

Contrast discrimination in peripheral vision

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Contrast discrimination provides a psychophysical method for studying contrast coding in vision. Our purpose was to compare properties of contrast discrimination in central and peripheral vision. We used forced-choice procedures to measure contrast-increment thresholds as a function of pedestal contrast. Our stimuli were 2-cycle/deg Gaussian-windowed sine-wave grating patches. They were centered at retinal loci ranging from 10° nasal to 20° temporal on the horizontal meridian. At each eccentricity, curves relating increment threshold to pedestal contrast had the same shape. When increment thresholds and pedestal contrasts were both normalized by the contrast thresholds at the retinal eccentricity in question, the curves became superimposed and fell along the same dipper-shaped contrast-discrimination function. We conclude that, after scaling by the local contrast sensitivity, properties of contrast discrimination are qualitatively and quantitatively similar from 0° to 20° on the retina. These findings suggest that mechanisms of contrast coding are similar in central and peripheral vision.

INTRODUCTION

The detection or discrimination of contrast plays a role in most visual tasks. The way in which the visual system codes contrast is therefore of central importance. Psychophysical methods that have been used to infer properties of contrast coding include contrast-magnitude estimation,^{1,2} contrast matching,^{3,4} and contrast discrimination.⁵⁻⁷ Typically, data from psychophysical experiments are used to develop or test models of contrast coding. These models propose a relationship between stimulus contrast and internal response. Efforts have also been made to relate cellular contrast responses to psychophysical measures.⁸⁻¹⁰

In a contrast-discrimination experiment, subjects are required to distinguish between pairs of stimuli that are identical except for their contrasts C and $C + \Delta C$. The threshold value of ΔC is called the *contrast-increment threshold*. The value of C to which ΔC is added is called the *pedestal contrast*. The relation between ΔC and C is the target's *contrast-discrimination function*.

It is generally agreed that the contrast-discrimination functions for foveal targets are dipper shaped.^{5,6,11-13} This is illustrated in Fig. 1 for contrast discrimination of sine-wave gratings. As the pedestal contrast rises from zero, the increment threshold first drops. This facilitation effect occurs for pedestal contrasts near the contrast-detection threshold. For suprathreshold pedestal contrasts, ΔC rises steadily, typically following a power law with an exponent near 0.6.¹⁴

There is a substantial degree of invariance in the shape of contrast-discrimination functions measured foveally. For many stimuli, the functions superimpose when both ΔC and C are normalized by the contrast threshold for the stimulus. This means that the entire contrast-discrimination function can be specified simply by giving the contrast sensitivity for

the stimulus. Evidence for shape invariance comes from studies of sine-wave gratings of different spatial frequencies,^{13,15} gratings at different luminance levels,¹⁵ gratings presented monocularly or binocularly,¹⁶ and gratings having few or many cycles.⁶ The shape invariance extends to luminance profiles other than gratings.^{5,17,18} The similarity in the shapes of contrast-discrimination functions suggests that the underlying processes of contrast coding are also similar.

Are the properties of contrast processing similar in central and peripheral vision? There are two rather different viewpoints concerning pattern processing in peripheral vision. One holds that peripheral vision is a scaled version of central vision; there are only quantitative differences. The other view argues for qualitative differences. Virsu and Rovamo¹⁹ have shown that peripheral contrast sensitivity is the same as central contrast sensitivity when grating stimuli are scaled in shape by the cortical magnification factor. Subsequently, M scaling has been shown to apply to several other visual capacities. Such a scaling principle suggests a measure of qualitative similarity between central and peripheral vision. However, there is also evidence for qualitative differences. Studies of Westheimer²⁰ and Levi *et al.*²¹ have shown that visual sensitivities of different kinds—grating acuity, vernier acuity, and motion detection—decline at different rates with retinal eccentricity. As a consequence, relative sensitivities for basic visual tasks will vary from place to place in the periphery. Such variation in relative sensitivity may underlie qualitative differences in the manner by which complex visual tasks are performed. For example, people with central-field loss who must rely on peripheral vision are particularly handicapped in reading, even when their acuities are relatively high.²² No type of spatial scaling (such as simple magnification) has been found to cancel the deficit.

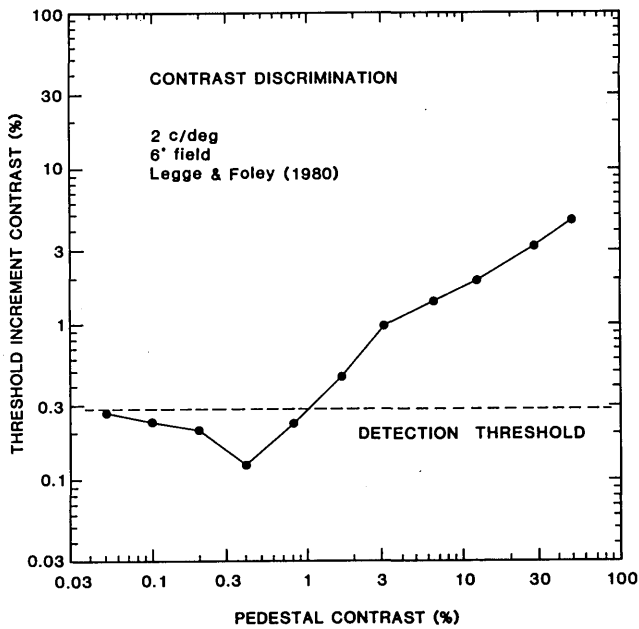


Fig. 1. A dipper-shaped contrast-discrimination function is illustrated. The data, from Ref. 6, are for foveally fixated 2-c/deg sine-wave gratings subtending 6°. Each point is the mean threshold for three observers. The horizontal dashed line is drawn at the ordinate value representing the contrast-detection threshold.

Bradley and Ohzawa¹⁵ measured one subject's contrast-discrimination function for a 4-cycle-per-degree (c/deg) grating at 10° of retinal eccentricity. Although they did not specifically address the issue of shape invariance of contrast-discrimination functions at different retinal loci, their limited data are consistent with this possibility. Swanson and Wilson²³ used an oblique-masking method (pedestal and increment stimuli differing by 14.5° in orientation) to study contrast discrimination at 8° of retinal eccentricity. They report data for D6 targets (sixth derivatives of Gaussians) with peak frequencies at 2 and 0.25 c/deg. The log-log slopes for pedestals ranging from 5 to 40% contrast were 0.8 and 0.62, respectively. These values were a little higher than corresponding foveal values for *M*-scaled stimuli, suggesting a possible difference in contrast coding between central and peripheral vision.

Cannon¹ used a magnitude-estimation method to study perceived contrast for 2°-diameter sine-wave grating patches at retinal eccentricities ranging from 0° to 40°. He found that threshold-corrected power functions with about the same exponent fit the data at all eccentricities. As a result, despite substantial variations in contrast thresholds across the retina, targets well above threshold that were matched in physical contrast tended to have similar appearance. This result is consistent with the contrast-matching data of Georgeson and Sullivan.³ They found that suprathreshold peripheral gratings matched foveal gratings of the same physical contrast, despite substantially higher thresholds. This finding may reveal a contrast-compensation mechanism in which neural response rises more rapidly with stimulus contrast in the periphery.

The purpose of our study was to determine whether the shape invariance of the contrast-discrimination function holds at different retinal eccentricities and whether differences in scale can be related to the decline of contrast sensi-

tivity with eccentricity. We measured contrast-discrimination functions for 2-c/deg sine-wave-grating patches from the fovea to 20° of retinal eccentricity.

METHOD

Apparatus and Stimuli

Stimuli were presented on the face of a Joyce Electronics CRT display by *Z*-axis modulation. The display had a white P4 phosphor, an unmodulated mean luminance of 170 cd/m², and a dark surround. At the viewing distance of 57 cm, the screen subtended 30° horizontally by 16° vertically.

All measurements were made with 2-c/deg vertical sine-wave gratings modulated in space and time by Gaussians. The horizontal Gaussian was centered on a bright bar and had a space constant of 1°. The vertical Gaussian had the same space constant and was centered on the screen. The temporal Gaussian had a time constant of 100 msec. Contrast is specified as the Michelson contrast of the sine wave without spatial windowing.

The luminance waveforms were synthesized digitally by a PDP-11/40 computer. A 12-bit multiplying digital-to-analog (D/A) converter generated a sinusoidal waveform modulated by the temporal envelope. The output of the D/A converter in turn modulated a horizontal Gaussian envelope produced by a second multiplying D/A converter. The output of the second D/A converter was low-pass filtered to prevent aliasing and was passed to a 9-bit programmable attenuator. The output of the attenuator was passed to the *Z*-axis input of the display. This signal was modulated along the raster lines (vertical axis of the display) by a Gaussian envelope. The Gaussian waveform was generated by an 8-bit fast-buffer store and was synchronized with the sweep of each raster line. It was applied to the high-bandwidth-multiplying *Z*-axis input of the display. Fine adjustments in contrast could be made by appropriate settings of the attenuator and multiplying D/A converters.

Procedure

The subject fixated a small black dot on the screen located 5° from the edge opposite the target. Relative to the fixation dot, contrast discrimination was measured along the horizontal meridian at 0°, on the temporal retina at 2.5°, 5°, 10°, and 20°, and on the nasal retina at 2.5°, 5°, and 10°. Viewing was monocular (left eye) with the natural pupil. The other eye was occluded.

Contrast-increment thresholds were measured with a temporal two-alternative forced-choice procedure. In the discrimination paradigm, a grating target with pedestal contrast *C* is presented in both intervals of the trial. In one of the intervals, the contrast increment ΔC is added. The subject is required to indicate which interval contained the increment. The QUEST algorithm²⁴ was used to estimate a threshold value of ΔC (75% correct criterion) in a block of 50 trials. Before each block, the subject was shown a series of high-contrast examples of the grating patch at the retinal eccentricity under study. These examples informed the subjects about the location of the stimuli.

Contrast-discrimination functions were obtained by measuring increment thresholds for several pedestal contrasts, ranging from 0 to 48%, at each eccentricity. Four to six such

functions were collected at each eccentricity, one at a time, in the following staggered sequence of eccentricities—0, +5, +20, -10, -2.5, +2.5, +10, -20, -5, 0, . . . Alternate functions at a given eccentricity were collected in ascending and descending order of pedestal contrasts.

Subjects

There were two subjects, WWL and RC. Both have corrected-to-normal acuity. Both were naive to the purposes of the experiment but very well practiced. In particular, both subjects were careful to maintain correct fixation during the forced-choice trials. Observer WWL completed the experiment at all eight retinal eccentricities, but observer RC's nasal retina was not tested.

RESULTS AND DISCUSSION

Figure 2 shows WWL's contrast-discrimination data for five retinal eccentricities. Each point is the mean of four to six threshold estimates. Standard errors ranged from 3–36% and were typically about 15%. X's show foveal data (0°). The remaining symbols show data for four locations on temporal retina. Symbols on the left vertical axis show the detection threshold, that is, the threshold when the pedestal contrast was 0. The five sets of data exhibit a similar pattern—a dip down from the detection threshold followed by a steady rise as pedestal contrast increases.

Fig. 3 shows corresponding discrimination data for subject WWL's nasal retina. Data were not collected at 20° nasal because the stimuli would have fallen within subject WWL's blind spot. The pattern of results is the same for nasal and temporal retina.

The similarity of the separate sets of data in Figs. 2 and 3 can be seen more clearly if contrast is scaled by the local contrast sensitivity. In Fig. 4, the eight contrast-discrimi-

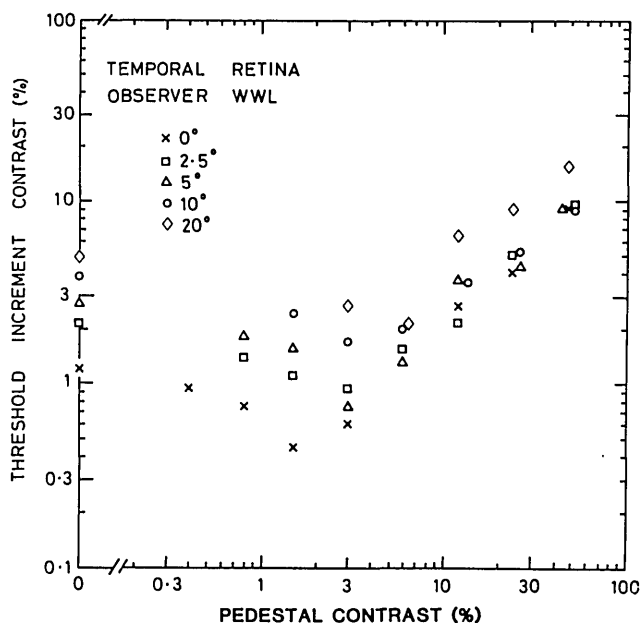


Fig. 2. Threshold-increment contrast is plotted as a function of pedestal contrast for several positions on the temporal retina of observer WWL. The target was a 2-c/deg sine-wave-grating patch, vignettted in space and time. The targets were centered at retinal eccentricities ranging from 0 to 20°, i.e., from 0 to 40 cycles into the periphery.

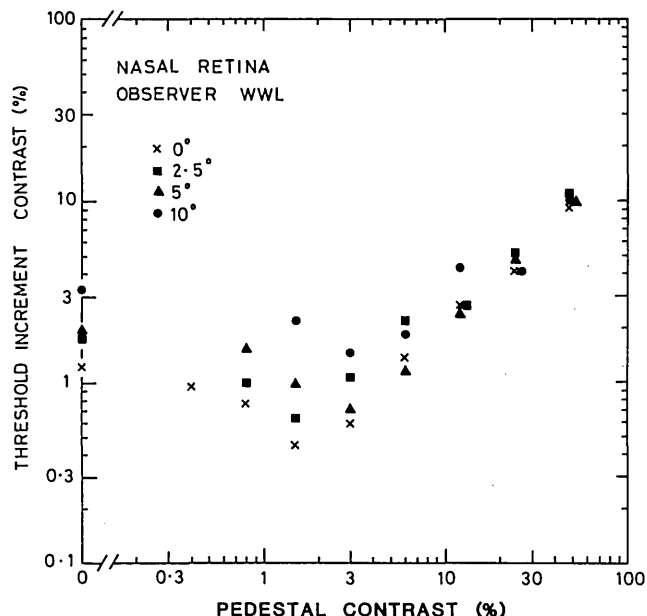


Fig. 3. Same as Fig. 2 but for WWL's nasal retina. Data were not collected at 20° nasal because the targets would have fallen within WWL's blind spot.

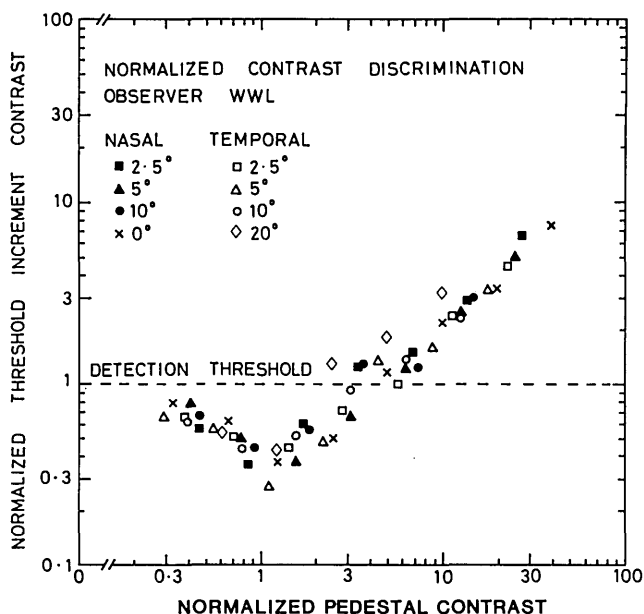


Fig. 4. The data of Figs. 2 and 3 have been replotted following normalization of both the increment-threshold contrast and the pedestal contrast by the contrast at detection threshold for the retinal locus in question. A normalized contrast of 1 corresponds to the contrast at detection threshold. Thresholds at different retinal eccentricities tend to cluster together and lie along the same dipper-shaped function.

nation functions from Figs. 2 and 3 have been replotted with increment thresholds and pedestal contrasts divided by the appropriate detection threshold. In these normalized coordinates, a value of 1.0 refers to the contrast at detection threshold. In Fig. 4, the data of the eight curves cluster closely together. They all follow the same dipper-shaped contrast-discrimination function. From this, we conclude that, when scaled by the local contrast sensitivity, contrast-discrimination functions are qualitatively and quantitatively similar in central and peripheral vision.

Figure 5 shows normalized data for subject RC for 0° and four locations in temporal retina. Her results are very similar to those of subject WWL.

We turn briefly to two quantitative features of the data. First, note that the dip in the contrast-discrimination function reaches its minimum at a normalized pedestal contrast near 1. This means that the lowest-increment threshold occurs when the pedestal contrast itself is at detection threshold. At this point, the increment threshold is two to three times small than the detection threshold. Second, data for suprathreshold pedestal contrasts can be fitted by straight lines in log-log coordinates. A slope of 1.0 would represent adherence to Weber's law. Several studies have reported slopes less than one for foveal contrast-discrimination functions.¹⁴ As listed in Table 1, the slopes of lines fitted to our data did not vary in any systematic way with retinal eccentricity. Least-squares fits yielded mean slopes

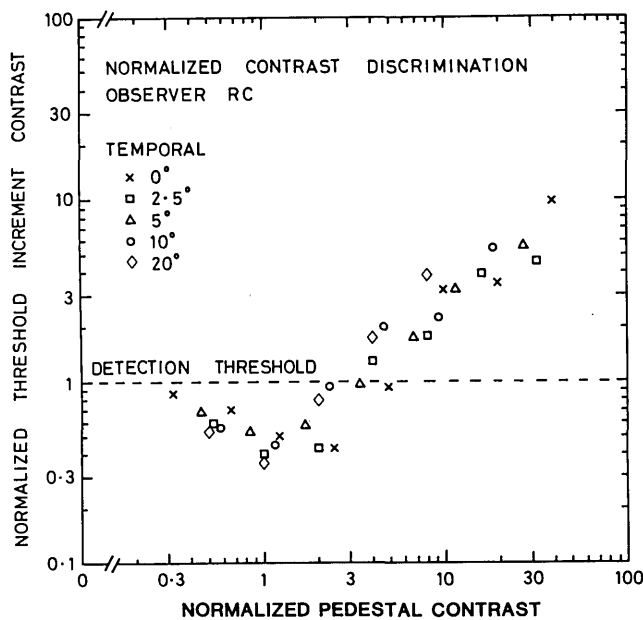


Fig. 5. Normalized data such as those in Fig. 4 but for observer RC.

Table 1. Contrast-Discrimination Functions: Mean Slopes^a

Retinal Position (°)	Subjects	
	WWL	RC
0	0.88	0.92
Temporal		
2.5	0.84	0.79
5	0.89	0.83
10	0.70	0.84
20	0.91	1.13
Nasal		
2.5	0.79	
5	0.94	
10	0.72	
Mean	0.83	0.90
Standard error	0.03	0.06

^a For suprathreshold pedestal contrasts, we found the best-fitting straight line (least squares criterion) relating increment threshold to pedestal contrast in log-log coordinates. The table contains means of the resulting slopes.

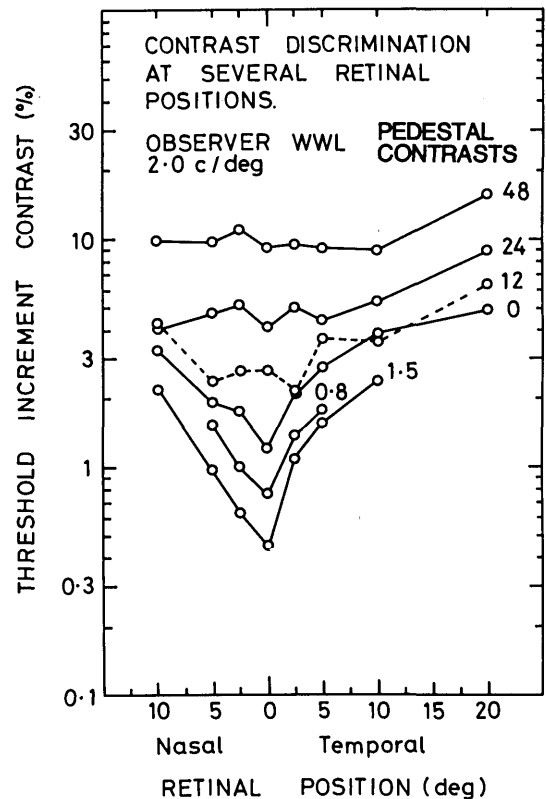


Fig. 6. Threshold-increment contrast is plotted as a function of retinal position for several pedestal contrasts. The data are for observer WWL. Notice that the curves are much flatter for high-contrast pedestals than for near-threshold pedestals or for detection (a pedestal of 0).

and standard errors of 0.83 ± 0.03 and 0.90 ± 0.06 for our two subjects. These slopes are a little higher than values found by Legge¹⁴ for full-field 2-c/deg gratings but close to values reported by Bradley and Ohzawa¹⁵ for foveal viewing of 4-c/deg gratings (0.88) and Swanson and Wilson²³ for 2-c/deg D6 patterns (0.80) at 8°.

In Fig. 6, WWL's data have been replotted as increment threshold versus retinal position with the pedestal contrast as a parameter. The curve labeled 0 shows the contrast-detection threshold for a 2-c/deg patch at different retinal eccentricities. It has a minimum at 0° and rises systematically in both directions. The variation in sensitivity is in relatively good agreement with similar measurements by Wilson and Giese²⁵ and Robson and Graham.²⁶ According to a formula derived by Wilson and Giese from their data, the reduction in contrast sensitivity for a grating target located N grating periods from the point of fixation is given by $\exp(-0.058N)$. The sensitivities of our subjects declined a little more slowly than predicted by this formula. Instead of a reciprocal space constant of 0.058, we found values of 0.035 (subject WWL, nasal and temporal) and 0.04 (subject RC, nasal). Our calculation of the corresponding value for the 3.0-c/deg data of Robson and Graham²⁶ gives 0.04.

In Fig. 6, the lowest curve on the graph represents data for a pedestal contrast of 1.5%. For this case, the increment threshold rises more rapidly with eccentricity than the detection curve. On the other hand, at high pedestal contrasts, the opposite is true. The curves become flatter. The top curve refers to a pedestal contrast of 48% and is almost flat. This means that the increment threshold is almost independent of eccentricity, increasing by a factor of only

about 1.5 from 0° to 20°. Functionally speaking, the peripheral retina is just about as good as the fovea for making discriminations among high-contrast targets. This result is reminiscent of the approximate contrast constancy revealed by studies of contrast matching³ and contrast-magnitude estimation.¹

The near equality of high-contrast increment thresholds from fovea to periphery in the face of substantial changes in the detection threshold is consistent with the shape invariance of the contrast-discrimination function. To understand this, first recall that the discrimination functions at different retinal eccentricities differ only by a contrast-scale factor. The scaling operation acts like a contrast attenuator; it changes the contrast of the increment and the pedestal by the same factor. Now suppose that Weber's law holds exactly for the rising portions of the contrast-discrimination functions. Weber's law requires that, at threshold, the ratio $\Delta C/C$ remains constant. The contrast-scaling operation associated with a shift from a curve at one retinal eccentricity to another leaves this ratio unchanged. Therefore increment thresholds (and the Weber fraction) would be independent of retinal eccentricity. In fact, increment thresholds do not rise as quickly as Weber's law predicts. Thus increment thresholds rise slightly with increasing eccentricity. In the neighborhood of the dip, near threshold, there is not even an approximate adherence to Weber's law, so the near equality in thresholds across the retina breaks down altogether.

The shape invariance of contrast-discrimination functions in peripheral vision suggests that the underlying processes of contrast coding are similar across the retina. The only effect of retinal eccentricity is a change of scale that is tied to the local contrast sensitivity. It is possible that the change in contrast sensitivity across the retina may be related to the area of innervated cortex.¹⁹ Scaling by the cortical magnification factor is fully consistent with our findings for contrast discrimination.

In summary, contrast-discrimination functions for 2-c/deg grating patches have the same shape from 0° to 20° of retinal eccentricity and differ only by a change of scale. The scale factor is just the detection threshold or, equivalently, the contrast sensitivity at the retinal location in question. To the extent that contrast discrimination reveals principles of visual contrast coding, we conclude that the coding process is similar out to 20°. A functional consequence of these findings is that discrimination thresholds for high-contrast targets show relatively little effect of retinal eccentricity, while discrimination thresholds for low-contrast targets are substantially affected by retinal eccentricity.

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