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A POWER LAW FOR CONTRAST DISCRIMINATION

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Abstract—*Contrast increment thresholds* were measured as a function of the background contrast of suprathreshold *sine wave gratings* at 2 and 8 c/deg. The resulting *contrast discrimination functions* obey *power laws* with exponents near 0.6 at 2 c/deg, and 0.7 at 8 c/deg. These exponents are influenced only slightly by pattern adaptation, gated vs continuous background gratings, and the psychophysical method. Weber's Law does not hold for contrast discrimination under any of the conditions studied.

INTRODUCTION

Contrast discrimination experiments provide an important means for studying the visual system's response to suprathreshold contrast. In such experiments, observers are typically required to discriminate between two sine wave grating stimuli that differ only in their contrasts, C and $C + \Delta C$. The smallest value of ΔC that allows for a reliable discrimination may be termed the *contrast increment threshold*. The contrast level C may be termed the *background contrast*. The relationship between the contrast increment threshold ΔC and background contrast C may be termed the *contrast discrimination function*. The shape of the contrast discrimination function and its dependence on a variety of stimulus parameters may provide important clues to the way suprathreshold contrast is encoded in the visual system.

There have been several studies of sine wave grating contrast discrimination, but the results are not in full agreement. The discrepancies may arise from differences in experimental procedures or stimulus parameters. The current study was designed to measure contrast discrimination functions for a number of experimental conditions.

The contrast discrimination function is dipper-shaped. As background contrasts increase from 0, the increment threshold drops below the detection threshold before beginning to rise with background contrast (Campbell and Kulikowski, 1966; Nachmias and Sansbury, 1974; Stromeyer and Klein, 1974). This "dip" in the contrast discrimination function may be described as a facilitation effect for which the increment threshold is actually lower than the detection threshold. The facilitation effect, however, is confined to very low background contrasts. Foley and Legge (1981) and Legge and Foley (1980) have examined this effect in some detail.

When background contrast exceeds some very low value, increment thresholds rise steadily with background contrast. However, there exists considerable uncertainty about the shape of the contrast discrimination function over the rising part of its course. There is further uncertainty about the way various stimulus parameters affect the shape of the function. Of particular interest is the question, whether suprathreshold contrast discrimination obeys Weber's Law. In other words, does the contrast increment threshold rise in proportion to background contrast?

There is one situation involving contrast in which there is little doubt that Weber's Law holds. Under a variety of experimental conditions, It has been found that the threshold contrast for the detection of sine wave gratings in visual noise rises in proportion to the RMS contrast of the noise (Pollehn and Roehrig, 1970; Stromeyer and Julesz, 1972; Pelli, 1980). However, the factors that limit grating detection in noise may be rather different from the factors that limit contrast increment detection (see the Discussion below).

Typically, measured contrast discrimination thresholds are plotted against background contrast in log-log coordinates. The rising part of the contrast discrimination function is summarized by the best-fitting straight line through the data. The slope of the line is an index of the shape of the contrast discrimination function, since it represents the exponent of a power function relation between increment threshold ΔC and background contrast C:

$$\Delta C = kC^N.$$

The exponent N is the slope of the best-fitting straight line in log-log coordinates, and k is a sensitivity parameter. A value of N of 1.0 represents Weber's Law performance. Values of N less than 1.0 mean that the contrast increment threshold rises more slowly than the background contrast, and hence the Weber fraction $\Delta C/C$ grows progressively smaller.

Several studies have indicated that the contrast increment threshold rises more slowly than background contrast. Nachmias and Sansbury (1974) and Tolhurst and Barfield (1978), both using the two-alternative forced-choice technique, found this result at 3 and 4.5 c/deg respectively. Pantle (1974) found values of the power function exponent N of 0.47 and 0.69 for contrast discrimination at 2 and 10 c/deg respectively. Pelli (1979) found an exponent of approximately 0.5 for contrast discrimination at 4 c/deg. Legge (1979) measured monocular contrast discrimination functions at spatial frequencies ranging from 0.25 to 16 c/deg. The largest value of N was 0.70 at 16 c/deg, still well below Weber's Law. Legge and Foley (1980) have examined the relationship between ΔC and C when the increment grating differed in spatial frequency from the background grating. This paradigm is usually referred to as *contrast masking*. They found that for masking spatial frequencies within a range of one octave from a 2 c/deg "signal" grating, ΔC increased approximately as $C^{0.6}$. Pantle (1977) in similar experiments found the same value for the exponent. All of these experiments suggest that contrast discrimination does not obey Weber's Law.

Several other studies have found Weber's Law behavior for contrast discrimination. Kulikowski (1976) and Kulikowski and Gorea (1978) have suggested that two factors may be associated with the emergence of Weber's Law behavior: pattern adaptation and a shift from sustained to transient detection at low spatial frequencies. Spatial pattern adaptation is the elevation of contrast thresholds for the detection of a grating of a given spatial frequency after a period of exposure to a high contrast grating of the same spatial frequency (Pantle and Sekuler, 1968; Blakemore and Campbell, 1969). Kulikowski and Gorea (1978) state that complete adaptation to patterned stimuli is a necessary and sufficient condition for Weber's Law for contrast. The second factor pertains to the relative importance of sustained and transient mechanisms for detection at high and low spatial frequencies. There exists a good deal of evidence that grating detection at low spatial frequencies is accomplished by mechanisms sensitive to stimulus transients, and that detection at higher spatial frequencies is accomplished by mechanisms sensitive to sustained (steady) signals (see e.g. Kulikowski and Tolhurst, 1973; Legge, 1978). Kulikowski and Gorea (1978) argue that pattern adaptation at low spatial frequencies may not result in Weber's Law because the relevant transient mechanisms are little stimulated by steady state adapting patterns. These considerations suggest that three factors may influence the shape of the contrast discrimination function, spatial frequency, the extent of pattern adaptation, and the temporal properties of the contrast increment and the background pattern.

A common paradigm for studying contrast discrimination has been to first pattern adapt the observer to the continuously present background contrast, and then measure the increment threshold. The temporal waveform of the contrast increment may be a square pulse or sinusoidal modulation. Using the former, Campbell and Kulikowski (1966) found Weber's Law behavior at 10 c/deg for contrast discrimination. Using the latter, Bodis-Wollner *et al.* (1972) found a slight, downward departure from Weber's Law at 6 c/deg. Bodis-Wollner *et al.* (1973) found Weber's Law to hold at 12 c/deg and growing departures from it as spatial frequency was decreased to 1.5 c/deg. Kulikowski (1976) measured contrast discrimination with and without pattern adaptation to the background grating. At 5 c/deg, pattern adaptation increased the exponent only from 0.74–0.88. According to Kulikowski, Weber's Law was not achieved, even in the presence of adaptation, because the 0.5 Hz modulation of the increment was detected by transient mechanisms, sensitive at 5 c/deg, that had not been pattern adapted. At 15 c/deg, he found that pattern adaptation increased the contrast discrimination exponent from 0.84–1.03. In a similar experiment, Kulikowski and Gorea (1978) have demonstrated that pattern adaptation can increase the exponent of the contrast discrimination function.

In apparent contradiction to the foregoing results with adaptation, Barlow *et al.* (1976) found very little effect of pattern adaptation on contrast discrimination. They measured successive and simultaneous contrast discrimination thresholds with and without adaptation to a high contrast grating at 6 c/deg. Only slight increment threshold elevations were observed. Pelli (1979) measured contrast discrimination over a wide range of grating contrasts at 4 c/deg with and without adaptation to a grating of 90% contrast. He found that adaptation elevated discrimination thresholds only over a range of very low background contrasts. He found no effect of adaptation upon contrast discrimination when the background contrast exceeded the adapted threshold. Pantle's (1974) method involved exposing observers to a continuously present background, a situation in which pattern adaptation would be expected to occur. Nevertheless, he did not find even a close approach to Weber's Law at 2 or 10 c/deg.

The experiments in which the effects of pattern adaptation have steepened the contrast discrimination function have generally used the method of adjustment (Kulikowski, 1976; Kulikowski and Gorea, 1978) while those that have found less effect have used two-alternative forced-choice (Pelli, 1979; Pantle, 1974). It might be argued that pattern adaptation leads to response criterion changes in the method of adjustment that are not present in the two-alternative forced-choice procedure, thereby accounting for the discrepancy in findings.

The exponents of the contrast discrimination function may more closely approach the Weber's Law value of 1.0 at higher spatial frequencies. Carlson and Pica (1979) briefly report that Weber's Law holds for contrast discrimination above 12 c/deg.

There is even a report of a nonmonotonicity in the contrast discrimination function at high contrasts. Kohayakawa (1972), using a spatial contrast discrimination paradigm and the method of adjustment at 2.1 c/deg, found that the increment threshold reached a peak for background contrasts of about 25% and thereafter declined.

In the face of these diverse findings, we are left with several unanswered questions. (1) Is contrast discrimination affected by pattern adaptation? (2) Do properties of contrast discrimination depend on the relative balance between transient and sustained detecting mechanisms? (3) Does spatial frequency influence the shape of the contrast discrimination function? (4) Do the methods of adjustment and two-alternative forced-choice yield different shapes for the contrast discrimination function? These questions were addressed in the experiments to be reported in this paper.

METHOD

Apparatus

Vertical sine wave gratings were produced on the face of an HP 1300A X-Y display by Z-axis modulation (Campbell and Green, 1965). The display had a P31 phosphor with a constant mean luminance of 10 cd/m^2, and a dark surround. At the viewing distance of 114 cm, the screen subtended 13° horizontally by 10° vertically. Experiments were conducted at 2 and 8 c/deg. Photometric calibration ensured that all grating contrasts were kept within a range for which the display's luminance contrast was linearly related to Z-axis voltage.

Sinusoidally varying voltages were produced by an HP 3312A function generator. The function generator's output was routed through three buffered paths, whose corresponding voltage amplitudes were separately controlled by dB attenuators. The three output voltages provided *adapting*, *background*, and *increment* gratings, identical in frequency and phase, and differing only in contrast. A set of four timer-controlled switches, linked together in a "timing chain", provided accurate timing and sequencing of stimuli.

Procedure

Contrast increment thresholds ΔC were measured by a version of the temporal two-alternative forced-choice staircase procedure (Wetherill and Levitt, 1965). The background grating of contrast C was present in both intervals of a trial. The contrast increment ΔC was assigned at random to one of the two intervals. The intervals were 200 msec long, separated by 600 msec, and were marked by auditory tones. Prior to a block of forced-choice trials, the observer was presented with a series of trials in which he adjusted the increment contrast to a conservatively high estimate of threshold by turning a hand-held potentiometer. The observer was told to adopt a constant criterion for these adjustment settings throughout the series of experiments. These adjustment settings were recorded. The observer was then given a series of forced-choice trials. In each trial, the observer was required to identify the interval in which the contrast increment occurred. Three correct choices at one contrast level were followed by a one dB reduction in the increment contrast. An incorrect choice was followed by a one dB increase in the increment contrast. Feedback was provided. The mean of the first six contrast peaks and valleys in the resulting sequence was taken as the forced-choice estimate of the increment threshold.

A session consisted of obtaining adjustment and forced-choice increment threshold estimates for a series of background contrasts. At 2 c/deg, the background contrasts were 0, 0.75, 1.5, 3.0, 6.0, 12, 24 and 48%. At 8 c/deg, background contrasts were 0, 1.0, 2.0, 4.0, 8.0, 16 and 32%. Four sessions were conducted with each observer under each of the experimental conditions. Adjustment and forced-choice thresholds were computed as the geometric means of the four threshold estimates so obtained. The data in Figs 2 and 3 are the forced-choice geometric means. Standard errors of the forced-choice estimates were typically 5 to 10%, and rarely exceeded 15%. The standard errors were slightly larger for the adjustment thresholds.

Contrast discrimination functions were measured in five experiments. Consult Fig. 1.

A sixth experiment was a control to measure detection threshold as a function of adaptation contrast.

Gated background. The background grating was gated on only during the two 200 msec intervals of the trial. Since the increment was added to the background in only one interval, the observer's task amounted to discriminating between two briefly pulsed gratings, one of contrast C and the other of contrast $C + \Delta C$.

Gated background and background adaptation. Prior to a series of trials, the observer was pattern adapted for 4 min to a grating whose contrast was equal to the background grating's contrast. The observer was told to continually scan back and forth across the adapting pattern in order to minimize the formation of negative after-images. A trial consisted of turning off the adapting pattern for 600 msec before the first exposure interval and turning it on again 600 msec after the second exposure interval. Typically, 10–20 sec intervened between trials. The intent of the experiment was to measure contrast increment thresholds under conditions of adaptation to the prevailing background contrast.

Continuous background. In this experiment, the background grating was turned on 600 msec before the first interval and remained on until 600 msec after the second interval. The observer's task was to detect an increment in the steady background during one of the 200 msec intervals. The experiment was designed to measure increment thresholds on a steady background, in the absence of pattern adaptation.

Continuous background and background adaptation. During the entire block of trials, a steady background was present. Prior to the block of trials, the observer was given 4 min of adaptation to this grating.

Gated background with fixed adaptation. Contrast discrimination functions were measured with gated backgrounds, but subject to pattern adaptation at the fixed level of 24%. This high contrast was approximately 2 log units above contrast threshold.

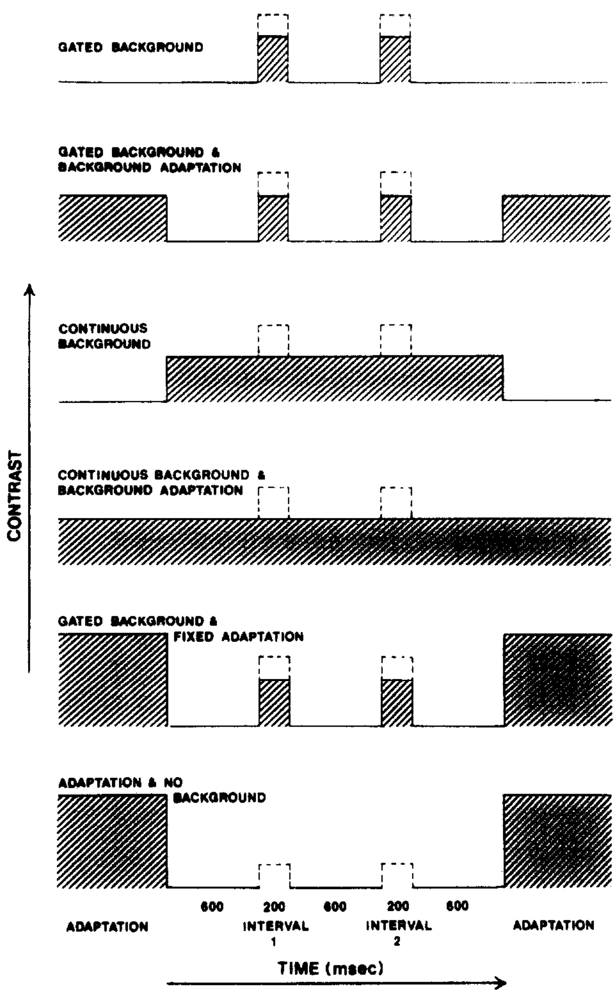

Fig. 1. Temporal waveforms of the stimuli used in the six experiments. A discrimination trial consisted of two 200 msec intervals separated by 600 msec. Except in the *adaptation and no background* condition, the background grating was present in both intervals. An increment was added to the background in one of the two intervals. Adapting gratings, when present, preceded and followed the trial. The *adapting*, *background* and *increment* gratings were identical, except for contrast. Experiments were conducted at 2 c/deg and 8 c/deg.

Adaptation and no background. A control experiment was conducted to measure contrast detection threshold as a function of adapting contrast. After four minutes pattern adaptation at a given contrast, test trials were run in which the adapting patterns were switched off 600 msec before the first exposure interval, and back on again 600 msec after the second exposure interval. Observers were required to detect the presence of the grating that appeared in one of the intervals.

Observers

Two females in their early twenties served as observers. LA was emmetropic. JS wore her $-3D$ myopic correction throughout. Viewing was binocular with natural pupils and no fixation point. The observers were well practiced with the psychophysical task, but naive to the details of the experiment.

RESULTS

Figure 1 schematically depicts the time course of the stimuli in the six experiments. Figures 2 and 3 present the forced-choice data for 2 c/deg and 8 c/deg respectively.

Each point is the geometric mean of four threshold estimates, each derived from a forced-choice staircase. In Figs 2 and 3, separate panels present the data for observers LA and JS. Contrast increment thresholds are plotted as a function of the background contrast in log-log coordinates. The five symbols represent five experimental conditions. (The sixth experimental condition was a control and will be discussed below.) The

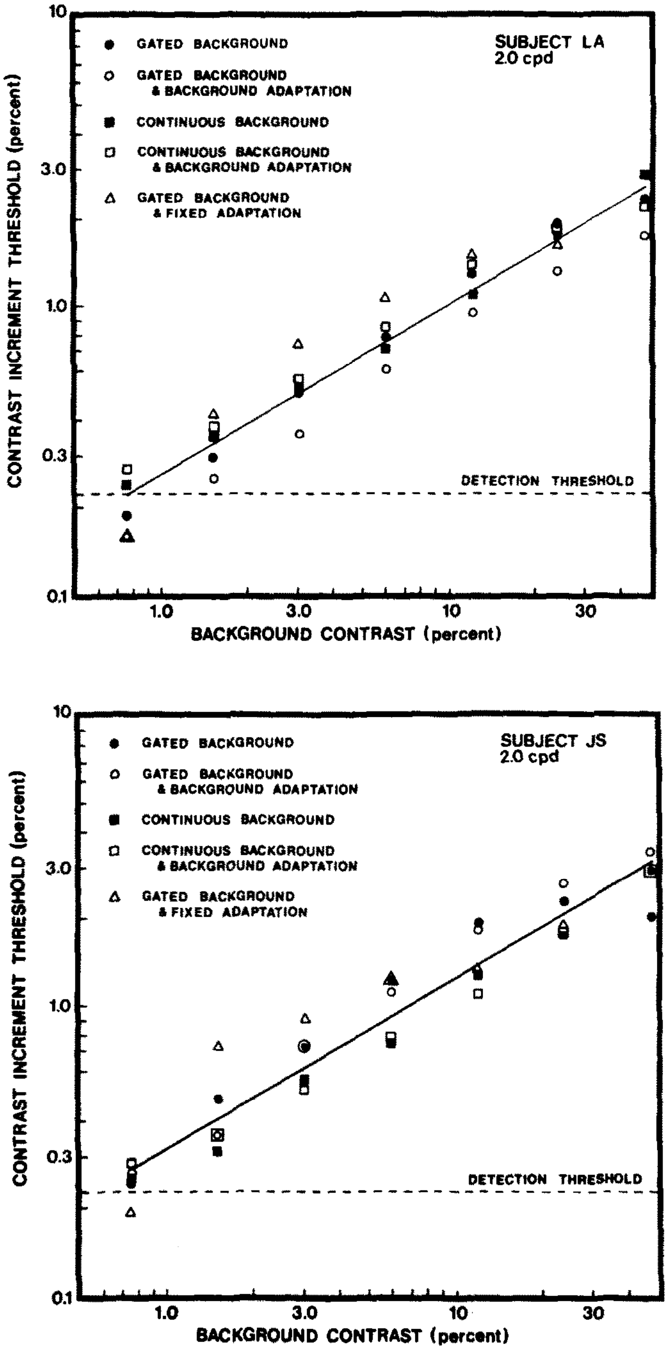

Fig. 2. Contrast discrimination functions at 2 c/deg. Increment threshold contrasts are plotted as a function of background contrast for five experiments. Data points are the geometric means of 4 threshold estimates, each derived from a block of forced-choice trials. Standard errors were almost always less than 10%. The two panels show separate results for observers LA and JS. The horizontal dashed lines are drawn at the observers' detection thresholds. The oblique lines through the data of slope 0.59, are best fitting straight lines, computed across the five experimental conditions. Separate slopes for the 5 sets of data for each observer are presented as power function exponents in Table 1.

horizontal dashed lines are drawn at ordinate values corresponding to the observers' detection thresholds in the absence of adapting or background gratings.

For each experimental condition, the best-fitting straight line (least squares criterion) to the points in log-log coordinates was found. The slopes of these lines are exponents of power function fits to the contrast discrimination functions. These exponents are given in Table 1, with the standard error of estimate, computed by the formula of Mansfield (1973).

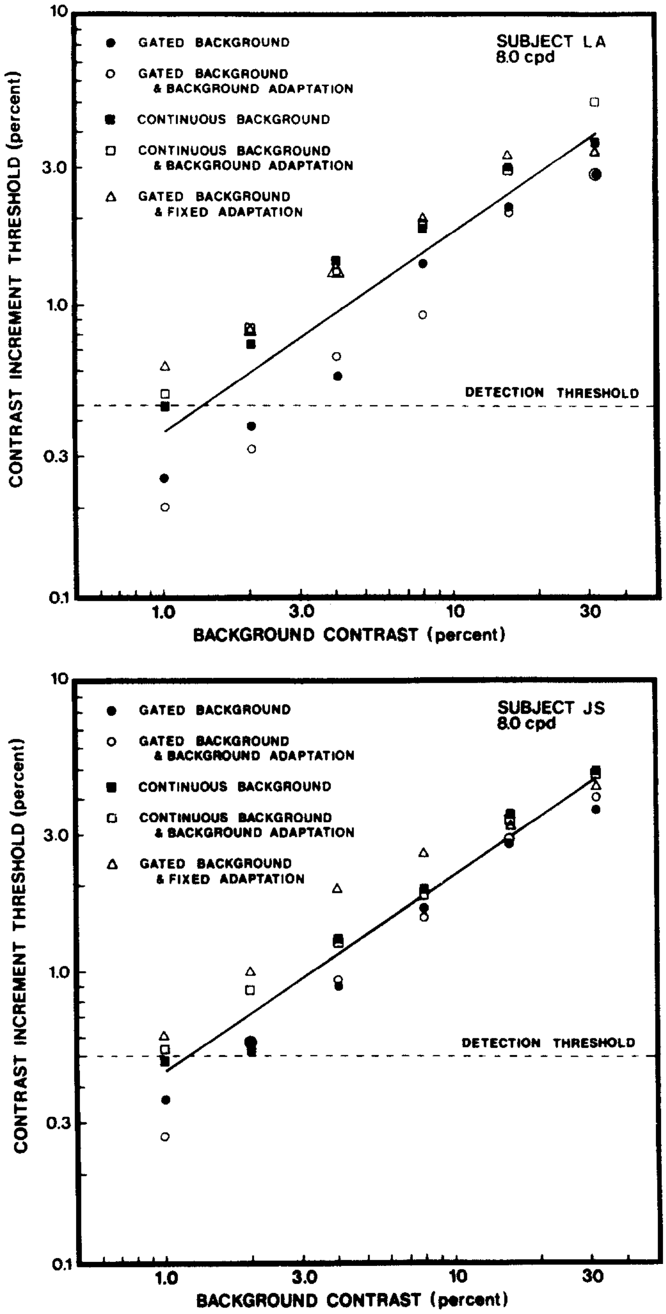

Fig. 3. Contrast discrimination functions at 8 c/deg. The details are as in Fig. 2, except that the oblique lines through the data have slope 0.68.

In Figs 2 and 3, the oblique solid lines are best fits, computed across all the data for both observers. They have slopes of 0.59 and 0.68 at 2 and 8 c/deg respectively.

Some of the sets of data in Figs 2 and 3 appear to be vertically shifted with respect to others. Accordingly, the mean vertical shift for each set of data was computed relative to the *gated background* condition. These values are given in Table 1 in the columns headed *relative threshold*. In effect, these values are vertical scaling factors. For instance, a value of 1.18 means that the contrast increment thresholds for the condition in question were, on average, 1.18 times higher than the contrast increment thresholds in the *gated background* condition.

Table 1 also presents the corresponding summary data for the adjustment settings. They will be discussed below.

The contrast discrimination functions obtained with the *gated background* may be taken as measurements to which the remaining measurements will be compared. See the top panel in Fig. 1 and the filled circles in Figs 2 and 3. These data are well approximated by straight lines in log-log coordinates. At

Table 1. Exponents of the contrast discrimination functions

Condition	Observer	Procedure	2.0 c/deg Exponent	2.0 c/deg SE	2.0 c/deg Relative threshold	8.0 c/deg Exponent	8.0 c/deg SE	8.0 c/deg Relative threshold
Gated background	LA	2AFC	0.62	0.03	1.0	0.75	0.06	1.0
	JS	2AFC	0.55	0.07	1.0	0.70	0.03	1.0
	LA	adjustment	0.53	0.06	1.83	0.77	0.06	2.89
	JS	adjustment	0.67	0.06	1.96	0.73	0.07	2.46
Gated background and background adaptation	LA	2AFC	0.59	0.02	0.76	0.79	0.04	0.90
	JS	2AFC	0.66	0.04	1.04	0.78	0.04	0.98
	LA	adjustment	—	—	—	0.66	0.02	1.62
	JS	adjustment	0.63	0.04	1.36	0.77	0.02	1.36
Continuous background	LA	2AFC	0.59	0.02	1.05	0.62	0.05	1.66
	JS	2AFC	0.60	0.02	0.81	0.73	0.06	1.25
	LA	adjustment	0.45	0.02	1.31	0.77	0.04	2.75
	JS	adjustment	0.59	0.03	1.34	0.76	0.05	1.95
Continuous background and background adaptation	LA	2AFC	0.54	0.03	1.12	0.65	0.01	1.80
	JS	2AFC	0.57	0.03	0.82	0.64	0.02	1.35
	LA	adjustment	0.59	0.04	1.64	—	—	—
	JS	adjustment	0.55	0.03	1.20	0.70	0.03	2.08
Gated background and fixed adaptation	LA	2AFC	0.65	0.10	1.18	0.54	0.05	1.78
	JS	2AFC	0.56	0.13	1.06	0.57	0.06	1.56
	LA	adjustment	0.44	0.08	3.28	0.36	0.06	3.24
	JS	adjustment	0.52	0.11	1.50	0.51	0.09	2.63

2 c/deg, the slopes of the best fitting straight lines are 0.62 ± 0.03 and 0.55 ± 0.07 for observers LA and JS respectively. At 8 c/deg, the corresponding slopes are 0.75 ± 0.06 and 0.70 ± 0.03. Accordingly, at both spatial frequencies, the contrast discrimination functions can be represented by power functions with exponents well below 1.0. This result confirms previous contrast discrimination experiments, conducted with gated backgrounds and the two-alternative forced-choice procedures (Nachmias and Sansbury, 1974; Tolhurst and Barfield, 1978; Pelli, 1979; Legge, 1979; Legge and Foley, 1980).

When comparing the remaining four sets of data in Figs 2 and 3 to the *gated background* condition, the most striking observation is the similarity of results. Apparently, contrast discrimination is largely insensitive to the procedural and stimulus manipulations carried out. The effects of pattern adaptation and continuous vs gated background that do occur appear to be small. All the exponents summarized in Table 1 have values well below 1.0, indicating that Weber's Law behavior was never observed, and that contrast increment thresholds rose more slowly than background contrast in all of the experimental conditions. Finally, the exponents obtained with the method of adjustment, although slightly more scattered, do not deviate systematically from those obtained with the two-alternative forced-choice procedure.

Effects of pattern adaptation on contrast discrimination

Two experiments were conducted to assess the effects of pattern adaptation on contrast discrimination with gated backgrounds. In the first experiment, observers were pattern adapted to a grating having the same contrast as the background grating. The adapting grating was turned off during the contrast discrimination trial. See the second panel in Fig. 1. The forced-choice results are represented by the open circles in Figs 2 and 3. This form of pattern adaptation had no consistent effect at 2 c/deg. At 8 c/deg, the contrast discrimination exponents (Table 1) are slightly higher for the adaptation condition, 0.79 and 0.78, than for contrast discrimination in the absence of adaptation, 0.75 and 0.70.

Perhaps pattern adaptation to a high, fixed contrast would have a greater effect on contrast discrimination than adaptation to gratings whose contrast rises in step with the background contrast. The fifth panel in Fig. 1 schematically represents an experiment in which gated background contrast discrimination was measured when the adapting grating was kept at a constant contrast of 24%. The forced-choice results are shown by the triangles in Figs 2 and 3. The power function exponents at 2 c/deg are again unaffected by adaptation. However, high contrast adaptation produced small elevations in increment thresholds for both observers, 18% for LA and 6% for JS. This small effect is approximately the same size reported by Barlow *et al.* (1976). At 8 c/deg, high contrast adaptation actually reduced the exponents of the contrast discrimination functions. Adaptation tended to elevate increment thresholds more at low background contrasts than at high background contrasts, in qualitative agreement with similar findings of Pelli (1979). Over all, the contrast increment thresholds were 50–75% higher for the case of high contrast adaptation at 8 c/deg than for the case of no adaptation, with the effect being more pronounced at low compared with high contrasts.

These results suggest that the effects of high contrast adaptation are manifest only on contrast detection and contrast discrimination at low background contrasts. Low contrast adapting patterns have little effect. It is not surprising, therefore, that pattern adaptation to gratings having a contrast equal to the background contrast has little effect at any contrast. This result would appear to be of practical significance to vision. Apparently, observers' abilities to discriminate small changes in patterned scenes are not reduced by looking at the scenes.

A control experiment was performed to ensure that pattern adaptation was having its usual effect on detection threshold. Daugman and Mansfield (1979) have shown that contrast adaptation decays with a time constant that depends on spatial frequency, about 2.6 sec at 2.4 c/deg, and 3.5 sec at 8 c/deg. Since the discrimination trials in the current experiments required about 1.6 sec in which the adapting pattern was switched off, some significant decay in adaptation would be expected. The effects of adaptation have commonly been measured by adjustment techniques in which settings take much more than 1.6 sec. Nevertheless, as a check, contrast detection thresholds were measured as a function of adapting contrast (bottom panel in Fig. 1). The forced-choice thresholds rose slowly and regularly with adapting contrast, in confirmation of the results of Blakemore and Campbell (1969) and Tolhurst (1972). For the maximum adapting contrast of 24%, forced-choice thresholds were elevated by factors of 2.3 and 2.9 for LA and JS respectively. At 8 c/deg, the 24% adapting contrast caused threshold elevation by factors of 3.3 and 2.4. (The method of adjustment thresholds rose slightly more with adapting contrast. For instance, at 2 c/deg, the high contrast adapting grating produced adjustment threshold elevations by factors of 3.7 and 4.4.) These results ensure that the procedures of the current experiments produced the usual adaptation effects upon the detection threshold.

The effect of the temporal relationship between contrast increment and background

Perhaps contrast discrimination behaves differently when the contrast increment is detected against a continuously present background rather than against a gated background. Such a difference would be expected if contrast increments were detected by visual mechanisms sensitive only to stimulus transients. These mechanisms should be insensitive to continuous backgrounds, but quite responsive to gated backgrounds. As a result, contrast increment thresholds should be lower for continuous backgrounds, and relatively insensitive to background contrast. Since transient mechanisms are believed to affect detection principally at low spatial frequencies, a greater effect should be noticeable at 2 c/deg than at 8 c/deg.

The third panel in Fig. 1 depicts an experiment in which a background grating was switched on 600 msec before a discrimination trial, left on throughout the trial, and switched off 600 msec after the trial. (Such periods of steady exposure to the background have little pattern adaptation effect. Daugman and Mansfield (1979) have shown that pattern adaptation grows exponentially with a time constant of about 6 sec). The experiment measures contrast discrimination thresholds on steady backgrounds in the absence of adaptation. The forced-choice results are shown by the filled squares in Figs 2 and 3. Inspection of Table 1 indicates that there is no consistent difference between the contrast discrimination exponents for gated and continuous backgrounds at either 2 or 8 c/deg. At 8 c/deg, the increment thresholds are a little higher for the continuous background than for the gated background, 66% higher for LA and 21% higher for JS. For LA, the effect of the continuous background at 8 c/deg is analogous to the effect of the high contrast adapting pattern, increment thresholds at low background contrasts were raised more than those at high contrasts, leading to a slightly shallower contrast discrimination function. Over all, the results do not support the idea that contrast discrimination at 2 c/deg relies more heavily on a transient mechanism than contrast discrimination at 8 c/deg.

In the final experiment, observers were continuously exposed to the background grating, even between trials (Fig. 1, fourth panel). Observers were given 4 min of pattern adaptation to the background grating. This experiment combines pattern adaptation with continuous background presentation. The results are given by the open squares in Figs 2 and 3. At 2 c/deg, the combination of adaptation and continuous background produced results that are not systematically different from the results for the *gated background* reference condition. At 8 c/deg, the exponents were slightly lower, and increment thresholds were slightly higher. At 8 c/deg, the combination of adaptation and continuous background elevated thresholds slightly more at low background contrasts than at high background contrasts, accounting for the slightly lower exponents in Table 1.

It is concluded that the contrast discrimination functions at 2 c/deg are unaffected by a change from a gated to a continuous background. At 8 c/deg, the exponents of the contrast discrimination functions are slightly lower for continuous backgrounds than for gated backgrounds, the effect being principally due to a small threshold elevation that is more pronounced at low background contrasts.

The effects on contrast discrimination of the psychophysical procedure: method of adjustment and two-alternative forced-choice

Contrast discrimination functions derived from the method of adjustment are summarized in Table 1 by the power function exponent and relative threshold parameter. At 2 c/deg, the mean ratios of forced-choice to adjustment exponents, computed across experimental conditions, are 1.23 ± 0.11 and 0.98 ± 0.05 for LA and JS respectively. At 8 c/deg, the corresponding mean ratios are 1.12 ± 0.16 and 1.0 ± 0.04. Apparently, the contrast discrimination exponents computed from the adjustment data are, on average, almost identical to those computed from two-alternative forced-choice data. There is only a slight hint that LA's forced-choice exponents are a little higher than her adjustment exponents. The relative thresholds (Table 1) are much higher for the adjustment data than for the forced-choice data. The difference is largely an artifact of the measurement procedure, in which initial conservative adjustment settings were made prior to the forced-choice staircase.

It may be concluded that the forced-choice and method of adjustment procedures do not lead to important differences in the exponents of the contrast discrimination functions.

The effect of spatial frequency on contrast discrimination

The mean exponent for contrast discrimination at 2 c/deg, averaged across experimental conditions and observers, is 0.59. The corresponding mean exponent at 8 c/deg is 0.68. At 2 c/deg, contrast discrimination is largely impervious to pattern adaptation and to the distinction between gated and continuous backgrounds. At 8 c/deg, continuous backgrounds and high contrast adaptation have similar small effects. Both tend to elevate contrast discrimination thresholds, the effects being slightly larger at low contrasts than at high. The consequence is that the contrast discrimination functions are slightly shallower and the corresponding exponents in Table 1 are slightly lower.

DISCUSSION

In a variety of experimental conditions reported here, Weber's Law was not observed for contrast discrimination. Can these findings be reconciled with reports of Weber's Law behavior in the literature?

Weber's Law seems well established for the detection of sine wave gratings as a function of noise contrast. This result is not inconsistent with a violation of Weber's Law for contrast discrimination. The simple model for contrast detection, discrimination and masking proposed by Legge and Foley (1980) accounts for both sets of phenomena. According to their model, the shape of the rising portion of the contrast discrimination function is accounted for by a compressive nonlinearity, termed the *nonlinear transducer*. According to the model, a contrast discrimination function with power law exponent 0.6 would result from the action of a compressive nonlinearity whose output rises as the 0.4 power of input amplitude, with Gaussian noise added to the output. Contrast discrimination amounts to sampling the output of such a device in both intervals of a forced-choice trial, and choosing the interval with the largest value. However, in a detection task, the nonlinearity becomes transparent when performance is limited by noise added *before* the nonlinearity (Lasley and Cohn, 1979). In this case, a fixed level of detection performance will be determined by a fixed signal to noise ratio, and Weber's Law will result. Such an analysis appears appropriate for the detection of sine wave gratings in visual noise.

Legge and Foley's nonlinear transducer model accounts for the power law of contrast discrimination and for Weber's law for sine wave grating detection in noise, but it does not account for contrast magnitude estimation results. The nonlinear transducer's exponent of 0.4 is less than exponents derived from contrast magnitude estimation data, for instance, 0.7 according to Gottesman *et al.* (1980), or 1.0 according to Cannon (1979). The reason for this discrepancy is not known, but may be related to the growth of internal noise. A similar problem exists in reconciling brightness estimates and photopic luminance increment detection data, and has been treated in some detail by Mansfield (1976).

The findings of this paper are not consistent with the idea that pattern adaptation results in Weber's Law. Pattern adaptation had little effect at 2 c/deg, and if anything, lowered the contrast discrimination exponents at 8 c/deg. It might be argued that pattern adaptation desensitized sustained mechanisms, but left the transient mechanisms available to detect contrast increments. However, if this were the case, it is to be expected that gated backgrounds should yield much higher discrimination thresholds than continuous backgrounds and that the contrast discrimination functions should be much flatter for continuous backgrounds. These effects should be more pronounced at 2 c/deg than 8 c/deg. In fact, at 2 c/deg, there was very little difference between contrast discrimination with gated and continuous backgrounds.

The discrepancies between the findings of this paper and those of Kulikowski and Gorea (1978) are puzzling. In one condition, their observer pattern adapted to a steady 7.5 c/deg grating, and used the method of adjustment to set the threshold for a repetitive on-off (0.5 Hz) increment. This procedure is highly similar to the *continuous background and adaptation* condition of the current paper at 8 c/deg. Whereas Kulikowski and Gorea's observer yielded a contrast discrimination function with exponent 1.0 ± 0.06, the two observers in the current paper yielded exponents of 0.65 ± 0.01 and 0.64 ± 0.02. At 5 c/deg, however, Kulikowski and Gorea measured contrast discrimination for two observers and found exponents of 0.82 and 0.7, more nearly in agreement with the exponents found in Table 1 of this paper.

As discussed in the introduction, the overall contrast discrimination function is dipper-shaped, with the "dip" occurring for very low contrast backgrounds. The data in Figs 2 and 3 lie along the "handle" of the dipper. Legge (1979) has noted that the contrast discrimination function rises steeply from the bottom of the dipper before commencing its steady growth with suprathreshold background contrast. As a result, slopes of straight lines that are fit to data from the bottom of the dipper will be larger than the slopes of lines fit to data corresponding to suprathreshold background contrasts only.

The power law that describes suprathreshold contrast discrimination has an interesting parallel in auditory pure tone intensity discrimination. Over a wide range of suprathreshold intensities, pure tone intensity discrimination obeys a power law with exponent near 0.90 (Jesteadt *et al.*, 1977). McGill and Goldberg (1968a, b) have coined the phrase "the near-miss to Weber's law" to describe this result. Like its contrast counterpart, the exponent associated with the "near-miss" appears to be insensitive to frequency (Jesteadt *et al.*, 1977; Schacknow and Raab, 1973) and to gated vs continuous backgrounds (Green *et al.*, 1979). Considerable theoretical attention has been given to the "near-miss" and attempts have been made to reconcile it with the loudness power function (see e.g. McGill and Goldberg (1968a)).

The following conclusions seem warranted from the experiments reported in this paper. In the spatial frequency range from 2–8 c/deg, contrast discrimination follows a power law relation between contrast increment threshold and background contrast under a variety of stimulus conditions. The exponent of the power law is approx. 0.6 at 2 c/deg and approx 0.7 at 8 c/deg. These exponents are relatively impervious to pattern adaptation, continuous vs gated backgrounds, and the psychophysical procedure used.

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