A POWER LAW FOR PERCEIVED CONTRAST IN HUMAN VISION

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Abstract—The dependence of *perceived contrast* on *stimulus contrast* of sinewave gratings was measured by the method of magnitude estimation. The resulting *perceived contrast functions* are well described by threshold-corrected power functions with exponents near 0.7. The exponents are insensitive to changes in mean luminance from 10–340 cd/m^2, and to changes in spatial frequency from 0.25 to 12 c/deg. The exponents are also insensitive to a change in the range of grating contrasts from 1–2 log units. However, the distribution of contrast levels within the range produces small, but predictable, effects. Several factors are identified that may account for discrepancies in previous measurements of perceived contrast functions.

INTRODUCTION

How is perceived contrast related to stimulus contrast? Some studies have found this relationship, which we may term the *perceived contrast function*, to be linear, while others have found it to be nonlinear. This paper reports results which may help to resolve this discrepancy.

Various aspects of the perception of suprathreshold contrast have been studied by a number of different experimental techniques. Initial investigations used brightness matching (Heinemann, 1955) or magnitude estimation (Stevens, 1961; Bartleson and Breneman, 1967) to measure the brightness of a target as a function of different stimulus contrast conditions. In recent research, observers have been asked to respond to the contrast of sinewave grating stimuli. Brightness profiles based on apparent luminance matching (Bryngdahl, 1966; Springer, 1979) have been measured for different grating contrasts. Reaction time (Harwerth and Levi, 1978) and contrast matching (Davidson, 1968; Watanabe *et al.*, 1968; Blakemore *et al.*, 1971; Blakemore *et al.*, 1973; Georgeson and Sullivan, 1975; Kulikowski, 1976; Cannon, 1979; and Ginsburg *et al.*, 1980) have been used to compare suprathreshold perceived contrast across spatial frequencies. However, none of these methods was principally concerned with measuring the perceived contrast function.

The method of magnitude estimation has been used to study perceived contrast. The technique, in which observers assign numbers that represent the perceived contrast of the stimuli, is the most direct method of measuring the perceived contrast function. The experimental results have shown a lack of agreement. This lack of agreement leaves the form of the perceived contrast function uncertain. Franzen and Berkley (1975) found nonlinear perceived contrast functions, with a power function form, whose exponent varied from 0.58 to 1.71 over a range of 3.5 to 18 c/deg (cycles per degree). Hamerly *et al.* (1977), Cannon (1979) and Ginsburg *et al.* (1980) found linear contrast sensation for contrasts greater than 0.05. At low contrast, Hamerly *et al.*, found positively accelerating nonlinearities, while Cannon found a negative acceleration. Kulikowski (1976) used the method of magnitude production to measure the perceived contrast function. Two of his seven observers showed linear perceived contrast functions.

The different results obtained from experiments using the method of magnitude estimation may be due to stimulus or procedural differences. Our purpose was to measure the perceived contrast function and its dependence on several stimulus and procedural factors. Factors of luminance, spatial frequency, stimulus range and distribution of contrast levels within a range were varied to determine their effects on the form of the perceived contrast function.

METHODS

Apparatus

Vertical sinewave gratings were generated on a Joyce Electronics CRT display, using Z-axis modulation (Campbell and Green, 1965). The display had a P31 phospor. Some experiments were also conducted on an HP 1300A X-Y display also having a P31 phosphor. Sinewave voltages at the Z-axis input were produced digitally by an LSI-11/2 computer. Signal amplitudes were set by a computer-controlled dB attenuator. The computer selected and timed stimuli, and collected and analyzed the data.

Sinewave grating contrast C, is defined as $C = (L_{max} - L_{min})/(L_{max} + L_{min})$ where L_{max} and L_{min} are the maxima and minima in the sinusoidal luminance modulation. Both CRT displays were calibrated with a UDT 80X Optometer. All stimuli were kept within the range for which contrast was linearly related to Z-axis voltage.

Observers sat in a room illuminated by the CRT screen. Prior to experiments, they adapted at least five minutes to the screen luminance. Observers wore their normal spectacle corrections and viewed the screen binocularly with natural pupils. At the viewing distance of 213 cm the screen subtended 6.8° vertically by 8.1° horizontally. When 0.25 c/deg stimuli were used, the viewing distance was reduced to 57 cm. At this distance the screen subtended 24° vertically by 28.1° horizontally.

Procedure

Contrast thresholds and contrast magnitude estimates were obtained from all observers.

Thresholds were measured with a two-alternative forced choice procedure which estimated the 79% correct level (Wetherill and Levitt, 1965). A trial consisted of 500 msec sinusoidal modulation of either the left or right half of the CRT screen, while the unmodulated half was maintained at the same mean luminance level. A narrow translucent divider separated the two halves of the screen. The observer's task was to press one of two keys, indicating on which side of the screen the pattern appeared. A tone notified the observer of a correct choice. Three correct choices at one contrast level were followed by a one dB reduction in grating contrast. An incorrect choice was followed by a 1 dB increase in contrast. The geometric mean of the first six peaks and valleys in the resulting sequence was taken as an estimate of the observer's threshold. Six such estimates were obtained from each observer, three before and three after the magnitude estimation experiment. A t-test showed that no significant difference existed between the initial and final sets of threshold estimates. The mean of the three lowest estimates was taken as a measure of the observer's contrast threshold.

In the magnitude estimation experiment, the observer's task was to assign numbers to sinewave grating stimuli to represent the perceived contrast. All observers received the same instructions from a written script. A modulus-free version of the method of magnitude estimation was used (Marks, 1974). Observers were shown gratings of contrast 0.05 and 0.26 as examples of the stimuli before the magnitude estimation experiment began. Gratings were presented for five seconds with a five second inter-trial interval. Observers entered their numerical estimates on a keyboard. Each observer was presented with a set of 12 contrasts, each repeated four times. The order of stimulus presentation was random except for the following two constraints: (1) the first trial could not be one of the two highest or two lowest contrasts in the set, (2) all 12 stimuli were presented once before the next repetition of the set. Occasionally observers did not detect the lowest contrast grating. In this case, they responded with a special code, and these trials were not used.

Eight groups of observers were used to study the dependence of perceived contrast on grating contrast.

Groups 1–5 were presented with 2.0 c/deg gratings at a mean luminance of 10 cd/m². They differed as follows:

Group 1. The 12 stimuli ranged over 2 log units of contrast from 0.006–0.60 with equal logarithmic contrast steps—0.006, 0.009, 0.014, 0.021 . . . . . 0.6.

Group 2. The 12 stimuli ranged over 2 log units of contrast from 0.006–0.60 with equal linear contrast steps—0.006, 0.060, 0.114, 0.168 . . . . . 0.6.

Group 3. The 12 stimuli ranged over 2 log units of contrast from 0.006–0.60 with equal reciprocal contrast steps—0.006, 0.0066, 0.0073, 0.0082 . . . . . 0.6.

Group 4. The 12 stimuli ranged over approx. 1 log unit of contrast from 0.05–0.60 with equal logarithmic contrast steps—0.05, 0.063, 0.0786, 0.0985 . . . . . 0.6.

Group 5. The 12 stimuli ranged over approx. 1 log unit of contrast from 0.05–0.60 in equal linear contrast steps—0.05, 0.10, 0.15, 0.20 . . . . . 0.6.

Comparing the results of Groups 1, 2 and 3 with those of 4 and 5 shows the effects of 2 vs 1 log unit of stimulus range. Comparisons among Groups 1, 2 and 3 show the effects of the distribution of contrast levels within a given range. On a logarithmic scale, Group 1's stimulus contrasts were equally distributed, Group 2's stimuli were crowded toward the high end of the range, and Group 3's stimuli were crowded toward the low end of the range.

The effects of luminance and spatial frequency were examined with Groups 6, 7 and 8. All three groups received stimulus contrasts ranging over 2 log units (0.006–0.60) in equal logarithmic steps. Mean luminance was 340 cd/m² rather than 10 cd/m². The groups were presented stimuli as follows:

Group 6. The 12 stimuli were presented at 2.0 c/deg.
Group 7. The 12 stimuli were presented at 0.25 c/deg.
Group 8. The 12 stimuli were presented at 12.0 c/deg.

Magnitude estimation experiment: data analysis

Individual and group data were analyzed to determine whether perceived contrast is a power function of stimulus contrast. If this were true, a graph of contrast magnitude estimates S vs stimulus contrast C should result in straight lines in log-log coordinates, and the slope of the line would be equal to the exponent n of the power function.

$$\text{Log } S = n(\text{Log } C) + \text{Log } k \qquad (1)$$

Inspection of the data for individual observers indicated that straight lines were not good fits. There seemed to be two parts to each function with a steeper section at low stimulus levels. This form was suggestive of a threshold-corrected power function: $S = k(C - C_{th})^n$ where S is the contrast magnitude estimate, C is the stimulus contrast, C_{th} is the subject's contrast threshold, and k is the gain constant. This equation is represented by a straight line when S is

plotted vs $C - C_{th}$ on log-log coordinates. The slope is the exponent n of the threshold-corrected power function on such a log-log plot.

$$\text{Log } S = n[\text{Log}(C - C_{th})] + \text{Log } k \qquad (2)$$

To determine if this function would be a satisfactory fit to our data, a bilinear regression analysis (Hinkley, 1969; Hinkley, 1971) was used. First, the least squares linear regression is calculated, and then the best least squares regression is found using two line segments. Second, an F-test is used to test the hypothesis that the two line segments have equal slope. If the hypothesis is rejected, the data are not fit by a straight line and the bilinear fit is appropriate. This bilinear approach was used rather than curvilinear regression because our initial examination suggested a two-limbed function for the non-threshold-corrected data. The bilinear regression was performed using both stimulus contrast values C and threshold-corrected stimulus values $C - C_{th}$.

The modulus-free magnitude estimation task allows for between subject variability in the numbers assigned to the same contrast stimuli. Such differences are not necessarily related to actual sensation differences. Since observers choose their own starting values, their responses are relative scaling responses (unless one holds to the idea of absolute sensory scales (Zwislocki, 1978)). Stevens and Stevens (1960) call this variability "intercept variability" since the task permits shifting perceived contrast functions up or down on the Y-axis without altering the slope of the function. To analyze group data, the grand mean of the log values of all estimates with the group was found. The individual observers' means were calculated. For each observer, the difference between the grand mean and the individual mean was added to all the observer's estimates (see Stevens and Stevens, 1960).

Observers

Eighty-five undergraduates, 46 male and 39 female, volunteered as observers. All were naive to the purpose of the experiment, and none had participated in psychophysical experiments before. Five observers' results were not used because their thresholds were higher than the lowest stimulus contrast used in the magnitude estimation experiment. All observers reported having corrected-to-normal acuity. A typical session lasted for 1 hr. No observer participated in more than one magnitude estimation experiment.

A group of five graduate students, experienced in psychophysical tasks, but naive to the experimental purpose, were also tested.

RESULTS

Individual observer data

The exponents for each individual observer in Group 1 (see Methods) are shown in Table 1. They were determined by finding the slopes of the least squares regression lines for the threshold-corrected data. The SE of each exponent was found by the technique of Mansfield (1973). Eight of the 10 observers showed single straight line fits. This supports the hypothesis that a threshold-corrected power function is a good description of the data. The regression analysis was performed on the geometric mean of the four trials at each contrast level. There was no systematic relationship between observer threshold and slope of the power function (Pearson product-moment correlation $r = 0.03$) across all observers in all conditions.

Threshold-correction

For group data analysis, each observer's estimates were normalized (see Methods) to eliminate the intercept variability. After normalization, geometric means of estimates were computed across observers. Group contrast threshold was determined by taking the arithmetic mean of the observers' thresholds. Group threshold values appear in appropriate Figure legends.

Figure 1 shows the data for Group 1, plotted in two ways. The open triangles plot contrast magnitude estimates vs stimulus contrast on log-log coordinates. The filled circles plot the same magnitude estimates with a different abscissa, which is stimulus contrast minus threshold contrast. The open triangle data were fit by the bilinear regression lines (see Methods), shown by the dashed lines in the Figure. The filled circle data were well fit by a single straight line. The slope of this line is 0.65 (SE = 0.013). The group of experienced observers viewed the same stimuli, and their threshold-corrected data were well fit by a line of slope 0.74 (SE = 0.026). The threshold-corrected power function provides a very good fit to the data. In all subsequent Figures and discussion, the data have been analyzed using the threshold-corrected stimulus contrast values. We have chosen to analyze the data as threshold-corrected power functions instead of two-limbed power functions because the

Table 1. Power function exponents for observers in Group 1

Observer No.	1	2	3*	4	5	6	7	8*	9	10	MEAN
Exponent	0.55	0.65	0.73	0.55	0.41	0.75	0.65	0.48	1.08	0.56	0.65
SE	0.031	0.041	0.061	0.030	0.020	0.028	0.024	0.047	0.060	0.111	0.06

Exponents and standard errors are shown for threshold-corrected power function fits to the perceived contrast data of observers in Group 1.

* The asterisk refers to observers whose data were significantly better fit by a two-limbed function.
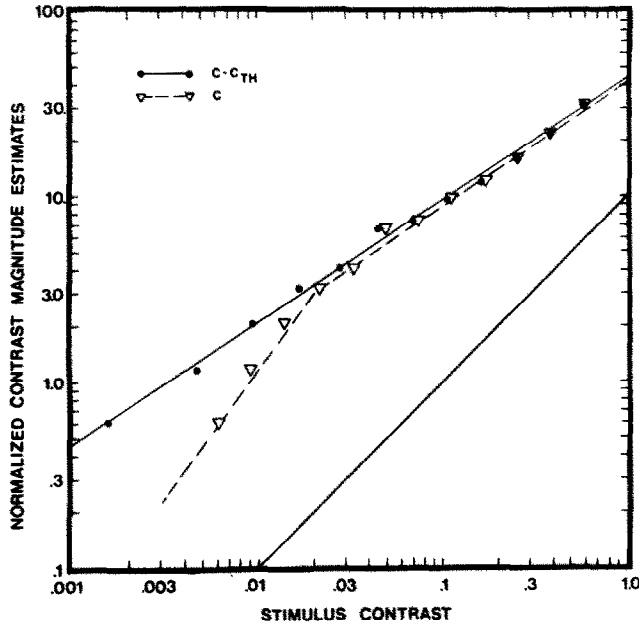
Fig. 1. Effect of threshold-correction. Group contrast magnitude estimates are plotted on two abscissae. The stimuli were 2 c/deg sinewave gratings that ranged in contrast from 0.006–0.6 at a mean luminance of 10 cd/m². Each point is the geometric mean of the magnitude estimates of 10 observers in Group 1, 4 estimates per observer. For (∇) the abscissa is stimulus contrast. The dashed lines are the bilinear regression fit. For (●) the abscissa is stimulus contrast minus group threshold contrast. The solid line through these data is the least squares regression line with slope 0.65 ± 0.013. The group threshold, mean of the 10 observers' thresholds, was 0.0045. A solid line of slope 1.0 is shown for comparison at the lower right.
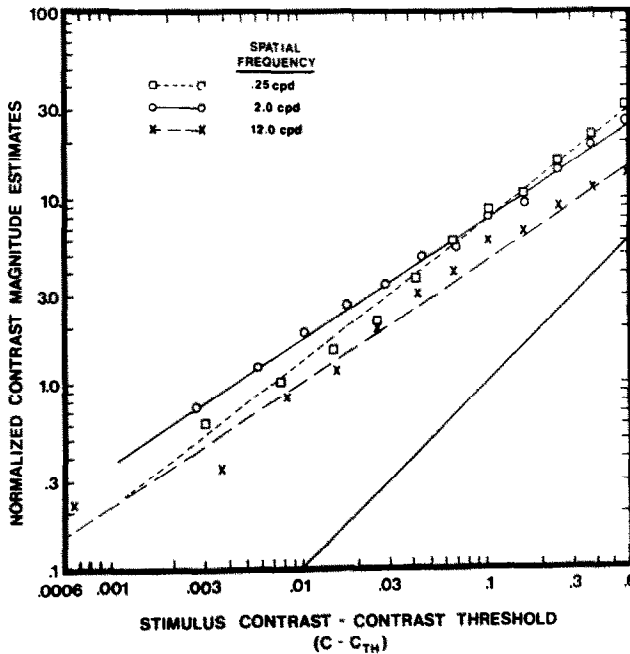

Fig. 2. Effect of spatial frequency. Group contrast magnitude estimates are plotted as a function of stimulus contrast minus threshold contrast for experiments at three spatial frequencies. The mean luminance was 340 cd/m². Best fitting straight lines have been drawn through each set of data: (O) Group 6. 2 c/deg, group threshold = 0.0034, slope = 0.64 ± 0.012; (□) Group 7. 0.25 c/deg, group threshold = 0.0062, slope = 0.76 ± 0.018; (×) Group 8. 12 cpd, group threshold = 0.0054, slope = 0.65 ± 0.032.

steepening of the perceived contrast functions at low stimulus contrasts is well accounted for by the threshold contrasts that we have measured. This use of measured thresholds obviates the need for additional free parameters in curve fitting.

Stimulus range

The group shown in Fig. 1 (Group 1) viewed contrasts ranging 2 log units from 0.006–0.6. Group 4 viewed contrasts that ranged from 0.05–0.06, just over 1 log unit. Group 4 had data well fit by a regression line of slope 0.64, as compared with the value 0.65 for Group 1. We conclude that the perceived contrast function exponent does not change if measured over one or two log units of stimulus contrast.

Luminance

Group 6 differed from Group 1 only in a change in mean luminance from $10–340 \, cd/m^2$. The data for Group 6 are shown in Fig. 2 as the open circles. The group data were well fit by a single regression line of slope 0.64. The comparable data for Group 1 (filled circles in Fig. 1) yielded a slope of 0.65. We conclude that changing the mean luminance from $10–340 \, cd/m^2$ does not affect the exponent of the perceived contrast function.

Spatial frequency

Figure 2 shows the data from Groups 6, 7 and 8 who saw gratings of 2, 0.25 and 12 c/deg respectively.

Mean luminance was $340 \, cd/m^2$, and the contrast levels were distributed across the two log unit range in equal log steps. The data for data for these groups were each well fit by a single regression line. The slopes of these lines for Groups 6, 7 and 8 were 0.64, 0.76 and 0.65, respectively. The differences were not significant in a one-way analysis of variance. (It should be noted that the difference in the vertical positioning of the data for the groups in this and other figures is the result of the normalization procedure. Group 6 data are higher on the vertical axis because the grand mean for that group was slightly higher than for the other groups. The shifts do not necessarily reflect any real absolute perceived contrast differences across conditions.) Our results indicate the change in the shape of the perceived contrast function is negligible from 0.25–12 c/deg.

Contrast spacing

Previous studies of contrast magnitude estimation have used different contrast spacings. Research in other sensory continua suggests that stimulus spacing might modify the form of perceived contrast functions. Figure 3 shows the data from Groups 1, 2 and 3, who all saw 2 c/deg gratings at a mean luminance of $10 \, cd/m^2$. The groups differed in the spacing between the 12 contrast levels within the 2 log unit range. Group 1, filled circles replotted from Fig. 1, were shown stimuli that were spaced in even logarithmic steps. (The data points are not equally spaced on
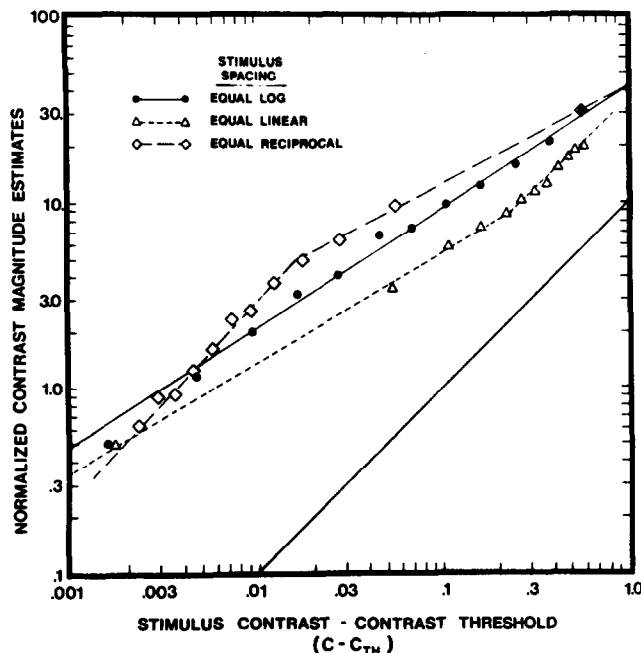

Fig. 3. Effect of the choice of contrast levels. Group contrast magnitude estimates are plotted as a function of the stimulus contrast minus group threshold contrast for 3 different sets of contrast levels. Stimuli were always 2 c/deg gratings, mean luminance $10 \, cd/m^2$ and ranged over 2 log units of contrast. (●) Group 1. Data of are replotted from Fig. 1. Their stimuli were equally spaced in log contrast. (△) Group 2. Stimuli were spaced in equal contrast steps. (◇) Group 3. Stimuli were spaced in equal reciprocal contrast steps. Bilinear regression fits to the data for Groups 2 and 3 are shown by the dotted and dashed lines. Mean thresholds for Groups 2 and 3 were 0.0044 and 0.0037 respectively.

the log scale, because of the threshold correction.) The open triangles show the results when the stimuli are spaced in equal linear contrast steps. On the log scale, the values are more densely packed at the high contrast end of the stimulus range. The group data were well fit by a two-limbed function, with a steeper section where the stimuli are more closely spaced on the log scale. A mirror image of the equal linear spacing distribution results from an equal reciprocal contrast spacing. The results are shown by the open diamonds. For this group, the data show a bilinear fit, and the steeper portion of the perceived contrast function is located at low contrasts, where the stimuli are more densely packed.

Similar spacing effects were found when the stimuli were presented over a one log unit range of contrast. Data from a group having equal log spacing were well fit by a straight line with slope of 0.64 (Group 4). Data from an equal linear spacing group (Group 5) were fit by a two-limbed function that was steeper at high contrasts. The slope of a single regression line through the data was 0.78 (SE = 0.033). An overestimate of the exponent results from using the equal linear spacing if a single regression line is fit to the data.

Stimulus repetition effects

The exponents of the perceived contrast functions increased systematically with repetitions of the set of stimuli for virtually all observers. For example, the exponents for consecutive sets for Group 1 were 0.58, 0.66, 0.76 and 0.80. Magnitude estimation experiments in other sensory continua (Stevens, 1975; Marks, 1974) have shown that no more than two repetitions of a stimulus set are usually needed to accurately measure perceived magnitude functions. Subsequent stimulus repetitions are redundant. Stevens and Stevens (1960) and Stevens (1971) have reported instances in which steepening has occurred in successive measurements. Stevens considers this effect to result from presenting experienced observers with a very narrow range of physical stimuli. Since these observers are accustomed to using a wide range of numbers, they have a tendency to artificially expand the range of their numerical estimates for successive repetitions. Since our observers were naive and only

saw one stimulus range, there does not seem to be reason to invoke this explanation.

It is possible that the repetition effect is due to practice at the magnitude estimation task. This seems unlikely because our group of five experienced observers also showed the repetition effect.

It may be that the repetition effect is due to pattern adaptation. Contrast matching results (Blakemore et al., 1973) suggests that pattern adaptation is likely to reduce perceived contrast more at low stimulus contrast than at high stimulus contrast. The magnitude estimates for the low contrast gratings would be lowered more than the estimates for the higher contrast gratings. This would result in growth of the exponent over sets if adaptation were cumulative over sets. Our experimental trial sequence was designed to minimize effects of pattern adaptation by allowing 5 sec between trials and by using a random stimulus order. However, we cannot rule out the possibility that small pattern adaptation effects are present in the data.

Although the prevailing opinion in the magnitude estimation literature appears to be that initial magnitude estimates are less likely to be contaminated by artifacts than repeated ones, we adopted the conservative strategy of averaging across our four repetitions because we remain uncertain as to the cause of the repetition effect. To the extent that the increase in exponent with repetition is artifactual, our estimates for the exponent of the perceived contrast function are high.

Table 2 summarizes the results of the eight experimental groups. The table shows the slopes of the least squares regression lines and corresponding standard errors for those groups that were best fit by a single line. The groups best fit with a two-limbed function (indicated by an asterisk) show the slopes of the two line segments.

DISCUSSION

The perceived contrast function is well described by a threshold-corrected power function with exponent near 0.7. Variations in the luminance, spatial frequency and stimulus range had little effect on the function for the conditions tested. Deviations from equal logarithmic spacing of contrast levels produced small but significant distortions of the power function

Table 2. Power function exponents for Groups 1–8

Group	1	2*	2 c/deg 10 cd/m^2 3*	4	5*	2 c/deg 6	340 cd/m^2 0.25 c/deg 7	12 c/deg 8
Exponents	0.65	0.91 0.58	0.52 1.04	0.64	1.15 0.68	0.64	0.76	0.65
SE	0.013			0.019		0.012	0.018	0.032

The exponents and standard errors are shown for threshold-corrected power function fits to the perceived contrast data of Groups 1–8.
* An asterisk indicates those groups whose data were significantly better fit by a two-limbed function. For these groups the slopes of the upper and lower segments of the bilinear fit are given.

fit. These "stimulus spacing" effects are consistent with similar effects found in other sensory continua (Stevens, 1958; Pradhan and Hoffman, 1963). A major conclusion arising from these results is that perceived contrast is a nonlinear function of stimulus contrast for sinewave grating stimuli.

Prior experiments using the method of magnitude estimation to measure the perceived contrast function have yielded varying results. We believe some of these differences can be clarified as a result of our experiments.

Franzen and Berkley (1975) show results similar to ours. They used equal logarithmic spacing over a range of 1.5, 1.25 and 0.6 log units for spatial frequencies of 3.5, 9.0 and 18.0 c/deg respectively. Their power function fits had exponents of 0.58, 0.66 and 1.71 respectively. For the two lower spatial frequencies, their exponent values are close to ours. They fit the data with non-threshold-corrected power functions, perhaps because their lowest stimulus contrasts were approx. 0.6 log units above threshold. The exponent of 1.71 at 18.0 c/deg seems surprisingly high. At 18.0 c/deg Franzen and Berkley's observers saw five stimuli over a 0.6 log unit range. For other sensory continua, Stevens and others (see Marks, 1974) have shown that a small range of stimuli and a small number of stimuli in that range will tend to result in steeper functions. Threshold effects may have been present at this frequency, and if this were the case, the exponent estimate obtained from a threshold-corrected power function would be lower than a non-corrected function. On the other hand, it is possible that the exponent may, in fact, increase at high spatial frequencies.

Hamerly et al. (1977) found linear perceived contrast functions above approximately 0.05 contrast. They used equal linear steps of stimulus contrast. Under these conditions we have found that the power function exponent increases. Their results at low contrast do not show the form that would be expected from a threshold-corrected power function, and we have no rationale to account for such a result.

Cannon (1979) also found linear perceived contrast functions, and his data follow a threshold-corrected power function form for a two log unit range. Cannon did not measure perceived contrast functions over this range in any one subject however. Data were obtained over the ranges of 0.05–0.60 and 0.00625–0.10 contrast. The exponents for his power functions were derived from data collected over the upper one log unit range only. These stimuli were spaced in equal linear steps, a procedure we have found increases the exponent of the perceived contrast functions. Cannon presented five trials at each contrast level, but he only averaged data over the last three. If Cannon's data contains a repetition effect like ours, this procedure would yield a higher exponent than if all five trials had been used. Cannon's results supported the conclusion that over a range of 1–12 c/deg, perceived contrast is independent of spatial frequency. Our data

agree with this conclusion, and extend the low frequency range to 0.25 c/deg.

Ginsburg et al. (1980) interleaved sinewave and squarewave grating stimuli in a magnitude estimation task. They found linear perceived contrast functions using equal linear contrast steps over a range of 0.03–0.54. Our results suggest that the linear performance may be partly due to the use of equal linear stimulus spacing.

Stimulus familiarity may influence magnitude estimates. Data collected on author J.G., who began the experiment inexperienced with gratings, showed an increase in exponent over the course of several months of testing, from 0.60 to nearly 1.0. Kulikowski (1976) noted that his experienced subject J.K., who was very familiar with gratings, had an exponent of 1.0, whereas inexperienced observers did not show linear perceived contrast. Similarly, the observers in Hamerly et al.'s study were experienced with gratings, and had linear perceived contrast functions above a contrast of 0.05. Two possible explanations exist for these results. Kulikowski (1976) suggested that subjects may need practice on the task. However, data collected over many different sensory modalities indicate that there is no difference between naive and experienced observers (Stevens and Poulton, 1956; Stevens and Tulving, 1957; Marks, 1974, p. 43). Moreover, our data from the group of experienced observers were no different from our naive observers' data.

A second possible explanation is based on the idea of the "stimulus-error" introduced by Titchener (Boring, 1921). The term "stimulus error" refers to the fact that in some experimental conditions, observers make responses that are more related to the observer's knowledge of the stimulus than to his sensation arising from that stimulus. It is possible that an observer who knows a great deal about the stimuli will tend to base his responses on recognition of the stimulus contrasts. This seems reasonable for gratings when one realizes that psychophysicists who have seen many gratings can be fairly accurate in identifying the physical contrast if asked to do so. The data for J.G. suggest such an interpretation. This would argue in favor of using observers who are not familiar with grating contrast for magnitude estimation experiments.

We would like to compare our results with data from other suprathreshold contrast experiments. Equal perceived contrast contours, measured in contrast matching experiments, flatten with increasing contrast. This flattening is consistent with the existence of perceived contrast functions that are identical across frequency, except for theshold-correction. However, magnitude estimation experiments, such as ours, that deal with only one frequency at a time provide useful information about the power function exponent, and not the "gain" constant. Cannon (1979) and Ginsburg et al. (1980) had observers scale perceived contrast for gratings of different spatial fre-

quencies, and had them perform a contrast matching task. The agreement they found was good between the two sets of data. However, they could not be certain of their gain constants either, because they measured the perceived contrast functions for each frequency separately. An experiment in which observers provide magnitude estimates for the perceived contrasts of gratings varying in both contrast and spatial frequency might provide information about the relative gain of the perceived contrast function at different frequencies.

Evaluating the relationship of the perceived contrast functions to data on the brightness of local portions of sine wave gratings (Bryngdahl, 1965; Springer, 1979) is very hard. The issue is this. Is perceived contrast a separate sensation dimension, or is it some combination of other sensory dimensions? For example, perceived contrast might be the difference in brightness sensation elicited by the peaks and troughs of the grating. An experiment that had observers scale the peak and trough brightness of grating stimuli would provide data bearing on this possibility.

Sensory magnitude functions can be derived from intensity discrimination data. In fact, the first sensory magnitude functions were Fechner's logarithmic functions, derived from Weber's Law for intensity discrimination in several sensory continua (see Boring, 1957, chap. 14). Legge and Foley (1980) have used grating contrast discrimination data to infer a "transducer function" relating "internal response" to grating contrast. At high contrasts, this transducer function is a power function with exponent 0.4. The relationship between this hypothetical transducer function and the perceived contrast function is not well understood. The simplest model would identify the transducer function with the perceived contrast function as measured by magnitude estimation but this cannot be correct, because of the discrepancy in the exponent of the model and the magnitude estimation data. However, refinement of the contrast discrimination model, including perhaps an estimate for the growth of internal noise with stimulus contrast, might very well lead to closer agreement. A similar problem exists in reconciling brightness magnitude estimates and photopic luminance increment detection data, and has been treated in some detail by Mansfield (1976). It is also possible that alternate means of obtaining perceived contrast functions may yield a lower exponent. In audition, for example, the power function exponent characterizing the relation between loudness and sound pressure level is lower when derived from loudness interval comparisons (Parker et al., 1974) or bisection methods (Carterette and Anderson, 1979) than when derived from magnitude estimation.

Our conclusions are these. Perceived contrast is a nonlinear function of stimulus contrast for our experimental conditions. The mean of the individual exponents for all 80 observers is 0.69 (SE = 0.03). Changing the mean luminance from 10 to 340 cd/m², changing the range of stimulus contrasts, or changing the spatial frequency from 0.25 to 12 c/deg, does not alter the form of the perceived contrast function. This result warrants the conclusion that the perceived contrast function is a stable experimental measure. The nonlinearity is in the form of a threshold-corrected power function with an exponent near 0.7.

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