial frequency is shown in Figure 3 for two sets of three
frequencies. Thresholds for low frequencies are plotted as phase offsets in Figure 3a and spatial offsets in Figure 3c. Figures 3b and 3d do the same for high-frequency data from the observer who shows the least evidence of a dip (and had the least experience with the task). In both cases thresholds scale with frequency, showing much greater overlap and similarity in shape when plotted as phase disparities than as spatial disparities. The scaling is not perfect, however. The dip shifts slightly with grating frequency (Fig. 3a) and phase-disparity constancy gives way to spatial-disparity constancy at higher frequencies (Fig. 3d), as typically seen for stereoacuity measured at pedestals of zero (e.g., Schor, Wood & Ogawa, 1984a).

Increment thresholds for random-dot displays appear in Figure 4. The 2-interval detection method was used. There is no dip. Exponential functions provide an excellent fit to the data points ($r=0.997$ for observer S3 and $r=0.989$ for observer S1 vs $r=0.954$ and 0.961, respectively, for the best-fitting linear functions).

**Figure 4** Disparity thresholds for RDSs as function of disparity pedestal for two observers. The method was two-interval detection. The dotted line shows the best-fitting exponential function. Error bars are ±1 s.e.m.

In principle, a fixation disparity could account for both the dip and the small threshold range in some of the data sets, but not in all of them. If the true increment threshold function is monotonic, the observed threshold minimum should be at zero pedestal. But if nominal and effective pedestal values differ because of a consistent fixation disparity, the minimum would occur at a non-zero value corresponding to the observer’s actual fixation plane. Such a discrepancy could be prepared in advance of the single interval containing the bipartite gabor. It might be more likely to occur with two-interval stimulus presentations: The stimulus in the first interval, even if brief, can be a potent target for vergence eye movements, bringing fixation closer to the stimulus in the second interval. However, this leaves the depth interval that the observer presumably judges—that between fixation point and grating (Westheimer, 1979)—unchanged. Moreover, the absolute-identification task, with stimuli symmetrically arrayed about the fixation point, seems to allow no strategy that would impart an advantageous fixation disparity; vergence changes that bring positive-disparity stimuli closer to fixation move negative-disparity stimuli farther away. Since the dip and modest threshold range are not confined to any one of the methods used, they would appear to be real features of the increment threshold function for the grating stimuli used here.

**Discussion**

The detection of disparity increments has been characterized by two main features: Thresholds are smallest near the fixation plane and they increase, usually exponentially, as the pedestal extends in depth in either direction from this plane. In our study, increment thresholds for single-grating patches rose sharply with pedestal size, but typically only after the pedestal was large (>60° phase), roughly half the diplopia threshold. At smaller pedestals thresholds were quite flat overall and usually displayed a dip. Thus, while both of the classic features apply to our data for random dot stereograms, new features characterize our data for narrowband grating patches at pedestal phase disparities ranging between about ±π/4.

One can find in the literature several studies that hint at non-monotonocities suggestive of a disparity dipper, and two studies in which the dipper is full-blown. The latter are the studies of Duwaer and van den Brink (1982) and McKee, Levi and Bowne (1990), where the disparities giving rise to the dip were vertical. Using horizontal lines, Duwaer and van den Brink found that thresholds for discriminating vertical disparities dropped by roughly a factor of two as the pedestal increased from zero, before rising again. Thresholds were minimal at pedestals ranging from 2.4’ to 15.3’, depending on line length, distance from fixation, and presentation duration. Similarly, minimal thresholds for horizontal lines in the McKee, Levi and Bowne (1990) study occurred at pedestals of about 15’. In studies of horizontal disparity thresholds, non-monotonocities appear faintly in the data of Smallman and MacLeod (1997), whose filtered RDSs were tested at quite large pedestal phase disparities but not at zero, and possibly in those of Siderov and Harwerth (1993a, 1995), who used difference-of-gaussian patterns.
Duwaer and van den Brink (1982) interpreted the dip in vertical disparity thresholds as evidence for two near- horopter processes, loss of sign and increased noise. Either process alone would be sufficient to generate a dip in disparity discrimination thresholds, provided that disparity resolution decreases away from the horopter. By itself, however, a loss of sign would not affect detection thresholds. At zero pedestal the detection task used here requires only a discrimination of disparity magnitude, while the discrimination task requires discrimination of sign. The two methods yielded similar threshold values, however, a loss of sign applies to horizontal disparities. The second factor, increased noise near the horopter, may apply to horizontal disparities, but without support from measures other than threshold elevations it is not an explanation. However, it is clear that the rising portion of the function in the data of McKee, Levi and Bowne (1990) occurs at pedestals at which the stimulus is diplopic and thresholds are actually for discriminating dichoptic width increments. For vertical disparities, then, the dip may mark the transition between disparity and width judgments, where thresholds fall as increments and decrements become discriminable by single-vision and diplopia, respectively. The same transition occurs with horizontal disparities of vertical lines, but there is no dip (McKee, Levi and Bowne, 1990). The reason, perhaps, is that observers continue to use depth as a cue even above the horizontal diplopia threshold (Ogle, 1952, 1953).

Non-monotonicities for horizontal disparity increments have appeared more robustly in model simulations than in the empirical studies just mentioned. Lehky and Sejnowski (1990) considered a population-code model based on the Poggio and Fischer (1977) three-channel disparity-coding scheme, containing broadly tuned “Near” and “Far” channels and a narrowly tuned near-horopter channel. Predicted increment thresholds from this model were sharply scalloped, with thresholds reaching their lowest values on either side of the horopter (their Fig. 6). This bore little resemblance to the target data set, that of Badcock & Schor (1985), and the model was rejected; modified models containing larger sets of disparity channels were more successful (Lehky & Sejnowski, 1990). Tsai and Victor (2003) considered a multiscalar disparity-energy model, also with a population read-out process, and reported a nearly flat but yet discernibly dipper-shaped increment threshold function when the model was reduced to contain only a single scale matched to the stimulus (their Fig. 4d). This reduced version ought to approach the response of the full multiscalar model when the stimulus spatial-frequency bandwidth is narrow and contrast is low, as in the case of the gratings used here. Finally, Zhao and Farell (2002) have shown that a disparity-energy model incorporating the full set of spatial frequency, orientation, and disparity sensitivities found in a V1 cortical column yields a dipper-shaped increment threshold function for grating stimuli. This outcome depended on a hierarchical read-out across disparity, orientation, and spatial frequency channels.

In general, a dip will appear in the increment threshold function when the disparity channel with the sharpest tuning (relative to peak response), or the gradient of channel sensitivities, is centered on zero disparity. Increment thresholds will then be smallest for non-zero pedestals, which place the stimulus where the tuning curve is at its steepest, on its flanks (McKee, Levi & Bowne, 1990). The dip commonly found in contrast discrimination threshold functions (Nachmias & Kocher, 1970; Nachmias & Sansbury, 1974; Foley & Legge, 1981) has a similar explanation in terms of an accelerating contrast response function (Nachmias & Kocher, 1970). However, note the empirical difference: The contrast dip occurs at pedestals near the detection threshold, whereas the disparity dip occurs at pedestals exceeding stereo-acuity by a factor of three or four.

We simulated increment thresholds for our uniform-contrast (hard-edged) grating patterns using Tsai and Victor’s (2003) phase-disparity energy model. Tsai and Victor found that the model’s response to 1.75-octave gabor patterns approximated the exponential threshold functions seen in the literature for comparable stimuli.

![Figure 5](image-url)
For our gratings patterns the model shows a dip centered a pedestal of around 20° and a threshold range of about 1:1.6 over pedestals between 0° and 90°. Both results are quite robust across both stimulus and model parameters. Typical model output is seen in Figure 5. Predicted thresholds are based on a mismatch function, an index of neural response information that cannot be accounted for by responses of template neurons. The shape of the mismatch function can give the smallest disparity increment that would be needed to overcome a specified amount of noise and so be detected; this is the threshold disparity increment shown, on arbitrary scaled units, in Figure 5. But in fact the model includes no sources of noise yielding trial-to-trial variation, so the details of the simulation results reflect deterministic model processes (Tsai & Victor, 2003). The model neurons’ disparity tuning functions form an envelope whose shape is a Gaussian centered at zero disparity. The dip in the increment threshold function occurs at the disparity where the gradient of these functions under the Gaussian is steepest. This gradient is specific to phase-disparity implementations of the model; a position-disparity implementation would have uniformly peaked tuning functions across the range of disparities covered. Hence no dip would be expected. For multi-scale stimuli the dip is washed out by scale differences in the gradients in the phase model; at a particular disparity pedestal a mixed set of gradients would set the model’s sensitivity.

Size-disparity correlation and increment thresholds: The disparity thresholds measured here with narrow-bandwidth patterns typically show modest, and non-monotonic, variation over roughly half of the single-vision pedestal range (phase disparities of 0°-60°). The rather steep and monotonically increasing function that is typical of multi-scale patterns is readily derived from single-scale functions, even entirely flat single-scale functions. The size-disparity correlation provides the linkage. Small pedestals place increments within the matching range of channels selective to high-frequency components of the pattern and small spatial disparities. Successively larger pedestals exceed the range of the higher-frequency channels and place increments within the range of channels selective to lower frequencies and larger disparities. Because disparity resolution scales with frequency, as seen in the approximately phase-disparity constancy of thresholds in Figure 3, the result is an increasing disparity threshold function, as shown in Figure 6. Thus increment thresholds can be a flat function of disparity pedestal at any one scale and still contribute to an increasing function for multi-scale patterns. The increase would not necessarily be linear. Disparity thresholds for spatial frequencies greater than about 3 c/d, measured at zero pedestal, are usually found to be constant on a spatial scale (and so increasing on a phase scale) (Schor, Wood & Ogawa, 1984a). The effect would be a flattening of the increment threshold function at small pedestals, where thresholds are limited by responses to high-frequency components.

The effect of pattern bandwidth on stereo thresholds could show whether the disparity increment thresholds for broad-band patterns can be accounted for without interactions between channels of different scales, as implied by the size-disparity correlation. Two studies, those of Smallman and MacLeod (1997) and Rohaly and Wilson (1993), compared increment thresholds for single-frequency and compound-frequency stimuli. In both cases the aim was to test for coarse-to-fine matching-range shifts (Marr & Poggio, 1979; Nishihara, 1984; Quam, 1987).

![Figure 6](image)

Figure 6 Individual increment threshold functions are shown for stimuli of different frequencies as they would appear with thresholds and pedestals plotted in spatial units. Dots depict sampling points for increment thresholds measured on a multi-scale stimulus. Even if the increment functions for the components were individually flat, increment thresholds for broadband patterns would increase over the range of pedestals mediated by components displaying constant threshold phase-disparity and a negative correlation between frequency and disparity range. A constancy of spatial disparities at high frequencies (Schor & Wood, 1983; Schor, Wood & Ogawa, 1984a) would flatten the broadband function at small disparities.

Thresholds for two-frequency compounds were found to be roughly similar to those of the low-frequency component alone (Rohaly & Wilson, 1993) or to rise at an even faster rate with pedestal size (Smallman & MacLeod, 1997). Matching-range shifts were expected to produce flattened increment threshold functions for compound stimuli; such functions were not found. These results imply that disparities of components of different scales are independently detected, perhaps with interference from finer scales as the size of the pedestal increases. With allowances made for probability summation, compound thresholds based on independent component detections would trace the lower envelope of the component thresholds, as seen in Figure 6. The dip
found at any one scale would contribute little to threshold functions sampled as coarsely as is typical for multi-scale patterns; scalloping of the function, as seen in Lehky and Sejnowski's (1990) initial simulation, would be smoothed by noise in any real threshold data. The expectation, then, is that increment thresholds for broadband patterns should be approximately as steep as would be produced solely by means of independent disparity detection within channels tuned to different scales. We show in a subsequent report that this independence-based expectation is incorrect, overestimating thresholds at small-to-moderate pedestals and in some cases underestimating them at large pedestals (Farell, Li & McKee, 2003). The discrepancy is due to previously unobserved coarse-to-fine interactions among the components of multi-scale stimuli.

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Footnotes

1. An inability to compare a depth estimate with a memorized standard would not prevent an observer from performing the absolute-identification task, but it would explain the low performance level. The observer could compare depth estimates across successive trials, in effect treating successive trials as two intervals of a single trial. The difficulty of the task would then be understandable if depth judgments were ordinal, not metrical, for then between-trials comparisons would be productive on only a fraction of the trials. If depth order were judged separately for positive and negative disparities, the fraction is 50% (the fraction in which the stimulus on the previous trial had the same depth polarity); if depth order were judged on the basis of distance from observer without regard to sign of disparity, it is 37.5% (the fraction in which the stimulus on the previous trial had the same disparity or a larger disparity of the same sign). Remaining trials would require a guess, so the upper limit on performance would be 75% in the signed case and 68.75% in the unsigned case. Trial-by-trial analysis supports the former case. Observers can readily learn to use a single memorized depth standard (Morgan, Watamaniuk & McKee, 2000); using two standards may be much more than twice as difficult [though the effect of number of standards is small for discriminating separations in the fronto-parallel plane (Morgan, Watamaniuk & McKee, 2000)].

References


