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Clinton F. Jenne

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DISCRIMINATION OF APERIODIC TWO-DIMENSIONAL PATTERNS: A COMPARISON OF FEATURE DETECTION AND FREQUENCY ANALYSIS MODELS

A thesis Presented
By
Clinton Jenne

Submitted to the Graduate School of
University of Massachusetts in
partial fulfillment of the requirements for the degree of
MASTERS OF SCIENCE

April (Month) 19__ (Year)

DEPARTMENT OF PSYCHOLOGY
DISCRIMINATION OF APERIODIC TWO-DIMENSIONAL PATTERNS: A COMPARISON OF FEATURE DETECTION AND FREQUENCY ANALYSIS MODELS

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April 1973
(Month) (Year)
ACKNOWLEDGEMENTS

The author wishes to thank the members of his thesis committee, Dr. William Eichelman and Dr. Arnold Well, for their thoughtful suggestions and criticisms concerning this thesis. Special thanks are due Dr. John Danielson for his invaluable assistance throughout the preparation of this thesis. An expression of deep gratitude is due my wife Dawna who graciously sacrificed many hours that would have been spent together while I was immersed in the preparation of this thesis.
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INTRODUCTION

Several theoretical models have been proposed of human and infrahuman vision and employed, with some success, to explain the characteristics of a biological system which detects stimulus equivalences (Deutsch, 1955; Sutherland, 1957; Thomas, 1970; Kerr and Thomas, 1972). The neural correlate of pattern vision, according to Deutsch and Sutherland, was a two-dimensional network of cells which transform the stimulus pattern into coded form that is qualitatively dissimilar from the original stimulus figure. A model of this sort was suggested in order to account for shape perception independent of retinal location. Later, Thomas (1970) outlined a detector system in which neural units responded optimally only if the stimulus has a certain width, orientation and position. The response properties that Thomas endowed to neural units were based upon electrophysiological evidence supplied by Hubel and Wiesel (1962, 1965); the model proposed by Thomas was an extension of the neural network concept proposed by Deutsch, whereby neural units that comprise the two-dimensional network were now driven by very special stimulus characteristics. A model of this kind implies that pattern vision is a
function of a specific feature analysis, and hence, stimulus equivalence is a byproduct of feature invariance. For this reason we will call it a feature detection model. Models based on feature detection have been widely proposed as the neural correlates of human pattern vision.

Recently Campbell and Robson (1968) suggested a frequency analysis model for the detection of sinusoidal and non-sinusoidal gratings. They provided evidence that complex periodic patterns are analysed into Fourier components, and these components will affect independent frequency channels. Also, adaptation to a specific spatial frequency will affect only the detectability of that spatial frequency. The work of Campbell, Carpenter and Levinson (1969) demonstrate that the human visual system, within a limited range, responds linearly to complex aperiodic patterns. Since 1969, the question still remains as to whether visual processing of aperiodic figures is mediated by the Fourier components of that figure. The data provided by Weinstein and Bisaha (1972) suggests that aperiodic figures are analysed by the visual system in terms of their Fourier harmonics. These data provide a measure of the sensitivity loss for bars after adaptation to a square-wave grating, but
provide no explicit theoretical predictions about the relationship between independent frequency channels and pattern processing.

The experimental results reported in the present study were collected in order to determine if the effect of changing the sensitivities of specific spatial frequency channels increases the discrimination threshold for two-dimensional shapes. To deduce the role played by individual channels in a discrimination task, assumptions are made about the properties of the channels.

Assumption 1: Analytical. The visual system processes the components which make up a complex two-dimensional pattern. Each of these components are processed independently by mechanisms which are sensitive to specific characteristics.

Assumption 2: Adaptation. A visual system's sensitivity to stimulus characteristic x will be depressed when exposed to characteristic x for an extended period.

Assumption 3: Masking. A visual system with depressed sensitivity to stimulus characteristic x responds less than maximally to a second stimulus which contains stimulus characteristic x.

In order to assess the implications of these assumptions two lines of reasoning can be developed. One point of view suggests that the units of analysis for
a visual mechanism are edges, contours or lines. This point of view was characterized earlier as the feature detection model. According to this theory and assumption 1, visual analysis is carried on by line detectors which are maximally sensitive to orientation and width. Pursuing the logic of this method further, we can conceptualize the effects on the psychophysical discrimination threshold for a complex pattern which contains two contours with a particular line-width-orientation specificity that stimulates a unique visual mechanism, or at most, some small class of similar mechanisms. Therefore, according to assumption 2, the presence of a specific contour in the visual field raises the threshold for discriminating the same contour a short time later. Consequently, according to assumption 3, the presence of the same unique contour presented as part of a test figure after prior viewing of the contour in isolation, raises the psychophysical threshold for responding to the second stimulus. This threshold elevation, known formally as forward masking, may be most dramatic in a case where the width of the figure was matched by the adaptation stimulus.

The feature detection model predicted that adapting gratings and the test figure with common orienta-
tion and bar width will interact, and that the gratings and test figures differing in orientation and bar width will be independent. Specifically, grating bars that subtend the same visual angle and have the same orientation as the test figure will raise its threshold, but grating bars with different visual angles or orientations will not affect the test figure's threshold. These predictions are consistent with a feature detection system as proposed by Thomas (1970).

An alternate point of view has hypothesized that visual pattern processing is mediated by independent channels, each of which are selectively sensitive to a narrow band of spatial frequencies. This point of view is known formally as the frequency analysis model. According to this theory, visual analysis is performed by frequency encoders which are maximally sensitive to discrete Fourier components in the physical energy distribution.

In order to assess the mechanism postulated by the frequency model, it is necessary to formally introduce the notion of Fourier analysis which is suggested as one way to describe two-dimensional aperiodic patterns. (See computer program for Fourier transform, Appendix A) Fourier analysis is a precise quantitative
means to specify the characteristics of a visual figure in terms of sine and cosine wave functions; this procedure is used in order to approximate a non-periodic array with a set of simple mathematical functions. Moreover, the theoretical application of Fourier theory to an aperiodic figure, specifies the frequency and amplitude of frequency components, which are believed to be the building blocks of perceptual analysis. The existence of visual channels selectively sensitive to different spatial frequencies was first proposed by Robson and Campbell (1964; see also Campbell and Robson, 1964 and 1968) who demonstrate that the threshold for detecting gratings possessing various complex waveforms is largely determined by the fundamental Fourier component of the grating. In addition they show that complex gratings are distinguished from a sinusoidal grating of the same frequency only when the second or third harmonics of the complex grating reach their independent threshold. Therefore, Fourier theory is used successfully to predict the perception of periodic patterns; however, Fourier theory has not been used to predict the threshold for aperiodic patterns. The predictive capacity of the frequency analysis model has yet to be pushed to its ultimate conclusion.
The logic of Fourier theory, which is both rigorous and elegant in a mathematical sense, is also intuitively appealing in its potential application to visual processing. The one disadvantage of pure Fourier theory in its application to complex patterns is that an infinite series of spatial frequency components in three dimensions are necessary in order to fully describe a single rectangle. The issue involves the following question: How does one pose an experimental question which attempts to determine the effect of frequency specific fatigue on aperiodic pattern discrimination, when the potential spatial frequency channels must in theory be infinite in number. This logical problem may be simplified by acknowledging that the neural modulation transfer function (MTF) places considerable real constraints on the spatial frequency parameters to which the human visual system is sensitive. The MTF indicates that the highest frequency which can theoretically be detected is 50 c/d (See Figure 1). Campbell and Green (1965) have measured peak sensitivity on the MTF to be 5 c/d. These parameters are taken to be fixed measures of the neural sensitivity of the human system. The investigator may now assume that spatial frequency components in excess of 50 c/d are not analysed by the human visual system dur-
Figure 1

The modulation transfer function (MTF)
(from Campbell and Green)
In Figure 2, the Fourier analysis of a 17' x 11' rectangle is displayed. The output presented as Figure 2A, represents the amplitude of the Fourier components of the rectangle in a vertical orientation; and in Figure 2B, the amplitude of each Fourier component is plotted for the horizontally oriented rectangle. These analyses differ in that at 4 c/d the vertically oriented rectangle has a higher amplitude vertical sinusoid component, and the horizontal rectangle has a higher amplitude horizontal sinusoid component.

The details of the Fourier transformation employed in the production of Figure 2, include the following: (1) the test figure in each orientation is symmetrical about the horizontal and vertical meridian; (2) the Fourier transform of a symmetrical figure is also symmetrical about the horizontal and vertical meridians; (3) therefore, one quadrant of the transform is sufficient to specify the whole figure. Figure 2 is one quadrant of the transform and shows the amplitude of the Fourier transform of one quarter of the original test figure. According to the syllogism stated above, the Fourier transform of one quadrant is equivalent to every other quadrant provided the original figure meets the
Figure 2
The Fourier transformations

A

Vertically Oriented Sinusoid

Spatial Frequency (c/d)

B

Horizontally Oriented Sinusoid

Horizontally Oriented Sinusoid

Spatial Frequency (c/d)
symmetry criterion.

According to the MTF (See Figure 1), sensitivity to spatial frequencies is maximum in the range of 5 c/d and approaches zero near 50 c/d. The general frequency parameters suggested by the MTF emphasize the importance of the frequency range around 10 c/d and below. In addition both Fourier transforms of the test rectangles (See Figure 2) show the larger amplitudes of Fourier components below 10 c/d. The combination of the size rectangle used and the MTF suggests that the frequency range of importance will be below 10 c/d. Therefore the question posed several pages earlier, which involved empirically determining the effect of frequency analysis in aperiodic pattern discrimination, has been theoretically resolved by specifying that the frequency range of importance will be less than 10c/d.

The theoretical import of the 10c/d frequency range and below raises two important practical implications for the human visual system. (1) What do these frequencies mean in terms of the shape of the figure? (2) What are the psychophysical results on shape discrimination after adaptation to frequencies of 10 c/d or below? The first question is a theoretical corollary of the frequency analysis model, while the second
Figure 3
The reconstructed test figure
question is an empirical issue which was measured in the present study. Figure 3 was constructed in order to answer the first question.

In Figure 3, a vertically oriented rectangle (one of the test figures used in this experiment) has been analysed into its frequency components, low pass filtered to remove the higher frequencies, and retransformed from the frequency domain into the space domain. Figure 3A illustrates the original two-dimensional test rectangle. Figure 3B has been reconstructed from the average luminance and the 2 c/d frequency components; all of the high frequency components greater than 2 c/d have been removed prior to reconstruction. Figure 3C has included the average luminance, 2 and 4 c/d frequency components, and Figure 3D has been reconstructed from the average luminance, 2, 4 and 6 c/d frequency components. The overall impression that suggests itself from the reconstructed rectangle data is that rectangularity reappears after the inclusion of the 4 and 6 c/d components. When only the average luminance and the 2 c/d components of the rectangle are employed in reconstruction the figure appears to be just a circular smear with no hint of rectangularity. Therefore, the specification of a two-dimensional rectangle may be achieved theoretically
by the low spatial frequency components, and the high spatial frequency information may be redundant for the discrimination of rectangularity. Special attention will be paid to the 4 and 6 c/d frequency components because of their theoretical relevance to the discrimination of rectangles.

Having discussed the virtue of Fourier theory, it is now possible to assess the implications of the frequency analysis model through the following line of reasoning. The proponents of the frequency analysis model suggest that the units of analysis for vision are discretely oriented spatial frequency specific mechanisms. According to this theory and assumption 1, visual analysis is carried out by frequency detectors which act like visual spatial filters with specific pass-bands. It is possible to conceptualize the effects of the psychophysical discrimination threshold for a complex pattern which contains the following spatial frequency components: an average luminance, and a 2, 4, 6, 8, 10, 12, and 14 c/d components. Each of these frequency components stimulates a unique visual mechanism or spatial frequency channel. Therefore, according to assumption 2, the presence of a specific spatial frequency grating, i.e. 4 c/d, in the visual field
raises the threshold for discriminating the same frequency a short time later. Consequently, according to assumption 3, if discrimination of a test figure depends on the detection of the 4 c/d frequency component, then the threshold of the test stimulus should be raised. This threshold elevation, known formally as forward masking, may be most dramatic in the present case where one clear difference exists in the amplitude of the frequency components that describe two similar sized figures. When this single difference is washed out, perhaps by frequency specific adaptation, the figure becomes apparently equivalent.

According to the frequency analysis model the 4 and 6 c/d frequency channels are crucial to discriminate a rectangle from a symmetrical figure such as a square or circle. The maximum energy at 4 c/d occurs within the vertically oriented sinusoidal component for the vertical rectangle and the horizontally oriented sinusoidal component for the horizontal rectangle (see Figure 2). The amplitude differences found at 4 c/d indicate that information about orientation is transmitted via the 4 c/d frequency component. Therefore, according to the frequency analysis model rectangularity for these figures is signalled in the 4 and
6 c/d frequency band and orientation is transmitted by whichever frequency component has the largest amplitude within this critical frequency band. In addition, the frequency analysis model makes the general prediction that high frequency adaptation, regardless of orientation, will not affect pattern discrimination.
METHOD

Subjects

Three graduate students available for long term study were used in the present experiment. One S was a student in the same laboratory, F.F., and two were male graduate students both experienced in visual observation, but unaware of the purpose of this study. All S's vision tested at least 20/20 in acuity with or without correction in the eye used for observation.

Stimulus Materials

The production and design of the experimental figures was accomplished by making each figure with waterproof black drawing ink on matte white construction paper. The figures used were a 0.8 x 0.4 cm. rectangle and a 0.5 x 0.5 cm. square. These were photographically reproduced for projection.

The masking stimuli used for the adaptation condition were square-wave gratings constructed from Chart-Pack black adhesive tape and matte white cardboard. Luminance of light and dark bars was 10.82 cd/m² and 0.74 cd/m² (contrast = 0.92). The luminance profile used to describe a square-wave is represented theoretically in Figure 4. The area enclosed beneath the luminance profile represented the relative energy of a stimulus array on the visual
Figure 4

The masking stimulus

Relative Amplitude

Spatial Position
receptor. The "d" term (see Figure 4) represents the width of the light and dark bars of the adapting gratings. One light and one dark bar interval was equivalent to one period. The dimension on the ordinate was the physical energy in relative amplitude which corresponds roughly to a black-white psychological continuum. The dimension on the abscissa was spatial position in arbitrary units.

Six gratings were constructed to be viewed as masking stimuli during adaptation. The six gratings differend along a spatial frequency dimension; the spatial frequencies of the square-waves were: 3, 4, 5, 6.5, 12, and 24 cycles per degree. The following formula was applied to determine the width of one period for the different spatial frequency gratings:

\[ S = D \times \tan \theta \]

where \( S \) is the width of a period, \( D \) is the distance from the projection screen to the S's eye, and \( \theta \) was the size of the angle subtended at the retina. The interval widths for the different frequency square-wave gratings were 0.36, 0.26, 0.22, 0.16, 0.09, and 0.05 cm. for the 3, 4, 5, 6.5, 12, and 24 c/d respectively.
**Apparatus**

The stimulating apparatus consisted of two slide projectors with 500 watt tungsten filament bulbs, illuminating a projection screen. The background channel was located directly in front of the projection screen and provided a background field of $7^\circ \ 17'$ on the screen. The test pattern channel was also located in front of the projection screen and the optical apparatus cast the test figure directly into the center of the background field. The luminance of the test pattern channel was controlled by crossed polaroids. The square-wave gratings, which subtended a $6^\circ \ 10'$ visual angle, were mounted on the projection screen. The lower border of the adaptation gratings was placed 32 cm. above the location where the center of the test figure was projected. One of the Ss viewed the adaptation gratings through an aperture which allowed him to see only the grating.

Each S sat facing the projection screen in a chair with an adjustable chin-rest and head-rest and was instructed to fixate on a point in the center of the preexposure field. The S was positioned 296 cm. in front of the screen and the test rectangles subtended $17' \times 11'$ of visual angle, and the square was
14' of visual angle on a side. The small angular subtense was used in order that the energy carried in the lower spatial harmonics would peak in the range of maximum sensitivity as determined by the modulation transfer function.

The background field radiance was controlled by Wratten neutral density filters. The luminance of the unfiltered field was 100.7 cd/m². The luminance of the test field, with uncrossed polaroids was 115 cd/m². The experimental laboratory remained normally illuminated (30 cd/m²) throughout psychophysical measurements. The exposure time of the test pattern channel was controlled by a photographic shutter. The onset of a trial was initiated by the E and changes in the illumination of the stimulus were controlled manually.

Procedure

S's observations were made monocularly by wearing an eye patch over the unfavored eye. The temporal exposure was 0.10 sec. for each test stimulus. The inter-stimulus interval was 10 sec.

An ascending method of limits was employed in order to obtain a discrimination threshold which was defined as 50% correct. The rectangles were presented randomly for ten observations in each of two orientations:
horizontal and vertical. The square was presented five times randomly intermixed between the presentations of the rectangles.

The S's were instructed to respond with either "Yes" or "No" in a typical forced choice paradigm. Each S was instructed to respond "Yes" if he identified a square; or "No", if he identified a shape other than a square. In the case when a S saw nothing, he was instructed to guess. Ss were also expected to give a subjective confidence rating, based upon a three point scale: a "1" was defined as a "guess", a "2" was defined as "almost sure", and a "3" was defined as "certainty".

Because of the possible individual differences involved in shape discrimination tasks each S's contrast sensitivity threshold for shapes was determined. In the manner described above, each S was shown a block of 25 stimulus presentations starting below threshold and increasing in 0.05 log unit steps until the S reached 100% discrimination. A measure of shape discrimination at various contrast conditions was necessary for two reasons: (1) it was important to determine if the threshold for both horizontal and vertical rectangles was the same; (2) it served as a reference measure for
empirical comparisons.

What has been explained above is the procedure for procuring the contrast sensitivity function for forced choice discriminations. The independent variable manipulated was the spatial frequency of a square-wave grating presented in a forward masking paradigm. Each S was instructed to monocularly scan back and forth across the center of a grating for a two minute period. The S was then instructed to scan the adaptation grating during the interstimulus interval. The direction of eye scanning was in the opposite direction from the orientation of the adaptation grating, i.e. if the grating was oriented vertically, the S would scan horizontally across the middle of the square-wave field.

Three different masking stimuli were used each day. On any given day the order of presentation of the square-wave gratings was from high to low frequency, i.e. 10, 5, and 3 c/d. On any one day the orientation of the masking gratings was either vertical or horizontal. The order of orientation for one S was the reverse of the order for the other Ss.

At the beginning of a day's run the S was adapted for two minutes to a grating in one orientation. Following this period of adaptation, each S received
25 stimulus presentations at the control threshold contrast as previously determined. The luminance of the stimulus channel was always raised in 0.01 log cd/m² increments and another 25 trials presented (5 squares, 10 horizontal, and 10 vertical rectangles) until discrimination had reached the 50% criterion. There was a two minute period of readaptation between each luminance increment before further psychophysical measures were obtained. Once the discrimination threshold was determined for a particular spatial frequency grating, S was adapted to a square-wave grating of a lower frequency for a two minute period.

Adaptation to a homogenous field of the same average luminance as the adaptation gratings provided a control for eye scanning movements. The control stimulus subtended the same visual angle as the adapting grating and was scanned monocularly in either a horizontal or vertical direction. The average luminance of the control field was 6.71 cd/m².

In Figure 5, the luminance profiles for the square-waves and test figures are presented. The contrast of the figures is defined as the log increment in intensity above background (ΔI + I/I), and the
contrast of the square-wave gratings is the amplitude of a bar divided by its mean luminance level ($\Delta I/I$).
Figure 5

The luminance profile of the square-wave grating and test figure in the horizontal orientation.
Table 1
The contrast of the test stimuli for each subject are expressed in percent contrast at that S's discrimination threshold

(Contrast was determined by the following formula: \( L_H - L_L / L_H \))

<table>
<thead>
<tr>
<th>S's FIGS</th>
<th>TEST (without adaptation)</th>
<th>A NORMAL</th>
<th>B CONTROL (gray adaptation field)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Vertical Scan</td>
<td>Horizontal Scan</td>
</tr>
<tr>
<td>A.C. VR</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>A.C. HR</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>F.F. VR</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>F.F. HR</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>T.G. VR</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>T.G. HR</td>
<td>48</td>
<td>48</td>
<td>48</td>
</tr>
</tbody>
</table>
Figure 6
The empirically observed change in contrast threshold produced by adapting to vertical and horizontal gratings

- vertical adaptation gratings
- horizontal adaptation gratings
- homogeneous adapting field
Table 2

The change in contrast threshold produced by adaptation to vertical and horizontal gratings.
(The numbers are the difference between the log cd/m² threshold measured before and after grating adaptation)

<table>
<thead>
<tr>
<th>S's test</th>
<th>Vertical Adaptation</th>
<th>Horizontal Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figs.</td>
<td>Spatial Frequency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(cycles per degree)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 4 5 6.5 12 24</td>
<td>3 4 5 6.5 12 24</td>
</tr>
<tr>
<td>A.C.</td>
<td>VR .05 .02 .10 .10 .00 .00</td>
<td>.00 .00 .00 .00 .00 .00</td>
</tr>
<tr>
<td></td>
<td>HR .00 .00 .00 .00 .00 .00</td>
<td>.04 .05 .10 .10 .00 .00</td>
</tr>
<tr>
<td>F.F.</td>
<td>VR .02 .02 .10 .10 .00 .00</td>
<td>.00 .00 .00 .00 .00 .00</td>
</tr>
<tr>
<td></td>
<td>HR .00 .00 .00 .00 .00 .00</td>
<td>.02 .02 .10 .10 .00 .00</td>
</tr>
<tr>
<td>T.G.</td>
<td>VR .04 .04 .10 .10 .01 .01</td>
<td>.01 .01 .01 .01 .01 .01</td>
</tr>
<tr>
<td></td>
<td>HR .01 .01 .01 .01 .01 .01</td>
<td>.02 .04 .10 .10 .01 .01</td>
</tr>
</tbody>
</table>
after adaptation to either 12 or 24 c/d square-wave gratings. Figure 6A, reveals that prolonged viewing of a vertically oriented square-wave grating of 3, 4, 5, and 6.5 c/d depressed sensitivity to a vertical rectangle. In Figure 6B, the threshold for horizontal rectangles was elevated after extended adaptation to 3, 4, 5, and 6.5 c/d horizontally oriented, square-wave gratings. Vertically oriented test gratings did not affect the threshold contrast necessary to discriminate the horizontal rectangle.

Both Figures 6A and 6B, were derived by averaging across the 3 Ss and each point is the difference between mean log cd/m² threshold contrast after adaptation to a specific orientation and spatial frequency grating.

Table 2, presents the data for each S and the change in contrast threshold employed to reach 50% correct discrimination. These data indicate that no systematic differences arise between Ss and so the averaging procedure employed to generate the curves in Figure 6 is justifiable. In Table 2, the vertical column represents the test figures and the horizontal row represents the spatial frequency of the masking stimuli. The data indicate that a vertical test figure was masked maximally by a vertical grating of a
specific spatial frequency; and a horizontal test figure was optimally masked by a horizontal grating of a specific spatial frequency. The results using the homogeneous adapting field reveal that the spatial frequency and orientation specificity are due to adaptation and are not an artifact of eye scanning or exposure duration.

To conclude, several regularities were found:

(A) There were only negligible differences in the discrimination threshold between Ss, and no difference in the contrast necessary to discriminate either the horizontal or vertical rectangles. Without prior adaptation, the discrimination threshold for the test figures in different orientations was 48% for all Ss.

(B) As the spatial frequency of the adaptation stimulus was varied from 3-24 c/d, the relative threshold for discrimination was shifted upwards and peaked at 50% after adaptation to 5 and 6.5 c/d gratings. Adaptation to the 3, and 4 c/d gratings raised the threshold slightly (48.5%), and 12 and 24 c/d adaptation gratings resulted in no change in the threshold contrast necessary for pattern discrimination.

(C) A 3, 4, 5, or 6.5 c/d adaptation grating selectively masked a rectangle of the same orientation.
The orientation of the masking stimulus always selectively disrupted the test figure in the same orientation and left unchanged the threshold for the test figure presented in the other orientation.
DISCUSSION

The present paper on the discrimination of aperiodic patterns provides additional evidence for the existence of spatial channels that serve functionally in the analysis of visual patterns. Spatial frequency specific after effects were greatest when adaptation to 5 and 6.5 c/d square-wave gratings were employed to mask rectangular test figures; and thus the adaptation process was found to affect a specific frequency channel previously shown to carry information about rectangularity. In addition, some adaptation occurred at 3 and 4 c/d. A threshold elevation after viewing 3 and 4 c/d gratings may be due to low frequency analyzers that start to signal rectangularity.

An alternate point of view is feature detection which predicts that grating bars which subtend the same visual angle as the test figure will raise its threshold but bars of dissimilar visual angle will not affect the contrast threshold (Thomas, 1970). In order to be consistent with the logic of feature detection theory, the bar width of the adaptation grating of exactly the width of the test rectangle would produce maximum threshold elevation. Kerr and Thomas (1972) have demonstrated that an adaptation
stimulus is most effective in reducing the visibility of stimuli nearest in size to the adaptation stimulus. As can be seen in the results presented in Table 2, the effective adaptation gratings are the 3, 4, 5, and 6.5 c/d square-wave gratings oriented in the same direction as the rectangles. The bar widths of the 3, 4, 5, and 6.5 c/d gratings were 10', 7.5', 6' and 4.6' respectively. Since the test rectangle subtended 11' x 17' of visual angle, the feature detection model predicts that the 3 c/d grating will produce the greatest adaptation. In fact, the data indicate that maximum sensitivity loss occurred when the bar widths are 6' and 4.6'. Some sensitivity loss occurred when the bar width are 7.5' and 10'. These findings do not support the theory that neural bar detectors of a specific width and orientation such as discussed by Kerr and Thomas (1972) are responsible for threshold elevation.

The theory of frequency analysis predicted that the 4 and 6 c/d gratings would elevate the contrast threshold of rectangularity because the major difference between a symmetric figure (the square) and a vertical rectangle is found in the 4 and 6 c/d
frequency band. In order to be consistent with the logic of frequency analysis theory, adaptation to the 4 and 6 c/d frequency range will produce maximum threshold elevation. As can be seen in the results presented in Table 2, adaptation to the 5 and 6.5 c/d is most effective for raising the threshold of the test figures. The vertical rectangle is perceptually equivalent to a non-rectangle between 48% and 50% contrast after adaptation to the 5 and 6.5 c/d vertical square-wave gratings. The orientation specificity found for the vertical rectangle is also found in the horizontal rectangle after extended viewing of 5 and, 6.5 c/d horizontal square-wave gratings. In addition no threshold change is observed after extended viewing of 12 or 24 c/d square-wave gratings nor after adaptation to a homogeneous gray adaptation field. These findings clearly indicate that discrimination of aperiodic patterns may be based upon frequency analysis.

The orientation specificity observed in the present data was not predicted by the frequency analysis model. The frequency analysis model which predicts that the 4 c/d vertical frequency component carries
information about the vertical orientation (See Figure 2), then threshold elevation for the vertical test figure would occur after adaptation to a vertical grating of 4 c/d. Similarly, the 6 c/d horizontal frequency channel contains information about the orientation of the vertical test figure, then adaptation to a 6 c/d horizontal grating would mask the discrimination of a vertical test figure. The data presented in Table 2, reveals that maximum adaptation occurred at 5 and 6.5 c/d rather than 4 c/d, and a vertical grating always masked the vertical figure and never the horizontal. There is no obvious reason, based upon frequency analysis theory why fatiguing the vertically oriented 6 c/d frequency component would mask the vertical test rectangle. A methodology will be proposed later in this report to tease out the role played by a frequency channel in the transmission of orientation specificity.

Further evidence is still necessary, however, to buttress the contention that the basis of pattern discrimination is frequency analysis. One approach that seems crucial for this point of view is to utilize different sized vertical and horizontal rectan-
gles. One advantage that favors employing different sized figures is that it would provide a more adequate test for feature detection because different width receptive fields (not just 11') would be activated. Another advantage in favor of such an extension is that by reducing the dimensions of the rectangles from approximately 3 units x 2 units to 5 units x 4 units would change the critical frequency band in which rectangularity was transmitted. If the critical frequency band for rectangularity was 9 c/d then adaptation to a 9 c/d grating might be expected to elevate the contrast threshold for discriminating a rectangle from a symmetric figure. This prediction, or one like it, must be confirmed as the next step in substantiating that the frequency analysis process is the biological basis for discriminating stimulus equivalences.

One general limitation of this study is the use of only horizontal and vertical masking gratings. The effect of masking either of the two major spatial frequency axes has an unknown influence on neighboring spatial frequency components oriented between the major coordinates. It first appeared that the
role of the spatial frequency components oriented between the major axes were less significant for visual processing than the spatial frequency components on the major axes; however, the equivocal results related to orientation specificity suggest that the influence of the intermediate spatial frequency components may be of greater importance to visual encoding than first assumed. In the present study, the information carried in the intermediate frequency channels was available to the visual system during all phases of experimental measurements. A unique approach to investigate the influence of spatial frequency analysers oriented off the major horizontal-vertical axes would be to utilize a circular sine-wave grating i.e., a quasi-bullseye. A sine-wave disc, of this sort, would affect the detectability of all spatial frequency analysers independent of orientation. Therefore, an investigation could theoretically be carried out, to test the transmission of orientation specificity in the absence of a specific bank of frequency analysers.
SUMMARY AND CONCLUSIONS

Contrast thresholds were measured for complex a-periodic test figures. These figures were low-pass Fourier analysed and it was determined that the 4 and 6 c/d frequency components carried the crucial information about rectangularity: Square-wave adaptation gratings of 3, 4, 5, 6.5, 12 and 24 c/d were viewed for an extended period prior to psychophysical discrimination. Two models of pattern vision were tested (1) a feature detection model in which pattern vision is a function of various width bar analysers and (2) a frequency analysis model in which a pattern is processed by many channels, each sensitive to a narrow range of spatial frequency. Results provide quantitative support for frequency analysis and reject the feature detection model. Additional recommendations are made concerning future research in frequency analysis.
REFERENCES


APPENDIX A

PROGRAM CFT 1
DIMENSION VR(32,32,1), HR(32,32,1)
TYPE COMPLEX VR, HR
READ (60,10) VR
READ (60,10) HR
10 FORMAT (64F1.0)
CALL COMPUTE (VR)
CALL COMPUTE (HR)
STOP
END

SUBROUTINE COMPUTE (DATA)
DIMENSION DATA (32,32,1), M(5), SV1(8), SV2(8), AMP(32,32,1),
SLOPPY(32,32,1)
TYPE COMPLEX TEMP, DATA, SLOPPY
M (1) = M (2) = 5
M (3) = 0
PRINT 10
PRINT 10
PRINT 15, ((DATA(I,J),J = 1,32), I = 1,32)
CALL SETUP (0,M,SV1,SV2,0, IFERR)
CALL FASTF0UR (DATA,M,SV1,SV2,1, IFERR)
DO 5 I = 1,32
DO 5 J = 1,32
TEMP = DATA (I,J,1)
5 AMP(I,J,1) = CABS(TEMP)/1024.
10 FORMAT (1H0)
15 FORMAT (32(2x,F2.0))
PRINT 10
PRINT 20,((AMP(I,J,1),J = 1,16), I = 17,32)
PRINT 20,((AMP(I,J,1),J = 1,16), I = 1,16)
20 FORMAT (16(1X,F7.4))
DO 21 J = 1,32
DO 21 I = 1,32
21 SLOPPY(I,J,1) = DATA (I,J,1)
CALL FASTF0UR(SLOPPY,M,SV1,SV2,-1,IFERR)
DO 23 I = 1,32
DO 23 J = 1,32
23 AMP (I,J) = Sloppy(I,J)
PRINT 10
PRINT 20,((AMP(I,J),J = 1,16), I = 1,32)
DO 50 N = 1,3
DO 25 I = 1,32
DO 25 J = 1,32
APPENDIX A

APPENDIX A. The protocol for the Fast Fourier Analysis program employed in the study of aperiodic pattern discrimination.

25 SLOPPY (I, J, 1) = DATA(I, J, 1)
   N1 = N + 2
   N2 = 32 - 1
   DO 30 I = N1, N2
   DO 30 J = 1, 32
30 SLOPPY (I, J, 1) = 0
   DO 40 J = N1, N2
   DO 40 I = 1, 32
40 SLOPPY (I, J, 1) = 0
   PRINT 10
   PRINT 10
   DO 45 I = 1, 32
   DO 45 J = 1, 32
45 AMP (I, J, 1) = CABS(SLOPPY(I, J, 1))/1024.
   PRINT 20, ((AMP(I, J, 1), J = 1, 16), I = 17, 32)
   PRINT 20, ((AMP(I, J, 1), J = 1, 16), I = 1, 16)
   CALL FASTFOUR (SLOPPY, M, SV1, SV2, -1, IFERR)
   DO 48 I = 1, 32
   DO 48 J = 1, 32
48 AMP(I, J) = SLOPPY(I, J)
   PRINT 10
   PRINT 10
50 PRINT 20, ((AMP(I, J), J = 1, 16), I = 1, 32)