Nonlocal determination of brightness in spatially periodic patterns

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Recent data require nonlinear spatial summation processes in models for detection of spatially periodic and aperiodic patterns. Contrast matching experiments with suprathreshold grating and spot patterns suggest that nonlinear models may be required for suprathreshold contrast data, but differences between the psychophysical tasks used with periodic and aperiodic patterns make comparison difficult. A series of experiments are reported in which subjects matched local brightnesses and brightness differences within single cycles of grating patterns. This task closely resembles the matching task in classical contrast experiments with aperiodic stimuli, allowing comparison of the data from the two types of experiments. Brightnesses within a 5-cycle/degree (c/deg) sinusoidal grating were largely unaffected by addition of a large 15-c/deg modulation component in either of two phases, in spite of the resulting large change in local luminances within the pattern. As at threshold, complex models are required in order to account for apparent differences between spatial interactions within periodic and aperiodic patterns.

Ten years ago, relatively simple linear summation models of spatial interaction could account for contrast threshold data for both spatially periodic and aperiodic patterns. Later experiments (Blakemore & Campbell, 1969; Graham & Nachmias, 1971; Sachs, Nachmias, & Robson, 1971) involving composite gratings with modulations at two spatial frequencies showed less interaction between closely spaced frequency components than would be expected from the simple models suggested by the aperiodic stimulus data. Recently, attempts have been made to account for detection of both aperiodic and periodic patterns, with more complicated models positing nonlinear summation of the responses of spatially localized detector mechanisms with medium bandwidth spatial frequency response (King-Smith & Kulikowski, 1975; Stromeyer & Klein, 1975; Wilson & Bergen, 1979). Due to the nonlinear summation, attributed in some models to probability summation, the response of the visual system as a whole is highly spatial-frequency specific.

Recent experiments on the apparent contrast of suprathreshold patterns have revealed a similar difference between spatial interactions for periodic and

aperiodic test patterns. Experiments with spatial gratings on pattern-specific adaptation (Blakemore, Muncy, & Ridley, 1973), masking (Weisstein, Harris, Berbaum, Tangney, & Williams, 1977), and frequency additivity (Arend & Lange, 1980) showed that, as in threshold experiments, there was little interaction between closely spaced spatial-frequency components. On the other hand, as in detection of aperiodic patterns, in classical studies of simultaneous brightness contrast the effects of isolated patches of light upon the brightness of a localized test field were found to diminish monotonically with increasing distance between the test and inducing fields (Leibowitz, Mote, & Thurlow, 1953), giving rise to contrast models in which an initial space-invariant nonlinear transform is followed by lateral inhibitory effects (Cornsweet, 1970; Jameson & Hurvich, 1964).

There is, however, a serious problem in comparing work with periodic and aperiodic stimuli. In the experiments with aperiodic stimuli, the subjects judged or matched the brightness of localized test fields. In the experiments with periodic stimuli, a complicated spatial array of brightness is perceived and the subject's task involves abstraction of a property of the distribution—that is, apparent contrast.

Unfortunately, in the experiments performed to date, the definition of "apparent contrast," the sub-

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ject's criterion content, has been left to the subject. The relationship between local brightnesses within a periodic pattern and the apparent contrast of the pattern may be quite complicated, thereby making comparison of data from the two kinds of experiments difficult or meaningless.¹

Since apparent contrast has been given relatively little psychophysical study, an analogy from color vision may clarify the problem. With proper training and instructions, subjects viewing chromatic stimuli can reliably abstract the perceptual properties hue and saturation. If the subject is asked to match the hues of stimuli differing in saturation as well as hue, the experimenter must rely upon careful training and instructions in order to be confident that saturation variation does not influence the matches. Complicated achromatic patterns also have multiple perceptual properties that may be abstracted. As with hue and saturation, apparent contrast and the brightness at specific points within the pattern are defined in terms of the subject's criterion content, controlled by the experimenter through training and instructions.

In the experiments reported here, we obtained suprathreshold grating data comparable to aperiodic pattern data by carefully defining the psychophysical task. We asked subjects to match brightnesses and brightness differences at clearly defined locations within single-frequency and two-frequency gratings, the test and matching gratings used in our previous apparent-contrast experiments (Arend & Lange, 1980). As in those experiments, there was little interaction between the two closely spaced spatial-frequency components in the complex gratings. As at contrast threshold, a model is required that can account for the apparent discrepancy between the spatial interactions in these data and the spatial interactions in classical contrast data.

METHOD

Side-by-side test and standard gratings were produced by z-axis modulation of a raster pattern on a cathode ray tube (P31 phosphor). The gratings were each 2.4 deg wide $\times$ 4 deg high, separated by a .25-deg-visual-angle vertical bar with a 1-min-diam dark fixation spot in the center. This entire modulated area was centered in a 16 deg wide $\times$ 17 deg high unmodulated surround. The bar and surround had the same hue and mean luminance ($L_m = 4.45$ cd/m²) as the modulated fields.

The left side of the screen (standard grating) was sinusoidally modulated at 8.66-cycle/deg (c/deg) spatial frequency and .075 contrast. The right side of the screen (test gratings) was modulated horizontally to produce gratings of the form $L(s) = 4.45[1 + k(a_s \cos 5s \pm a_{15} \cos 15s)]$, where $L(s)$ is the luminance (cd/m²) at horizontal position s (deg visual angle $\times 2\pi$).

In each experiment, the subject was instructed to match specified brightnesses or brightness differences within the test and standard grating by depressing switches increasing or decreasing, at a constant rate, the parameter k of the test grating.

The several experiments differed in the particular features of the test and standard gratings to be equated by the subject.

General Procedures

In each session, the subject initially dark-adapted for 5 min and then adapted to the unmodulated display at luminance L_m for 3 min. Eighty matching trials then occurred, with each of the eight test gratings appearing in pseudorandom order within each of 10 blocks of trials. The eight test gratings were the two one-component modulations ($a_s = 0$ or $a_{15} = 0$) and six two-component stimuli, the additive and subtractive phases for each of three ratios of a_s to a_{15} . On each trial, the subject matched the test and standard gratings according to one of several sets of instructions and then pushed a button recording the level and presenting the next test grating at a random initial-contrast level. The random start level and adjustment switches eliminated artifacts due to nonvisual cues and minimized possibilities for subject biases.

Two subjects were used, both corrected to normal acuity—A.W.S., a trained observer unaware of the purposes of the experiment, and B.L.S., one of the authors.

EXPERIMENT 1: BRIGHTNESS DIFFERENCE MATCHING, NONLOCAL

The following instructions were read to the subject before each session of the first experiment: "The right- and left-side patterns are periodic, that is, the same narrow pattern is repeated over and over. Within the narrow repeated pattern there is a brightest part and a darkest part. When you press the buttons, the brightness difference between the brightest parts and darkest parts will increase or decrease. I want you to adjust the right-side pattern until the brightness difference between the brightest and darkest parts of the right-hand pattern is equal to the brightness difference in the left-hand pattern. Try to use the brightness differences over the entire pattern in making your judgment, not just one small part."

Results

Figure 1 presents data from two subjects, plotted in the conventional manner (Arend & Lange, 1979, 1980; Graham & Nachmias, 1971; Graham, Robson, & Nachmias, 1978). Each data point is the scaled mean contrast of 10 matching trials for one of the eight test gratings from a single session. The plotted value of A_s for each point is M_{5c} , the mean matching contrast of the 5-c/deg component in the composite grating, divided by M_{5s} , the session mean contrast match for the 5-c/deg simple sinusoidal grating. Similarly, $A_{15} = M_{15c}/M_{15s}$. This procedure produces a graph for each day, with axes scaled such that the matches for the 5- and 15-c/deg simple gratings lie at (1,0) and (0,1), respectively. Standard errors of the scaled mean matches were calculated as distances along the radial lines of the subjects' contrast adjustments in this scaled space. The plotted standard error in each summary graph is the average of those error bars for all the composite gratings in the graph. The solid curves, discussed further in the Discussion section, are of the form $A_s^n + A_{15}^n = 1$, with $n = 3$ and $n = 5$, the latter being farther from the origin.

Figure 1. Data from Experiment 1. Ten-trial means denoting test gratings, composites of 5 and 15 c/deg, which match an 8.66-c/deg sinusoidal standard grating of fixed physical contrast. Test gratings were adjusted to match the standard grating with respect to the brightness difference between the brightest and darkest parts of the cycles. Peaks of 5- and 15-c/deg modulations coincided (plus signs) or were 180 deg out of phase (minus signs). Horizontal and vertical axes of the daily graphs were scaled to superimpose the axis data points in this summary graph. Error bars are plus and minus the mean standard error of the 10-trial means. Solid curves are $A_5^n + A_{15}^n = 1$ for $n = 3$ and $n = 5$, the latter curve being farther from the origin.

The data from B.L.S. fall outside the theoretical curves, with the differences between the peaks-add points about equally often inside and outside the peaks-subtract points. A.W.S.'s data show a more consistent effect of phase, with the peaks-subtract points lying near the $n = 3$ curve, and the peaks-add points lying slightly farther from the origin. As in our

earlier contrast match experiments, the data do not show strong additivity of the 5- and 15-c/deg modulations: They are far from the diagonal that indicates perfect linear additivity and are quite close to the box that indicates total lack of summation of any kind. Except for the phase effects, the data confirm our supposition that our earlier contrast match task (Arend & Lange, 1980) is simply related to brightness differences within the patterns. Again, the data approximate the form of the data from the analogous contrast threshold experiments, further confirming that the threshold experiments are a special case of a more general apparent-contrast phenomenon.

In these data (and those from the experiments described below), the means for the two phases were often separated by two standard errors, but the direction of the difference varied from session to session. To assess the consistency of the direction of the phase effect, we calculated for each subject and each experiment the probability of obtaining the observed mix of signs by chance alone. In all but three cases, the probabilities were greater than .05. In Figure 1, A.W.S.'s peaks-add points lay outside her peaks-subtract points more often than chance, but B.L.S.'s did not. In Figures 2 and 3 (discussed below), B.L.S. produced a small phase effect in the opposite direction, while A.W.S. did not. In Figure 4, there was no significant phase effect for either subject. We can think of no convincing explanation for these small but consistent effects, given the disagreement between the subjects and the opposite directions.

These data indicate that brightness differences within the overall pattern do not depend simply on the total peak-to-trough luminance differences but, rather, are nonlocally dependent on the test pattern luminance distribution.

EXPERIMENT 2: BRIGHTNESS DIFFERENCE MATCHING, LOCAL

To get further information about this nonlocal response to the luminance distribution, we redefined the subjects' task, asking them to equate the brightness differences within single identified cycles of the test and standard patterns. All conditions were the same as in the first experiment except for the following alteration of the last few lines of the instructions: "I want you to adjust the right-side pattern until the brightness difference between the brightest and darkest parts of the second cycle on the right side of the screen (N.B. Experimenter points to second cycle from fixation point) equals the brightness difference in the second cycle of the left-side pattern. Concentrate carefully on only those two small regions of the screen (while fixating the center spot)."

Results

The results of this second experiment are shown in Figure 2, with the same conventions as in Figure 1.

Figure 2. Data from Experiment 2. Ten-trial means denoting composite gratings which match the fixed-contrast standard grating with respect to the brightness difference within the second grating cycle from the fixation point. Peaks of 5- and 15-c/deg components were in additive (plus signs) or subtractive (minus signs) phases. Axes of daily graphs were scaled to superimpose axis data points. Error bars are plus and minus the mean standard error of the 10-trial means. Solid curves are $A_5^n + A_{15}^n = 1$ for $n=3.5$.

Once, again, the data for both observers fall near the theoretical curves. The instructions were effective in that both subjects thoroughly understood the instructions and reported that the task was subjectively very different from the former task. Nevertheless, the local brightness differences in this task were as

nonlocally dependent upon the luminance distributions as in the former task.

EXPERIMENT 3: BRIGHTNESS MATCHING, NONLOCAL

Even at these rather low contrasts, the peaks-add and peaks-subtract composite stimuli were clearly discriminable on the basis of the brightness distribution within single cycles of the composites, but there was no contrast additivity in the local difference matching task. There are several possible explanations. The difference between the maximum and minimum brightnesses within single cycles of the additive and subtractive phase two-frequency patterns may be equal, in spite of the large difference between the peak-to-trough luminance differences in single cycles of the two patterns. Discrimination between the two patterns could still be made on the basis of the perceived waveforms.

On the other hand, judgment of brightness differences may be more complicated than merely taking the difference between the perceived extreme local brightnesses. The latter possibility prompted two further experiments. We asked the subjects to match not the brightness differences within cycles of the test patterns but, rather, the brightness at a single location within cycles of the waveform. We chose to match the minimum brightness, since the peak brightness of a sinusoidal grating varies much more slowly than the trough brightness as the physical contrast is increased (Springer, 1978). In the first trough matching experiment, we used nonlocal instructions similar to those of Experiment 1. All other conditions were unchanged. The last part of the instructions were modified to read: "I want you to adjust the right-side pattern until the brightness of the darkest parts of the right-hand pattern is equal to the brightness of the darkest parts of the left-hand pattern. Try to use the brightness of the darkest parts in the entire pattern in making your judgment, not just one small part (while fixating the center spot)."

Results

The data are shown in Figure 3, again with the same convention as in the preceding figures. They are similar to the results obtained under the brightness difference instructions, with no evidence of contrast additivity. As before, the instructions were effective in that the subjects reported the task to be clearly defined and subjectively very distinct from that in the previous experiments.

EXPERIMENT 4: BRIGHTNESS MATCHING, LOCAL

In the fourth and final experiment, we once again asked the subject to attend to only a single location

Figure 3. Data from Experiment 3. Ten-trial means denoting composite gratings which match the fixed-contrast standard grating with respect to the minimum brightness in the gratings. Peaks of 5- and 15-c/deg components were in additive (plus signs) or subtractive (minus signs) phases. Axes of daily graphs were scaled to superimpose axis data points. Error bars are plus and minus the mean standard error of the 10-trial means. Solid curves are $A_5^n + A_{15}^n = 1$ for $n = 3, 5$.

Figure 4. Data from Experiment 4. Ten-trial means denoting composite gratings which match the fixed-contrast standard grating with respect to the minimum brightness within the second grating cycle from the fixation point. Peaks of 5- and 15-c/deg components were in additive (plus signs) or subtractive (minus signs) phases. Axes of daily graphs were scaled to superimpose axis data points. Error bars are plus and minus the mean standard error of the 10-trial means. Solid curves are $A_5^n + A_{15}^n = 1$ for $n = 3, 5$.

in the test and standard gratings. The last part of the instructions read: "I want you to adjust the right-side pattern until the brightness of the darkest part of the second cycle of the right-hand pattern is equal to the brightness of the darkest part of the second cycle on the left side. Concentrate carefully on only those two small regions of the screen (while maintaining fixation on the center spot)."

Results

The data, shown in Figure 4, are very similar to those in the previous experiments. Thus, even when the subjects matched localized minima in the brightness waveforms at points separated by less than .5 deg, the presence of a substantial second modulation component did not significantly reduce the required physical contrast of the stronger component, and the

substantial luminance differences between the troughs of the additive- and subtractive-phase composite gratings did not produce corresponding brightness differences.

DISCUSSION

One obvious interpretation of the similarities in the data from the several conditions is that the experimental manipulations were ineffective. There is no simple method of eliminating this alternative when changes in experimental conditions have no effect on the mathematical form of the data. We can conclude, therefore, only that the form of the data was unaffected by manipulations of training and instructions which did change the subjective nature of the task for experienced and motivated subjects. It is not clear, however, that this conclusion is significantly different from the conclusion that local brightnesses and brightness differences are dependent upon the spatial luminance distribution in much the same way as is the overall apparent contrast of the extended pattern.

Our data have the same mathematical form as contrast threshold data for two-frequency composite gratings and previous contrast matching data (Arend & Lange, 1980). The models proposed to account for the threshold data can be extended to account for the suprathreshold data, but not without strain. In the threshold models, narrow-band spatial-frequency tuning is a consequence of probability summation among independent, spatially local line detectors (Wilson & Bergen, 1974) or grating patch detectors (Graham et al., 1978) with somewhat narrower frequency tuning. A grating pattern is detected on any given trial by one or more detectors at different spatial locations. In addition, several sizes of line or patch detectors are assumed to exist at each spatial location. The mechanisms are assumed to have independent noise sources, so that probability summation occurs among detectors of various sizes at a given location as well as among detectors at different spatial locations.

For the contrast threshold paradigm analogous to the suprathreshold experiment reported here, these models predict data lying along curves of the form $A_5^n + A_{15}^n = 1$, with n between about 3 and 5, depending upon the steepness of the psychometric functions for the axial stimuli (for further detail, see Graham et al., 1978). The models can be extended to account for the form of our suprathreshold data by modifying the assumptions. As in the threshold model, assume the existence of independent "line detector" mechanisms of several sizes at various spatial loci, with their response levels probabilistically related to the local stimulus amplitude. Continuing the analogy, assume that an apparent contrast match occurs when the response in one or more line detectors reaches a criterion level. It is clear that the mathematical prop-

erties of the extended model are identical to those of the threshold models and, therefore, that the model predicts that modulation components of a composite grating of sufficiently different spatial frequencies will not interact in apparent contrast matching.

In this model, as in the threshold models, the responses of the various spatially distributed detectors are equivalent with respect to meeting the psychophysical criterion. This assumption seems fairly reasonable when our nonlocal definitions of apparent contrast are used, but it is implausible for the local tasks. If the local detector mechanisms are as broadly tuned as the line detectors of Wilson and Bergen's threshold model, then probability summation over spatial locations is required to make 5- and 15-c/deg modulations independent. For our local matching conditions, the brightness and brightness difference in the second cycle of the pattern would have to be as dependent upon momentarily large responses of the local detector centered on, for example, the fourth cycle of the pattern as they are upon responses of the local detector mechanisms centered on the second cycle. This seems to us an improbable mechanism. If the local detector mechanisms are more narrowly tuned, 5- and 15-c/deg modulations need not interact even in the absence of probability summation over spatial locations. Local matching experiments with smaller frequency separations than that used here might therefore reveal some effect of the local task restrictions on frequency interactions.

There are further problems for suprathreshold extension of threshold models with either kind of local detector. We (Arend & Lange, 1979) found strong phase-dependent interaction of 5- and 15-c/deg modulation components when they were detected in the presence of a suprathreshold 10-c/deg grating component. If line detectors are assumed to be responsible for detection in that situation, probability summation of their outputs must be somehow prevented or narrower tuning would be observed. While probability summation among narrowly tuned detectors can produce broad-band detection at contrast threshold (Graham & Rogowitz, 1976), we were able to show that detection in the presence of the suprathreshold component was independent of narrow-band contrast threshold mechanisms.

Together the two experiments indicate that extensions of current contrast threshold models will have limited suprathreshold application. Interpretation of these local matching data is complicated by the different spatial interactions in apparent contrast perception and apparent form perception. It is tempting to simply conclude from the experiments reported here that each local brightness is nonlocally determined, by a nonlinear algorithm that is not influenced by the subjects' voluntary adherence to the task instructions. This conclusion would ignore, however, the fact that the apparent waveform of a pattern involves the

spatial distribution of brightness within the pattern, and our data on discrimination of apparent waveforms (Arend & Lange, 1979) indicate that the relative brightness distribution within the pattern depends on more local regions of the stimulus. Thus, apparent contrast, involving primarily the maximum and minimum brightnesses, is nonlocally dependent upon the stimulus, while apparent waveform, important even at threshold (Nachmias & Weber, 1975), is more locally determined.

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NOTES

1. The same problem arises in comparison of detection data for periodic and aperiodic patterns. The subjects' criterion content may be different for the two tasks, and the deduced quantitative properties of spatial interactions may depend upon those differences.

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